Bioeconomic implications of solid aquaculture waste generation in hybrid grouper nursery systems under different stocking densities

[1,3]Wiwin Kusuma A. Putra, [1,4]Irzal Effendi, [1]Tatag Budiardi, [1]Iis Diatin, [2,5]Luky Adrianto

[1] Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Bogor, Indonesia; [2] Department of Aquatic Resource Management, Faculty of Fisheries and Marine Science, IPB University, Bogor, Indonesia; [3] Department of Aquaculture, Faculty of Marine Science and Fisheries, Raja Ali Haji Maritime University, Tanjungpinang, Indonesia; [4] Center for Regional System Analysis, Planning and Development (CrestPent), IPB University, Bogor, Indonesia; [5] Center of Coastal and Marine Resources Studies, International Research Institute for Marine, Ocean and Fisheries, IPB University, Bogor, Indonesia. Corresponding author: I. Effendi, irzalef@apps.ipb.ac.id

Abstract. Aquaculture intensification increases the accumulation of solid waste derived from uneaten feed and fish excretion, which may reduce water quality and compromise production efficiency. At the same time, such waste may represent a recoverable resource within circular aquaculture systems. This study evaluated solid waste generation under different stocking densities in a hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) nursery system and estimated its economic value using a willingness-to-pay (WTP) approach. The study was conducted from February to March 2025 using a completely randomized design with three stocking densities, namely 10, 30, and 50 fish per 0.5 m³ enclosure, with three replicates, over a 28-day culture period. Solid waste accumulation, water quality, biological performance, and economic valuation were analyzed. Solid waste production differed among treatments, with the highest accumulation recorded at the intermediate density, 926.39 g, whereas the highest density treatment produced lower solid waste, 87.35 g, due to early mortality associated with water-quality deterioration. The highest density also showed the highest ammonia, 1.76 mg L^{-1}, and hydrogen sulfide, 2.34 mg L^{-1}, indicating that the carrying capacity of the nursery system had been exceeded. The WTP survey involved 110 valid respondents and showed that the mean WTP for solid aquaculture waste was Rp4,527 kg^{-1}, equivalent to USD0.25 kg^{-1}, with observed values ranging from Rp0 to Rp23,000 kg^{-1}, equivalent to USD0.00-1.28 kg^{-1}. Bioeconomic evaluation indicates that the intermediate stocking density provides the most balanced outcome in terms of biomass retention, environmental stability, and recoverable waste value. These findings demonstrate that solid nursery waste can be quantified not only as an environmental burden but also as a potential bioeconomic resource, providing baseline information for circular aquaculture and Integrated Multi-Trophic Aquaculture development.

Keywords: carrying capacity, circular aquaculture, environmental valuation, nutrient recovery, resource recovery, willingness-to-pay.

Introduction. Aquaculture has become one of the fastest-growing food production sectors globally and plays a crucial role in meeting the increasing demand for aquatic protein (FAO, 2022; Afewerki et al., 2023; Huang et al., 2023). Intensification of aquaculture practices, particularly through increased stocking density and higher feeding rates, can improve production output and efficiency (Miller & Semmens, 2002; Dauda et al., 2019; Dewi et al., 2020; Diatin et al., 2021; Firdausi & Mubarak, 2021; Astari et al., 2023; Huang et al., 2023). However, intensification also increases the production of aquaculture waste, including uneaten feed, feces, and metabolic by-products. If not properly managed, these wastes may accumulate in culture systems and surrounding aquatic environments, leading to water quality deterioration and ecological imbalance (Boyd, 2020; Verreth et al., 2023; Masi et al., 2024; Cozzolino et al., 2025; Arduini et al., 2026). Solid aquaculture waste is one of the major environmental challenges in intensive fish culture systems (Miller & Semmens, 2002). Organic particulate waste and dissolved nutrients, particularly nitrogen and phosphorus, may contribute to eutrophication, oxygen depletion, and nutrient enrichment in receiving waters (Bureau & Hua, 2010; Lamprianidou et al., 2015). Only part of the feed input is converted into fish biomass, while the remaining nutrients are released into the culture environment as waste. Therefore, improving waste management has become an important component of sustainable aquaculture development.

In recent years, circular aquaculture has emerged as a promising approach to improve resource-use efficiency by converting waste-derived nutrients into recoverable resources (Tan & Lamers, 2021; Verreth et al., 2023; Checa et al., 2024; Arduini et al., 2026). Within this framework, aquaculture waste is no longer viewed only as an environmental burden, but also as a potential resource containing organic carbon, nitrogen, and phosphorus. One of the most widely recognized approaches for applying circular aquaculture is Integrated Multi-Trophic Aquaculture (IMTA), in which waste and nutrients released from fed species can be utilized by extractive organisms such as detritivores, filter feeders, and primary producers (Ahmad & Abdullah, 2025; Ruiz-Vanoye et al., 2025; Estévez Hernández et al., 2026; Lasco et al., 2026; Wang et al., 2026). Through nutrient recycling, IMTA has the potential to reduce waste accumulation while improving production efficiency and environmental sustainability.

Despite increasing attention to aquaculture waste management, most previous studies have focused mainly on nutrient discharge and environmental impacts in grow-out systems. Limited information is available on solid waste generation during the nursery phase, particularly in small-scale tank-based grouper nursery systems commonly used by coastal farmers. Furthermore, most studies have not integrated biological quantification of solid waste with economic valuation. As a result, the potential economic value of aquaculture waste and its role as a bioeconomic resource in circular aquaculture remain insufficiently understood.

This study addresses this gap by integrating solid waste quantification, water quality assessment, biological performance evaluation, and willingness-to-pay-based economic valuation in a hybrid grouper nursery system. Specifically, this study aimed to: (1) quantify solid aquaculture waste generation under different stocking densities, (2) evaluate the effects of stocking density on water quality dynamics and biological performance, and (3) assess the potential economic value of aquaculture waste using a willingness-to-pay approach. By combining ecological and economic perspectives, this study provides a bioeconomic framework for improving nursery waste management and supporting the development of circular aquaculture and IMTA systems.

Material and Method

Study area. The study was conducted from February to March 2025 in a small-scale aquaculture facility located in Kampung Madong, Kampung Bugis Village, Tanjungpinang City, Riau Islands Province, Indonesia. The area is one of the coastal aquaculture locations where grouper nursery activities are commonly practiced using tarpaulin tank systems. The experiment was carried out under controlled nursery conditions using tarpaulin tanks to simulate typical small-scale grouper nursery practices in coastal aquaculture systems.

Experimental design. The experiment employed a completely randomized design consisting of three stocking density treatments with three replicates each. The treatments were defined based on the number of grouper juveniles stocked in each net enclosure (waring). The treatments were as follows:
- treatment A: stocking density 10 fish 0.5 m^{-3};
- treatment B: stocking density 30 fish 0.5 m^{-3};
- treatment C: stocking density 50 fish 0.5 m^{-3}.

The selected stocking densities represent culture conditions ranging from relatively low to high intensity based on grouper nursery standards reported in technical guidelines and aquaculture literature, which recommend stocking densities between 25 and 125 fish m^{-3} for juveniles of approximately 10 cm length.

Grouper nursery conditions. The nursery experiment was conducted in tarpaulin tanks measuring 100 cm × 200 cm × 100 cm, each filled with seawater to a depth of approximately 40-45 cm. Each tank contained a net enclosure (waring) measuring 1 m × 1 m × 0.5 m, which served as the culture unit for grouper juveniles. A total of 270 hybrid grouper juveniles (*Epinephelus fuscoguttatus* × *E. lanceolatus*) with an average length of approximately 10 cm were used in the experiment. Fish were obtained from Bintan Nursery Grouper Hatchery, Pengujan, Bintan Regency. Each tank was equipped with eight aeration stones, installed approximately 9 cm above the tank bottom with a spacing of about 40 cm to ensure adequate oxygen distribution. Seawater used for culture was collected during high tide conditions and filtered before entering a reservoir tank, from which it was pumped into each culture tank. Fish were fed commercial pellet feed (Megami GR4) containing approximately 45-48% crude protein. Feeding was conducted at 7% of fish biomass per day, divided into two feeding times per day. Water exchange was conducted daily at approximately 75% of the total tank volume to maintain suitable water quality conditions.

Research parameters

Waste accumulation and collection. Unlike typical culture systems where accumulated solid aquaculture waste is periodically removed, no siphoning of waste was performed during the culture period. Uneaten feed and fish feces were intentionally allowed to accumulate at the bottom of the tarpaulin tanks to quantify the total waste generated during the nursery phase. At the end of the experiment, the accumulated solid aquaculture waste was collected using a filter cloth and weighed to determine the total wet weight of waste produced in each treatment. Waste samples were also dried in an oven to obtain dry weight measurements for further analysis. This approach was used to estimate the potential quantity of solid aquaculture waste that may serve as nutrient input in future integrated aquaculture systems.

Biological performance parameters. Several biological performance parameters were measured during the experiment, including: absolute weight growth 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 length growth 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); specific growth rate 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 lenght rate was calculated as $SGRL = [(\ln L_t - \ln L_0) / t] \times 100$; feed convertion ratio 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 was calculated as $FE = \{[(B_t + B_D) - B_0] / F\} \times 100$; survival rate 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; mortality rate was calculated as $MR (\%) = [(N_0 - N_t) / N_0] \times 100$ where MR is the mortality rate (%), N_0 is the initial number of fish (individuals), and N_t is the number of surviving fish at the end of the culture period (individuals); and total production was calculated as $TP = N_t \times W_t$ where TP is the total production (g), N_t is the number of surviving fish at the end of the culture period (individuals), and W_t is the mean final body weight of fish (g individual^{-1}). Fish length and weight measurements were conducted on day 0, day 14, and day 28 using a digital scale with a precision of 0.01 g and a measuring board for total length.

Water quality monitoring. Water quality parameters were monitored throughout the experiment. Daily measurements included: dissolved oxygen, total nitrogen in water, total ammonia nitrogen (TAN), ammonia, phospate, nitrite, nitrate, hydrogen sulfide, total phosphorus in solid waste, total organic matter, total dissolved solids (TDS), total suspended solids (TSS), total bacterial count, total *Vibrio* count, temperature, salinity, pH, plankton abundance, and total solid waste biomass. Water samples (1.5 L per treatment) were collected and analyzed in several laboratories, including: BPBL Batam Environmental Laboratory, Aquaculture Department Laboratory, IPB University and Marine Chemistry Laboratory, Universitas Maritim Raja Ali Haji (UMRAH).

Willingness-to-pay survey. The economic valuation of solid aquaculture waste was estimated using the Contingent Valuation Method (CVM) based on respondents' willingness to pay (WTP). A structured questionnaire was distributed to 110 respondents, including fish farmers, academics, and community members familiar with aquaculture activities. Respondents were presented with a hypothetical scenario describing the potential use of solid aquaculture waste products and were asked to indicate the maximum price they were willing to pay for: solid aquaculture waste (kg^{-1}), solid aquaculture waste (L^{-1}). The survey results were used to estimate the mean willingness-to-pay (EWTP) and total willingness-to-pay (TWTP) for solid aquaculture waste products.

Economic valuation. The economic valuation included estimation of: economic value of solid aquaculture waste was estimated as the product of the quantity of solid waste generated in each treatment and the EWTP obtained from the survey: $EVW_i = QW_i \times EWTP$ (where EVWi represents the economic value of solid waste in treatment i (USD), QWi is the quantity of solid waste produced (kg), and EWTP is the mean willingness-to-pay (USD kg^{-1}); production value of grouper nursery was calculated based on total output obtained at the end of the culture period. When fish were valued per individual, production value was estimated as: $PV_i = N_i \times P_f$ (where PVi is the production value in treatment i (USD), Ni is the number of surviving fish at harvest (individuals), and P_f is the selling price per fish (USD individual^{-1}); economic loss caused by fish mortality was estimated based on the number of fish that died during the culture period: $ELMi = Ndead,i \times P_f$ (where $ELMi$ represents the economic loss due to mortality in treatment i (USD), $Ndead,i$ is the number of dead fish, and P_f is the unit price per fish (USD individual^{-1}). Economic valuation was based on the WTP value obtained from the survey combined with the quantity of waste produced in each treatment.

Data analysis*.* Data on biological performance, solid aquaculture waste, water quality, and economic parameters were analyzed using analysis of variance (ANOVA). Prior to ANOVA, the assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk test and Levene's test, respectively. When the assumptions were not fully met, the affected variables were interpreted with caution, and Welch's ANOVA was considered for variables showing heterogeneity of variance. When significant differences were detected among treatments, Tukey's post hoc test was applied to identify pairwise differences between treatments. All statistical analyses were conducted using JAMOVI statistical software, with significance determined at $p < 0.05$. WTP data were analyzed descriptively by calculating the minimum, maximum, median, mean, and standard deviation values, and were used to estimate the economic value of solid aquaculture waste. The results were presented in tables and graphical forms to facilitate interpretation. This study integrates biological performance, environmental parameters, and economic valuation to provide a bioeconomic assessment of stocking density in grouper nursery systems.

Results

Statistical analysis*.* Prior to conducting ANOVA, the assumptions of normality and homogeneity of variance were evaluated. The Shapiro–Wilk test indicated that most variables followed a normal distribution ($p > 0.05$), except for economic loss from solid waste, which deviated from normality ($p < 0.05$). Levene's test showed that most variables met the assumption of homogeneity ($p > 0.05$). However, absolute weight gain, feed conversion ratio, and total production exhibited heterogeneity of variances ($p < 0.05$); therefore, these variables were interpreted with caution.

The one-way ANOVA results showed that stocking density had a significant effect ($p < 0.05$) on absolute weight gain, specific length growth rate, survival rate, mortality rate, total production, economic loss due to mortality, and economic loss from solid waste. In contrast, no significant differences were observed among treatments for absolute length gain, specific growth rate based on weight, feed conversion ratio, and feed efficiency ($p > 0.05$). Although feed conversion ratio showed heterogeneity of variance, the treatment effect was not statistically significant; thus, its interpretation was made cautiously.

For variables showing significant differences, Tukey's post hoc test was performed to identify pairwise differences among treatments. The results indicated that significant differences occurred mainly between the highest stocking density treatment and the lower-density treatments, particularly for survival, mortality, and total production. Overall, stocking density significantly influenced biological performance and production efficiency in hybrid grouper nursery systems, with the intermediate density providing the most balanced response in terms of survival, biomass retention, and economic outcome.

Biological performance. Biological performance of hybrid grouper juveniles varied across stocking density treatments. Absolute weight growth, absolute length growth, specific growth rate, specific length rate, feed conversion ratio, and feed efficiency are presented in Figures 1-6. Fish cultured at the lowest stocking density, treatment A with 10 fish per 0.5 m^3 enclosure, showed better individual growth performance, particularly in absolute weight gain. However, treatment B with 30 fish per 0.5 m^3 enclosure provided a more balanced production response because it maintained high survival and produced higher total biomass than the other treatments.

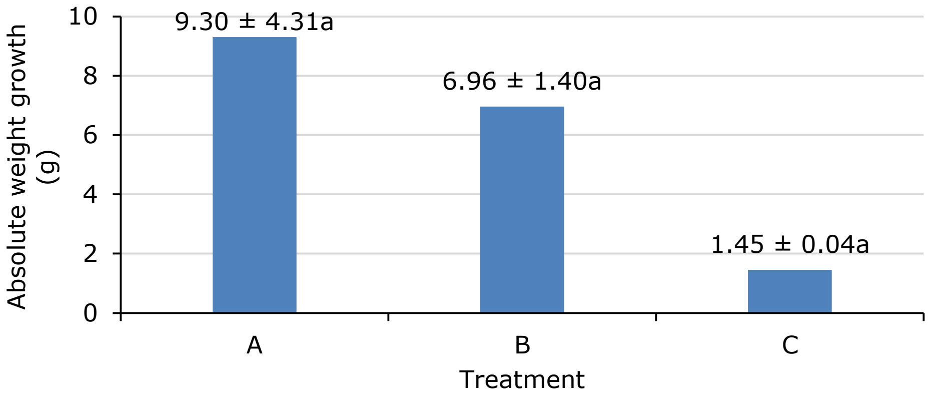

Figure 1. Absolute weight growth of grouper under different treatments.

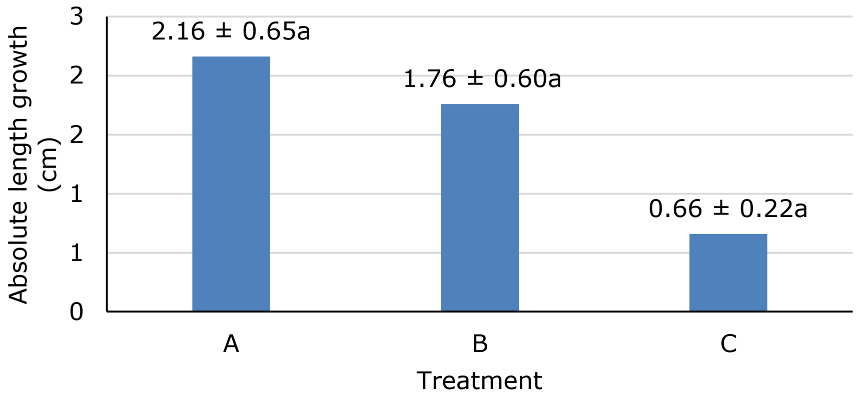

Figure 2. Absolute length growth of grouper under different treatments.

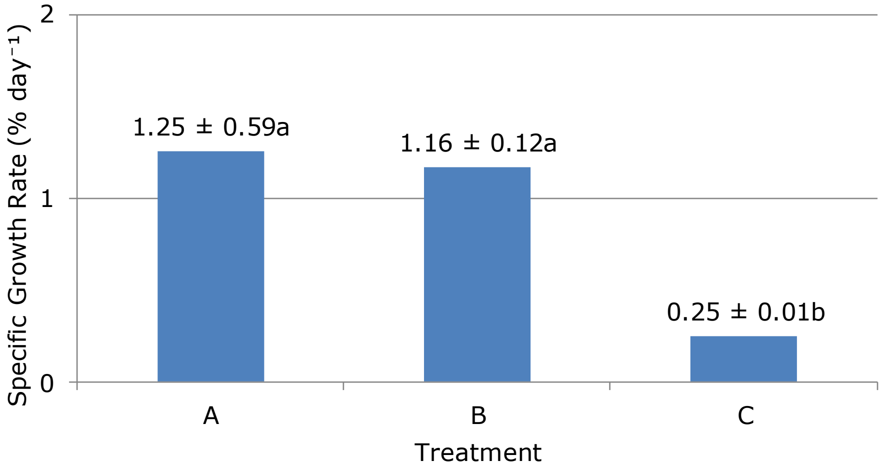

Figure 3. Specific growth rate of grouper under different treatments.

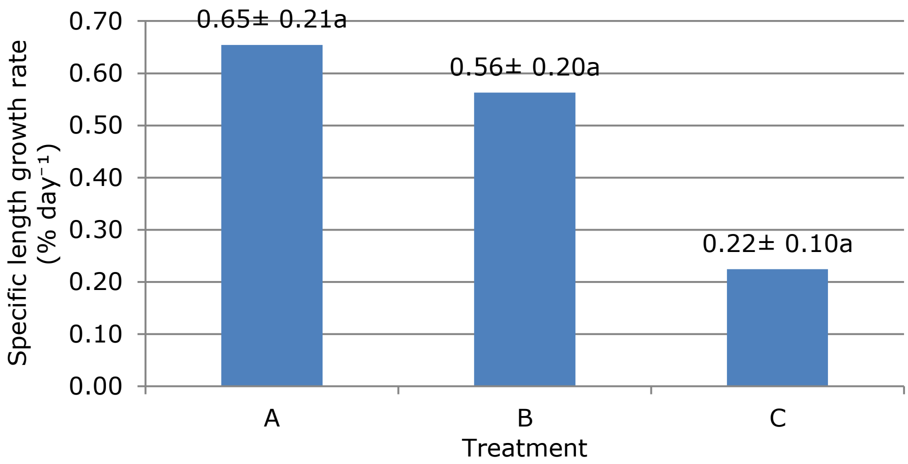

Figure 4. Specific length growth rate of grouper under different treatments.

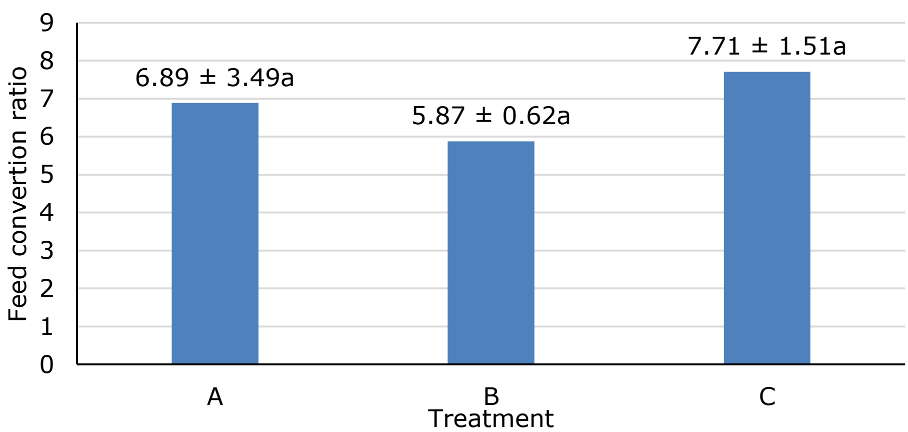

Figure 5. Feed convertion ratio of grouper under different treatments.

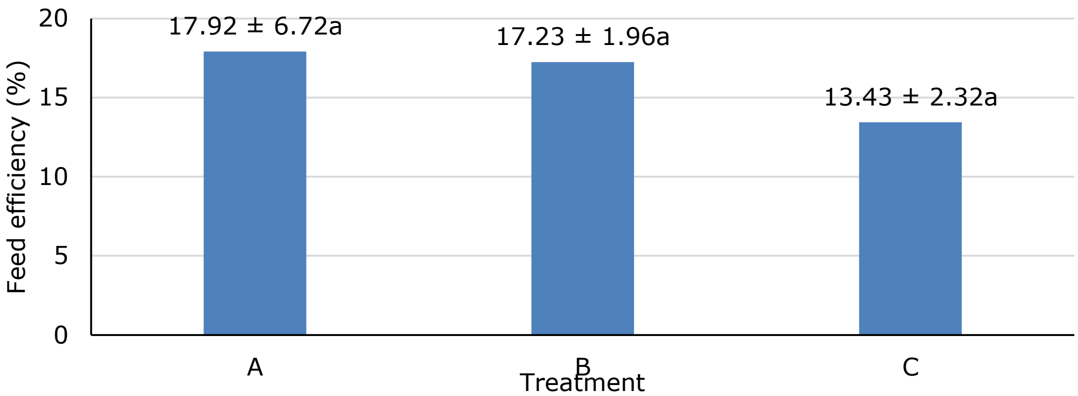

Figure 6. Feed efficiency of grouper under different treatments.

Survival rate and mortality rate are shown in Figures 7 and 8. The survival rate was 70% in treatment A and 72% in treatment B, whereas treatment C showed complete mortality by the end of the culture period. Accordingly, the mortality rates were 30% in treatment A, 28% in treatment B, and 100% in treatment C. These values confirm the consistency between survival and mortality data. Total production is shown in Figure 9, where treatment B produced the highest final biomass. Fish stocked at the highest density, treatment C with 50 fish per 0.5 m³ enclosure, experienced early mortality between day 8 and day 10, resulting in no final harvest biomass. These results indicate that excessive stocking density may negatively affect fish growth and survival due to increased physiological stress and deterioration of water quality conditions.

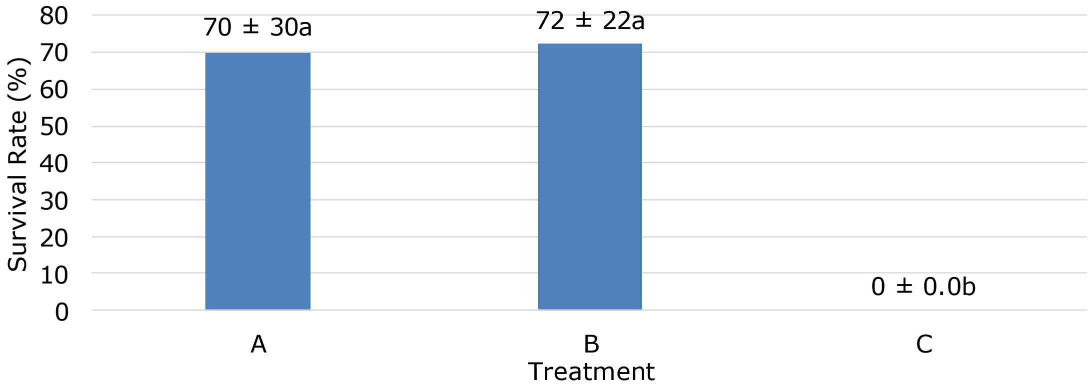

Figure 7. Survival rate of hybrid grouper juveniles under different stocking density treatments.

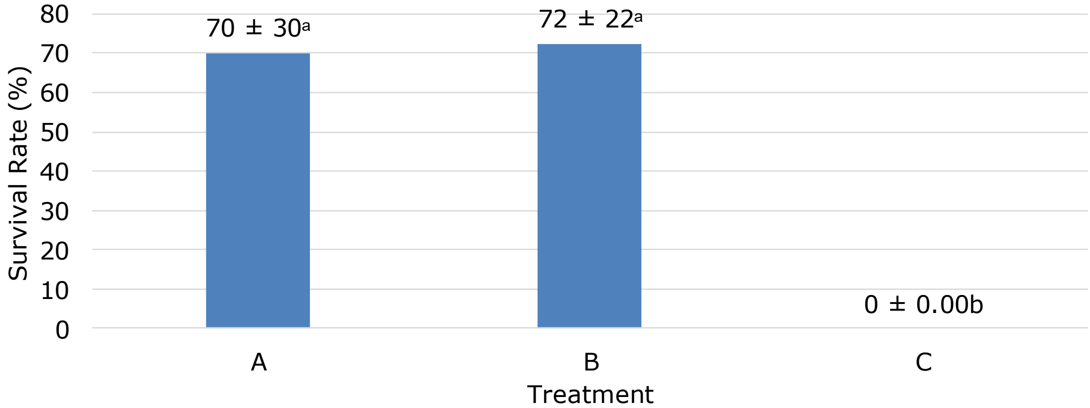

Figure 8. Mortality rate of hybrid grouper juveniles under different stocking density treatments.

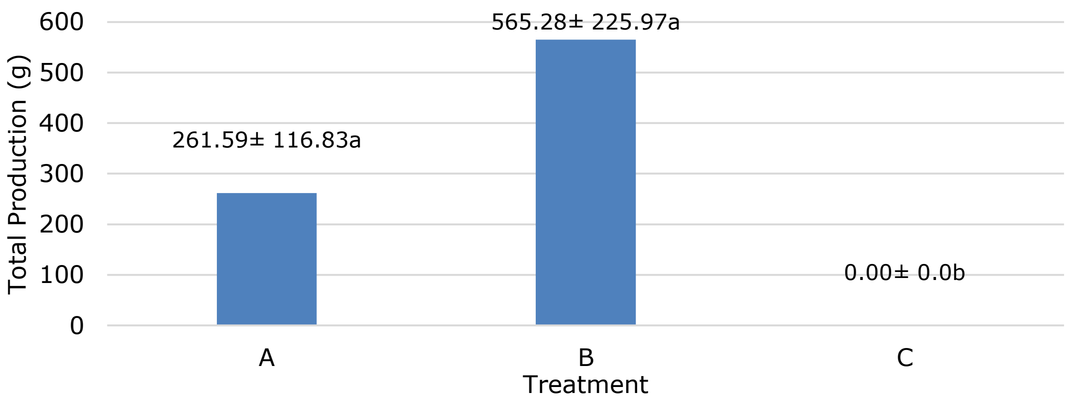

Figure 9. Total production of grouper under different treatments.

Water quality. Water quality parameters measured during the experiment are presented in Table 1.

Table 1

Water quality parameters were monitored throughout the experiment

Parameters	*Unit*	*Water quality on treatment*		
		A	*B*	*C*
Dissolved oxygen	mg L^{-1}	5.57 ± 0.45^a	5.65 ± 0.55^a	4.83 ± 0.53^a
Total nitrogen in water	mg L^{-1}	1.64 ± 0.09^a	1.89 ± 0.47^a	1.22 ± 0.41^a
Ammonia	mg L^{-1}	0.62 ± 0.58^a	0.54 ± 0.27^a	1.76 ± 0.48^a
Phospate	mg L^{-1}	0.12 ± 0.07^a	0.32 ± 0.03^a	0.32 ± 0.28^a
Nitrite	mg L^{-1}	0.55 ± 0.32^{ab}	0.96 ± 0.02^a	0.09 ± 0.08^b
Nitrate	mg L^{-1}	4.00 ± 1.04^b	7.00 ± 1.21^a	2.73 ± 0.40^b
Hydrogen sulfide	mg L^{-1}	0.03 ± 0.01^b	0.02 ± 0.01^b	2.34 ± 0.11^a
Total phosphorus in solid waste	mg L^{-1}	8.67 ± 0.07^a	1.38 ± 0.04^a	3.78 ± 0.15^a
Total organic matter	mg L^{-1}	56.62 ± 5.42^a	70.06 ± 4.62^a	76.09 ± 8.08^a
Total dissolved solids	mg L^{-1}	32.267 ± 403^a	30.900 ± 1.208^a	31.400 ± 1.840^a
Total suspended solids	mg L^{-1}	15.00 ± 9.27^a	9.23 ± 6.20^a	6.00 ± 1.41^a
Total bacterial count	CFU mL^{-1}	20.467 ± 11.681^a	16.067 ± 9.940^a	5.727 ± 4.421^a
Total *Vibrio* count	CFU mL^{-1}	2.547 ± 1.331^a	803 ± 848^a	2.673 ± 3.556^a
Temperature	°C	25.43 ± 0.25^a	26 ± 0.78^a	26.57 ± 0.17^a
Salinity	ppt	31.00 ± 0.00^a	30.33 ± 0.94^a	29.33 ± 0.47^a
pH	-	7.50 ± 0.17^a	7.39 ± 0.22^a	7.40 ± 0.22^a
Plankton abundance	Ind m^{-3}	$1.893.333 \pm 811.473^a$	400.000 ± 65.320^a	$1.946.667 \pm 779.287^a$
Total solid waste biomass	g	241.55	926.39	87.35

Values are presented as mean±standard deviation. Different superscript letters within the same row indicate significant differences among treatments ($p < 0.05$).

Dissolved oxygen concentrations ranged from 4.83 to 5.65 mg L^{-1} across treatments, with the lowest value recorded in treatment C. Although dissolved oxygen was numerically lower in the highest stocking density treatment, no significant differences were observed among treatments, as indicated by the same superscript letters. This suggests that oxygen concentration remained within a relatively comparable range among treatments during the observation period. Nitrogen-related parameters showed noticeable variation among treatments. Total nitrogen in water ranged from 1.22 to 1.89 mg L^{-1}, with the highest value recorded in treatment B. Ammonia concentrations were numerically highest in treatment C, reaching 1.76 mg L^{-1}, compared with 0.62 mg L^{-1} in treatment A and 0.54 mg L^{-1} in treatment B. However, ammonia did not differ significantly among treatments. Phosphate concentrations were 0.12±0.07, 0.32±0.03, and 0.32±0.28 mg L^{-1} in treatments A, B, and C, respectively, with no significant differences among treatments ($p > 0.05$). Total phosphorus in the solid waste was highest in treatment A (8.67±0.07 mg L^{-1}), followed by treatment C (3.78±0.15 mg L^{-1}) and treatment B (1.38±0.04 mg L^{-1}). Based on the statistical notation, total phosphorus did not differ significantly among treatments ($p > 0.05$). Nitrite and nitrate showed significant differences among treatments. Nitrite was highest in treatment B, whereas the lowest value was recorded in treatment C. Similarly, nitrate concentration was highest in treatment B and significantly higher than those in treatments A and C. These results indicate that nitrogen dynamics varied among stocking density treatments, likely reflecting differences in feed input, fish survival, organic matter accumulation, and microbial transformation processes. Hydrogen sulfide (H_2S), a toxic compound generated during the anaerobic decomposition of organic matter, showed a clear and significant increase in treatment C. The H_2S concentration in treatment C reached 2.34 mg L^{-1}, whereas treatments A and B showed much lower concentrations of 0.03 and 0.02 mg L^{-1}, respectively. This result indicates that the highest stocking density treatment experienced greater organic matter decomposition under unfavorable bottom conditions, which may have contributed to environmental stress and fish mortality during the culture period.

Other water quality parameters, including temperature, salinity, pH, total organic matter, total dissolved solids, total suspended solids, total bacterial count, total *Vibrio* count, and plankton abundance, showed no significant differences among treatments. Temperature ranged from 25.43 to 26.57°C, salinity ranged from 29.33 to 31.00 ppt, and pH ranged from 7.39 to 7.50. These relatively stable values suggest that differences in fish performance were more closely associated with organic waste accumulation and toxic nitrogen or sulfur compounds than with general physical water quality parameters. The accumulation of solid aquaculture waste differed markedly among stocking density treatments (Table 1). The highest total solid waste biomass was recorded in treatment B, with 926.39 g, followed by treatment A, with 241.55 g. In contrast, treatment C produced the lowest solid waste biomass, with 87.35 g. Although treatment C had the highest initial stocking density, the relatively low waste accumulation observed in this treatment was associated with early fish mortality, which reduced feed consumption, fecal production, and subsequent metabolic waste generation. In treatments A and B, fish remained alive for a longer duration of the culture period, allowing uneaten feed and fecal material to accumulate progressively at the bottom of the culture tanks. The higher waste accumulation in treatment B indicates that the intermediate stocking density maintained sufficient biomass and feeding activity while avoiding the severe mortality observed in treatment C. These findings suggest that solid waste generation in grouper nursery systems is influenced not only by initial stocking density, but also by fish survival, feeding activity, and biomass retention during the culture period.

Economic valuation of aquaculture waste based on willingness to pay. The economic valuation of aquaculture waste was conducted using a WTP survey to determine the potential economic value or price of aquaculture waste generated from fish culture activities. The survey involved 110 respondents, all of whom were considered valid and included in the analysis. The characteristics of respondents indicate that most participants had either direct or indirect involvement in aquaculture activities and aquatic environmental management.

Based on the survey results, most respondents were male and had direct involvement in aquaculture activities. Respondents came from various professional backgrounds, including academics or researchers, government employees, fish farmers, students, and the general public. This condition indicates that most respondents had adequate understanding of aquaculture practices, waste management, and the environmental impacts of aquaculture activities. The characteristics of respondents are presented in Table 2.

A total of 110 respondents were included in this study. Based on the questionnaire results, respondents were classified into two categories: those who were willing to pay and those who were not willing to pay. The number and percentage of respondents in each category are presented in Table 3.

Most respondents showed willingness to pay for the management or utilization of aquaculture waste. This finding indicates that fish farmers or aquaculture stakeholders have begun to recognize the importance of waste management in maintaining aquaculture environmental quality and increasing the economic value of aquaculture waste.

Table 2

Characteristics of respondents participating in the WTP survey

Variable	*Category*	*Frequency*	*Percentage (%)*
Gender	Male	89	80.91
	Female	21	19.09
Education	Senior high school	18	16.36
	Diploma	14	12.73
	Bachelor's degree	52	47.27
	Postgraduate degree	26	23.64
Occupation	Academics/researchers	34	30.91
	Government employees	26	23.64
	Fish farmers	18	16.36
	Students	20	18.18
	Others	12	10.91
Aquaculture involvement	Yes	92	83.64
	No	18	16.36

Table 3

Number of respondents willing and not willing to pay

Respondent category	*Number*	*Percentage (%)*
Willing to pay	104	94.5
Not willing to pay	6	5.5
Total	110	100.0

Multiple linear regression analysis was used to determine the influence of respondent characteristics on WTP values. The independent variables used in the model included age, aquaculture experience, education, income, and knowledge of the IMTA system. The general form of the multiple linear regression model is as follows:

$$Y = a + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + e$$

where Y is the WTP value, a is the constant, X_1 is age, X_2 is aquaculture experience, X_3 is education, X_4 is income, X_5 is knowledge of IMTA, b_1-b_5 are regression coefficients, and e is the error term.

The estimated coefficients of the multiple regression model are presented in Table 4.

Table 4

Estimated coefficients of the multiple regression model

Variable	*Coefficient*	*Direction of effect*	*Description*
Constant	1.245	Positive	Baseline WTP value
Age	-0.021	Negative	Older respondents tend to have lower WTP
Experience	0.118	Positive	More experienced respondents tend to have higher WTP
Education	0.337	Positive	Higher education increases WTP
Income	0.562	Positive	Higher income increases WTP
Knowledge of IMTA	0.441	Positive	Better understanding of IMTA increases WTP

Based on the estimated regression coefficients shown in Table 4, the WTP regression equation in this study can be expressed as follows:

$$Y = 1.245 - 0.021X_1 + 0.118X_2 + 0.337X_3 + 0.562X_4 + 0.441X_5 + e$$

This equation indicates that age had a negative effect on WTP, whereas aquaculture experience, education, income, and knowledge of IMTA had positive effects on WTP. The age coefficient of −0.021 indicates that increasing respondent age was associated with a slight decrease in WTP. In contrast, the aquaculture experience coefficient of 0.118 indicates that respondents with longer experience in aquaculture tended to have higher willingness to pay for the management or utilization of aquaculture waste.

The education coefficient of 0.337 indicates that respondents with higher education levels tended to have higher WTP. This suggests that education contributes to better understanding of waste management and the economic value of aquaculture waste. Income had the largest coefficient, 0.562, indicating that income was the strongest factor influencing respondents' ability and willingness to pay. In addition, the coefficient for knowledge of IMTA was 0.441, indicating that respondents who understood the IMTA system tended to have higher WTP because they recognized the potential of aquaculture waste as an additional economic resource.

The distribution of WTP values for aquaculture waste showed considerable variation among respondents. For solid waste, WTP values ranged from Rp0 to Rp25,000 kg^{-1}, equivalent to USD0.00-1.28 kg^{-1}, whereas for liquid waste, WTP values ranged from Rp0 to Rp23,000 L^{-1}, equivalent to USD0.00-1.28 L^{-1}. Most respondents provided WTP values in the range of Rp500-Rp5,000, equivalent to approximately USD0.03-0.28, indicating that aquaculture waste was generally still perceived as a by-product with relatively low economic value. However, several respondents assigned much higher WTP values than the majority. This indicates that some respondents recognized the potential utilization of aquaculture waste as a value-added product, such as organic fertilizer, biofloc material, compost, or other bio-based products. The descriptive statistics of WTP values are presented in Table 5.

Table 5

Descriptive statistics of willingness to pay for aquaculture waste

Waste type	*Unit*	*Minimum*	*Median*	*Mean (EWTP)*	*Maximum*	*Standard deviation*
Solid waste	USD kg^{-1}	0.00	0.11	0.25	1.28	High
Liquid waste	USD L^{-1}	0.00	0.06	0.23	1.28	High

Note: The exchange rate used for conversion was USD1 = Rp18,000.

The large variation in WTP values indicates a right-skewed distribution, in which most respondents provided relatively low WTP values, while a few respondents provided very high values that increased the overall mean. The EWTP for solid aquaculture waste was estimated at Rp4,527 kg^{-1}, equivalent to USD0.25 kg^{-1}, slightly higher than the EWTP for liquid waste, which was Rp4,118 L^{-1}, equivalent to USD0.23 L^{-1}. The higher EWTP for solid waste may be attributed to its easier utilization as organic fertilizer or compost, whereas liquid waste generally requires additional treatment, such as filtration or processing, before it can be optimally utilized.

To estimate the aggregate economic value of aquaculture waste utilization, the TWTP was calculated by multiplying the EWTP by the number of potential users. In this study, the number of fish nursery business units was assumed to be 300,000 based on data from the Ministry of Marine Affairs and Fisheries. The estimated EWTP and TWTP values expressed in USD are presented in Table 6.

Based on this approach, the estimated TWTP was Rp1,358,100,000, equivalent to USD75,450.00, for solid waste and Rp1,235,400,000, equivalent to USD68,633.33, for liquid waste. These results indicate that aquaculture waste has measurable economic potential if it can be properly utilized within a circular aquaculture framework.

Table 6
Estimated EWTP and TWTP of aquaculture waste

Waste type	*EWTP*	*Population of nursery business units*	*TWTP*
Solid waste	USD0.25 kg^{-1}	300,000	USD75,450.00
Liquid waste	USD0.23 L^{-1}	300,000	USD68,633.33

The economic value of solid waste was estimated by multiplying the weight of waste by the EWTP for solid waste, which was Rp4,527 kg^{-1}, equivalent to USD0.25 kg^{-1}. The results show that treatment B generated the highest economic value of waste compared with the other treatments. This indicates that the greater the amount of waste generated, the greater the potential economic value that may be lost if the waste is not reused. The estimated economic value of solid waste from hybrid grouper nursery under different stocking densities is presented in Table 7.

Based on the estimation shown in Table 7, treatment B contributed the highest proportion of solid waste, accounting for 73.80% of total aquaculture waste, whereas treatments A and C contributed 19.24% and 6.96%, respectively. Treatment B also generated the highest economic value of solid waste, with an estimated value of USD0.233 per treatment unit, followed by treatment A with USD0.061 and treatment C with USD0.022. The high contribution of waste in treatment B indicates that a large proportion of nutrients and feed was not fully utilized and was instead converted into solid waste.

Table 7
Estimated economic value of solid waste from hybrid grouper nursery under different stocking densities

Treatment	*Waste weight (kg)*	*Waste percentage (%)*	*WTP (USD kg^{-1})*	*Economic value of waste per treatment (USD)*
A	0.24155	19.24	0.25	0.061
B	0.92639	73.80	0.25	0.233
C	0.08735	6.96	0.25	0.022

Note: The exchange rate used for conversion was USD1 = Rp18,000.

To describe the potential economic loss from waste at a broader scale, a simulation was conducted by assuming that each treatment represented 300,000 fish nursery business units, based on data from the Ministry of Marine Affairs and Fisheries. The total economic value of lost solid waste was calculated by multiplying the economic value of waste per business unit by the number of nursery business units. The estimation results expressed in USD are presented in Table 8.

Table 8
Estimated total economic value of lost solid waste in a monoculture system under different stocking densities

Treatment	*Economic value of waste per business unit (USD)*	*Number of business units*	*Total economic value of waste (USD)*
A	0.061	300,000	18,225.00
B	0.233	300,000	69,896.17
C	0.022	300,000	6,584.33
Total	0.316		94,705.50

Note: The exchange rate used for conversion was USD1 = Rp18,000.

The estimation results show that if 300,000 fish nursery business units had similar waste production characteristics, the total economic value of lost solid waste would reach approximately USD94,705.50. Treatment B contributed the largest economic loss, reaching USD69,896.17, or approximately 73.80% of the total economic loss from solid waste. The magnitude of this lost economic value indicates that aquaculture waste still has considerable economic potential if it can be reused through a circular bioeconomic approach and IMTA in the second stage of the study.

Furthermore, the high economic value of lost waste also indicates that low efficiency in feed and nutrient utilization may result in significant economic losses at the industrial scale. Therefore, sustainable aquaculture waste management is important not only from an environmental perspective, but also from the perspective of economic efficiency and aquaculture production performance.

Economic valuation*.* The economic valuation analysis estimated the potential economic value lost from unutilized solid aquaculture waste and fish mortality. The value of solid waste was calculated by multiplying the amount of solid waste generated in each treatment by the EWTP value for solid waste. The highest potential economic value of solid waste was recorded in treatment B, which produced the largest amount of solid waste (Figure 10). In contrast, treatment C produced lower solid waste accumulation because early mortality reduced feeding activity and fecal production.

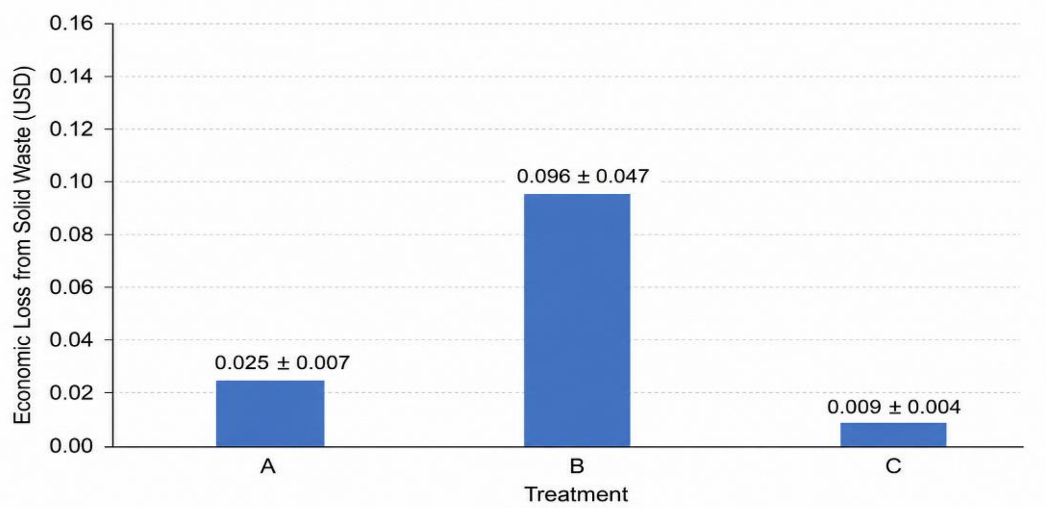

Figure 10. Economic loss from solid aquaculture waste.

Economic loss due to fish mortality was estimated by multiplying the number of dead fish by the unit price of fish. The highest mortality-related economic loss occurred in treatment C, where early mortality events between day 8 and day 10 substantially reduced final production output (Figure 11). These results indicate that excessive stocking density may reduce economic efficiency by increasing mortality risk and decreasing biomass retention.

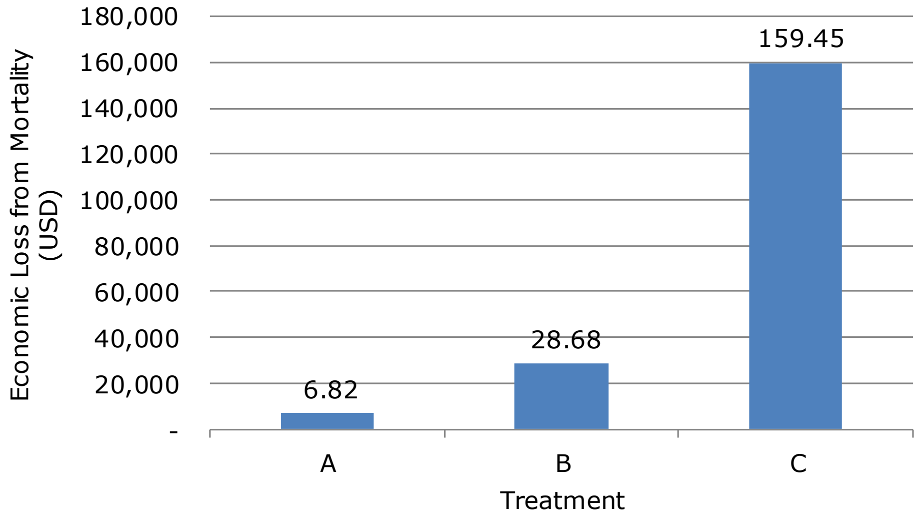

Figure 11. Economic loss from fish mortality.

Discussion

***Stocking density as a key driver of solid aquaculture waste generation*.** This study demonstrates that stocking density optimization should be evaluated not only from a biological perspective but also from a bioeconomic standpoint. Stocking density played a central role in determining the accumulation of solid aquaculture waste in hybrid grouper nursery systems. However, the relationship between stocking density and waste production was not strictly linear. The intermediate stocking density treatment produced the highest total solid waste biomass, 926.39 g, whereas the highest density treatment generated substantially lower solid waste, 87.35 g, due to early mortality occurring between day 8 and day 10 of the culture period.

This result indicates that waste generation in nursery systems is strongly influenced by the effective biomass retained in the culture unit rather than by initial stocking density alone. Solid aquaculture waste is primarily composed of uneaten feed and fish feces, both of which are directly associated with feeding activity and metabolic processes. When fish remain alive and actively feeding throughout the production cycle, organic waste continues to accumulate over time. Conversely, when mortality occurs early in the culture period, feeding activity declines rapidly and total waste production may decrease despite higher initial stocking density. This finding is consistent with previous studies showing that waste production in aquaculture is influenced by feed input, survival, biomass retention, and culture-system management (Dauda et al., 2019; Hanif et al., 2021; Astari et al., 2023). Therefore, solid aquaculture waste should be interpreted as an outcome of the interaction between biomass retention, feeding intensity, and survival dynamics within the production system.

From a bioeconomic perspective, the intermediate stocking density appears to represent a more balanced production strategy. This density maintained sufficient biomass to sustain feed consumption and waste generation while avoiding the severe system instability observed at the highest density treatment. Similar findings have been reported in grouper nursery studies using recirculating aquaculture systems, where stocking density management and bioremediation were shown to improve production performance and aquabusiness efficiency (Astari et al., 2023). This indicates that increasing stocking density should be accompanied by adequate water-quality management and waste-control strategies to prevent biological and economic losses.

***Environmental carrying capacity and water-quality deterioration*.** The deterioration of water quality observed in the highest stocking density treatment supports the interpretation that the nursery system exceeded its environmental carrying capacity. Treatment C showed the highest ammonia concentration, 1.76 mg L^{-1}, and a markedly higher hydrogen sulfide concentration, 2.34 mg L^{-1}, compared with treatments A and B. Although ammonia did not differ significantly among treatments, its higher numerical value in treatment C indicates greater accumulation of metabolic waste under high stocking density conditions. Hydrogen sulfide showed a clearer response, with treatment C having a substantially higher value than the other treatments.

These findings are consistent with Putra et al., (2025), who reported that water management through water exchange and siphoning improved survival and helped maintain more stable water quality in hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) culture. Therefore, the high ammonia and hydrogen sulfide concentrations observed in the highest stocking density treatment in the present study further emphasize the importance of water-quality management in intensive grouper nursery systems.

The experimental design intentionally allowed uneaten feed and fecal material to accumulate at the bottom of the tarpaulin tanks without siphoning in order to quantify total waste generation. This condition revealed the sensitivity of nursery systems to organic loading under excessive stocking density. The accumulation of organic matter likely promoted microbial decomposition processes that increased ammonia and hydrogen sulfide concentrations, ultimately creating stressful conditions for fish. Elevated waste loading from uneaten feed, feces, and metabolic by-products is widely recognized as a major source of water-quality deterioration in aquaculture systems (Dauda et al., 2019). In grouper fry culture, improvement of water quality through recirculating aquaculture system development and supporting technologies has also been reported to improve growth performance (Hanif et al., 2021).

The early mortality observed in treatment C therefore represents the point at which the environmental assimilative capacity of the system was exceeded. This finding emphasizes that stocking density management in nursery systems should consider not only the number of fish stocked, but also the capacity of the culture environment to process organic matter and maintain water quality. Excessive stocking density not only increases organic loading but also accelerates water-quality deterioration, thereby reducing the biological stability of the culture environment.

Biological performance and production efficiency in nursery systems. The biological performance results illustrate the trade-offs associated with stocking density management. Fish reared at the lowest stocking density showed the highest weight-related growth, including absolute weight gain and daily weight growth. However, the intermediate stocking density provided a more balanced production response because it maintained relatively high survival, higher total biomass production, and better environmental stability than the highest stocking density treatment.

Although low stocking density may reduce environmental stress and support individual growth, it also limits total biomass production. In contrast, excessive stocking density may induce physiological stress due to increased competition for feed, space, and dissolved oxygen. Under such conditions, fish may allocate more metabolic energy to maintaining physiological homeostasis rather than somatic growth. In the present study, early mortality in the highest stocking density treatment significantly reduced biomass retention and resulted in no final harvest biomass. These results suggest that excessive stocking density can undermine production efficiency by destabilizing both biological performance and environmental conditions.

Previous studies on hybrid grouper hatcheries and nursery systems also emphasize the importance of linking production performance, survival, stocking density, and economic output in aquaculture decision-making (Astari et al., 2023, 2024). Therefore, the intermediate stocking density appears to provide the most favorable balance between survival, biomass retention, environmental stability, and recoverable waste value in the nursery phase of hybrid grouper culture.

Bioeconomic valuation of nursery waste. One of the key contributions of this study is the integration of biological waste quantification with economic valuation using a willingness-to-pay approach. The results indicate that aquaculture waste generated during grouper nursery operations possesses measurable economic value from the perspective of stakeholders familiar with aquaculture activities. The estimated EWTP solid aquaculture waste was Rp4,527 kg^{-1}, equivalent to approximately USD0.25 kg^{-1}, with observed values ranging from Rp0 to Rp23,000 kg^{-1}, equivalent to USD0.00-1.28 kg^{-1}.

These results provide an indicative price signal for waste derived from grouper nursery systems. Although aquaculture waste is typically considered an environmental by-product requiring disposal or treatment, the positive WTP values observed in this study indicate that stakeholders recognize potential economic benefits associated with waste reutilization. Solid aquaculture waste contains organic carbon, nitrogen, and phosphorus that may be utilized in various applications, including organic fertilizer, compost, soil amendments, biofloc material, or nutrient sources for integrated aquaculture systems.

The financial and bioeconomic relevance of grouper hatchery and nursery systems has also been highlighted by Astari et al. (2024), who emphasized that production and financial performance in hybrid grouper hatcheries are strongly related to survival, larval rearing, nursery growth, and management efficiency. In this context, waste valuation provides an additional perspective by showing that material previously considered as residual waste may have recoverable economic value. As a result, nursery waste can potentially be reinterpreted as a recoverable bioresource within circular aquaculture frameworks rather than solely as an environmental liability.

The distribution of WTP responses also indicates variability in stakeholder perception of aquaculture waste value. Most respondents assigned relatively low values to aquaculture waste, while a smaller number of respondents expressed substantially higher valuations. Such variability is typical in contingent valuation studies, where perceptions of environmental resource value differ across stakeholder groups, knowledge levels, and expected utilization pathways. This finding indicates that market development, product processing, and awareness of waste-based products may be important for increasing the economic value of aquaculture waste.

Economic implications and production losses. Although the results demonstrate that aquaculture waste possesses measurable economic value, this value should be interpreted within the broader economic context of aquaculture production systems. Waste generation reflects nutrients and feed inputs that were not fully converted into fish biomass. Therefore, the economic value of solid waste represents a potential recoverable value when waste is reused, rather than a replacement for efficient production management.

In this study, treatment B generated the highest potential economic value of solid waste because it produced the largest amount of solid waste. At a broader scale, the estimated total economic value of lost solid waste reached USD94,705.50, with treatment B contributing the largest value, USD69,896.17, or approximately 73.80% of the total. Meanwhile, treatment C showed the highest mortality-related economic loss because early mortality substantially reduced final biomass production. These findings indicate that waste recovery strategies may provide complementary economic benefits, but optimizing stocking density to maintain survival, biomass retention, and environmental stability remains the primary strategy for improving nursery production efficiency.

This interpretation is consistent with the concept that waste valorization should complement, not replace, efficient aquaculture production management. Feed is one of the major operational inputs in aquaculture, and inefficient conversion of feed into biomass can generate both economic losses and environmental loading. Therefore, improving feed utilization, survival, water quality, and waste recovery should be integrated into a single bioeconomic management strategy.

Implications for circular aquaculture and integrated production systems. The findings of this study contribute to the growing body of literature on circular aquaculture and resource recovery in aquaculture production systems. Circular aquaculture approaches aim to improve resource efficiency by minimizing waste generation and converting residual nutrients into useful resources within integrated production systems.

The quantification of solid aquaculture waste conducted in this study provides baseline information on the potential availability of organic nutrients that could be utilized by secondary trophic organisms in integrated aquaculture systems.

From an IMTA perspective, solid organic waste derived from fish culture may serve as a nutrient source for deposit feeders, filter feeders, benthic organisms, or other extractive species. IMTA systems are designed to combine fed aquaculture with extractive aquaculture so that nutrients released from fed species can be recaptured by seaweeds, bivalves, deposit feeders, or other extractive organisms, thereby supporting biomitigation and economic diversification (Chopin et al., 2012). Recent circularity assessments also identify nutrient management and resource-use efficiency as important attributes in evaluating IMTA systems (Checa et al., 2024). Furthermore, nutrient retention studies suggest that a substantial proportion of nitrogen, phosphorus, and carbon supplied through fish feed can theoretically be retained IMTA systems when species combinations and system design are optimized (Nederlof et al., 2022).

However, the results also demonstrate that waste recovery strategies must be implemented within the ecological limits of the production system. When stocking density exceeds the carrying capacity of the system, environmental stress and fish mortality may occur, undermining both production efficiency and resource recovery potential. Therefore, the development of circular aquaculture systems should focus on optimizing stocking density to maintain stable biomass production while generating recoverable waste streams within environmentally sustainable limits. In this context, moderate stocking density appears to provide the most suitable balance between fish production, environmental stability, and recoverable waste value in hybrid grouper nursery systems.

The bioeconomic flow of hybrid grouper nursery under different stocking density treatments is summarized in Figure 12. Stocking density influenced feed input, fish activity, water quality, solid waste production, biological performance, and economic outcomes. Low and intermediate stocking densities allowed fish to survive for a longer culture period, resulting in continued feeding activity and measurable solid waste accumulation. In contrast, the highest stocking density caused water-quality deterioration, particularly through increased ammonia and hydrogen sulfide concentrations, which contributed to early mortality and reduced final biomass production.

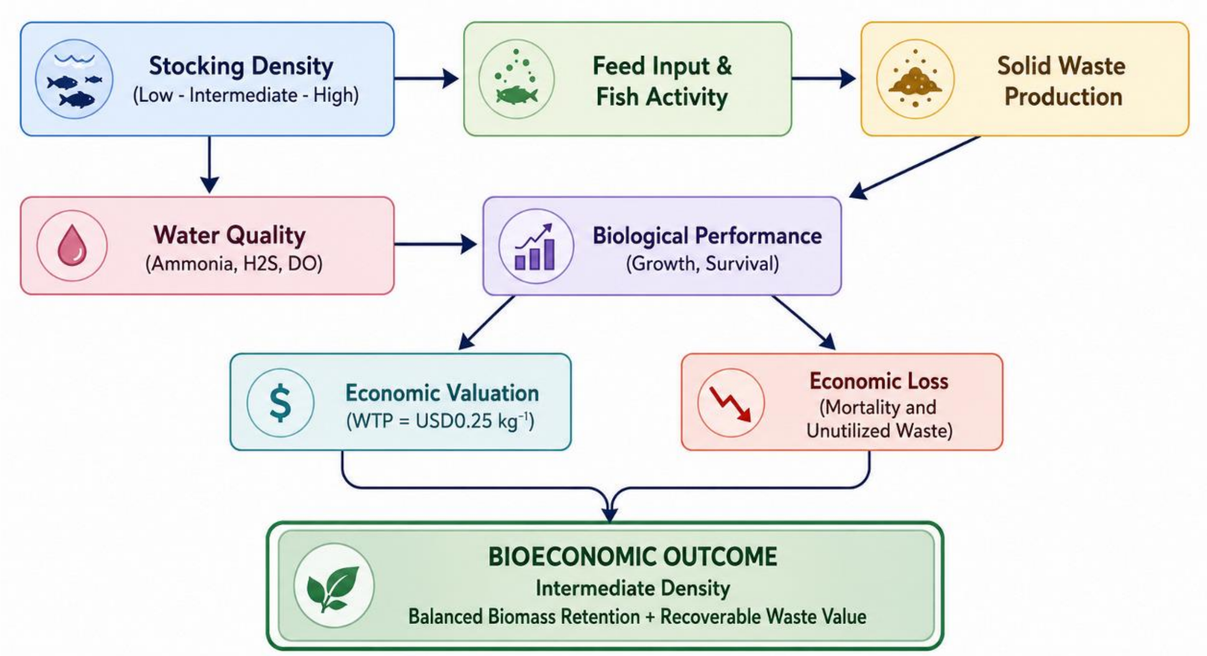

Figure 12. Bioeconomic flow summary of hybrid grouper nursery under different stocking density treatments.

The intermediate stocking density provided the most balanced bioeconomic outcome because it maintained relatively high survival, generated the highest recoverable solid waste biomass, and avoided the complete mortality observed under the highest stocking density. The estimated WTP value of solid aquaculture waste, USD0.25 kg^{-1}, indicates that solid waste can be interpreted not only as an environmental burden but also as a potential recoverable resource. Therefore, stocking density management should consider not only biological performance, but also water-quality stability, waste generation, and the potential economic value of waste within a circular aquaculture framework.

Conclusions. This study demonstrates that stocking density strongly influences solid aquaculture waste accumulation, water quality, biological performance, and bioeconomic outcomes in hybrid grouper nursery systems. The intermediate stocking density, 30 fish per waring, produced the highest solid waste biomass, 926.39 g, while maintaining better survival, biomass retention, and environmental stability than the highest stocking density.

The highest stocking density, 50 fish per waring, exceeded the environmental carrying capacity of the culture system, as indicated by increased ammonia and hydrogen sulfide concentrations, followed by complete mortality. These results confirm that waste generation is not determined by initial stocking density alone, but also by fish survival, feeding activity, and retained biomass during the culture period.

The WTP analysis showed that solid aquaculture waste has measurable economic value, with an estimated mean value of Rp4,527 kg^{-1}, equivalent to approximately USD0.25 kg^{-1}. Therefore, solid waste from grouper nursery systems can be considered not only as an environmental burden, but also as a potential bioeconomic resource for circular aquaculture and future Integrated Multi-Trophic Aquaculture development.

Acknowledgements. The authors would like to thank the small-scale aquaculture facility in Kampung Madong, Tanjungpinang City, Riau Islands Province, Indonesia, for providing technical support during the nursery experiment. The authors also acknowledge the laboratory teams involved in water quality and waste sample analyses.

Authors Contributions. WKAP: conceptualization, investigation, data collection, writing original draft; IE: supervision, methodology, validation, writing, review and editing; ID: supervision, methodology, writing, review and editing; TB: supervision, project administration, writing, review, and editing; LA: supervision, validation, writing, review and editing.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding. This study was funded by the Indonesian Education Scholarship through the Center for Higher Education Funding and Assessment, Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, and the Endowment Fund for Education Agency, Ministry of Finance of the Republic of Indonesia.

References

Afewerki, S., Asche, F., Misund, B., Thorvaldsen, T., & Tveteras, R. (2023). Innovation in the Norwegian aquaculture industry. *Reviews in Aquaculture, 15*(2), 759-771.

Ahmad, I., & Abdullah, N. (eds). (2025). Nature-based technologies for wastewater treatment and bioenergy production. IWA Publishing, London, 249 pp.

Arduini, D., Fraissinet, S., Rossi, S., Calabrese, C., Doria, L., & Giangrande, A. (2026). From biofouling to crop resource: novel opportunities as extractive species in a Mediterranean IMTA pilot. *Fishes, 11*(1), 47.

Astari, B., Budiardi, T., Ismi, S., Effendi, I., & Hadiroseyani, Y. (2023). Increasing the stocking density of grouper nurseries for aquabusiness efficiency in recirculating aquaculture system (RAS) with bioremediation. *HAYATI Journal of Biosciences, 30*(2), 198-206.

Astari, B., Effendi, I., Budiardi, T., Hadiroseyani, Y., Diatin, I., & Ismi, S. (2024). Financial analysis business of cantang (*Epinephelus fuscoguttatus* × *E. lanceolatus*) and cantik (*E. fuscoguttatus* × *E. polyphekadion*) hybrid groupers in hatcheries. *Aquaculture Reports, 39*, 102364.

Boyd, C. E. (2020). Dissolved oxygen and other gases. In: Water quality: an introduction. 3rd edition. Springer, Cham, pp. 135-162.

Bureau, D. P., & Hua, K. (2010). Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. *Aquaculture Research, 41*(5), 777-792.

Checa, D., Macey, B. M., Bolton, J. J., Brink-Hull, M., O'Donohoe, P., Cardozo, A., Poersch, L. H., & Sánchez, I. (2024). Circularity assessment in aquaculture: the case of integrated multi-trophic aquaculture (IMTA) systems. *Fishes, 9*(5), 165.

Chopin, T., Cooper, J. A., Reid, G., Cross, S., & Moore, C. (2012). Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. *Reviews in Aquaculture, 4*(4), 209-220.

Cozzolino, M., Salomone, R., Ricca, B., & Gulotta, T. M. (2025). Circular economy in aquaculture: an Italian survey to understand perceptions, challenges and options for transition. *Marine Policy, 176*, 106660.

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: sources, components and managements in different culture systems. *Aquaculture and Fisheries, 4*(3), 81-88.

Dewi, I. C., Putra, W. K. A., & Yulianto, T. (2020). The effect of fasting on the growth response of chopped grouper fish (*Epinephelus fuscoguttatus* × *E. lanceolatus*). *ECOTONE, 1*(2), 85-92.

Diatin, I., Shafruddin, D., Hude, N., Sholihah, M., & Mutsmir, I. (2021). Production performance and financial feasibility analysis of farming catfish (*Clarias gariepinus*) utilizing water exchange system, aquaponic, and biofloc technology. *Journal of the Saudi Society of Agricultural Sciences, 20*(5), 344-351.

Estévez Hernández, E. A., Santos, I., Moraes, L., Kashane, M. S., Okamoto, M. H., Sampaio, L. A., & Krummenauer, D., Costa, C. S. B., Rodrigues, R. V., Martinez-Llorens, S., & Poersch, L. H. (2026). IMTA production of Pacific white shrimp integrated with mullet, sea cucumber, oyster, and *Salicornia* in a biofloc system. *Fishes, 11*(2), 98.

FAO. (2022). The state of world fisheries and aquaculture 2022. Towards blue transformation. FAO, Rome, 266 pp.

Firdausi, S. L. Y., & Mubarak, A. S. (2021). [Nursery management of cantang grouper (*Epinephelus fuscoguttatus-lanceolatus*) at concrete pond in Balai Perikanan Budidaya Air Payau (BPBAP), Situbondo – East Java]. *Journal of Marine and Coastal Science, 10*(3), 129-137. [in Indonesian]

Hanif, I. M., Effendi, I., Budiardi, T., & Diatin, I. (2021). The recirculated aquaculture system (RAS) development with nanobubble application to improve growth performance of grouper fish fry culture. *Jurnal Akuakultur Indonesia, 20*(2), 181-190.

Huang, P. L., Afero, F., Chang, Y., Chen, B. Y., Lan, H. Y., Hou, Y. L., & Huang, C. T. (2023). The bioeconomic analysis of hybrid giant grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) and green grouper (*Epinephelus malabaricus*): a case study in Taiwan. *Fishes, 8*(12), 610.

Kurniawan, S. B., Ahmad, A., Imron, M. F., Abdullah, S. R. S., Othman, A. R., & Hasan, H. A. (2025). Achieving a biocircular economy in the aquaculture sector through waste valorization. *Toxics, 13*(2), 131.

Lamprianidou, F., Telfer, T., & Ross, L. G. (2015). A model for optimization of the productivity and bioremediation efficiency of marine integrated multi-trophic aquaculture. *Estuarine, Coastal and Shelf Science, 164*, 253-264.
Lasco, H. L., Close, H. G., Hoenig, R. H., Gillette, P. R., Benetti, D. D., & Stieglitz, J. D. (2026). Evaluation of native macroalgae species of the Southeast U.S. and Caribbean for use in integrated multi-trophic aquaculture (IMTA). *Aquaculture International, 34*, 70.
Masi, M., Adinolfi, F., Vecchio, Y., Agnusdei, G. P., & Coluccia, B. (2024). Toward the circular economy in the aquaculture sector: bibliometric, network and content analyses. *Sustainability, 16*(13), 5405.
Miller, D., & Semmens, K. (2002). Waste management in aquaculture. West Virginia University Extension Service Publication No. AQ02-1, USA, 8 pp.
Nederlof, M. A. J., Verdegem, M. C. J., Smaal, A. C., & Jansen, H. M. (2022). Nutrient retention efficiencies in integrated multi-trophic aquaculture. *Reviews in Aquaculture, 14*(3), 1194-1212.
Putra, W. K. A., Effendi, I., Diatin, I., Budiardi, T., Adrianto, L., Yulianto, T., Marnani, S., & Puspitasari, A. (2025). Water management strategies affecting the survival of hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*). *IOP Conference Series: Earth and Environmental Science, 1559*(1), 012001.
Ruiz-Vanoye, J. A., Díaz-Parra, O., Márquez Vera, M. A., Fuentes-Pena, A., Barrera-Camara, R. A., Ruis-Jaimes, M. A., Toledo-Navarro, Y., Bernabe-Loranca, M. B., Simancas-Acevedo, E., Trejo-Macotela, F. R., & Vera-Jimenez, M. A. (2025). A comprehensive review of quality of aquaculture services in integrated multi-trophic systems. *Fishes, 10*(2), 54.
Tan, E. C. D., & Lamers, P. (2021). Circular bioeconomy concepts: a perspective. *Frontiers in Sustainability, 2*, 701509.
Verreth, J. A. J., Roy, K., & Turchini, G. M. (2023). Circular bio-economy in aquaculture. *Reviews in Aquaculture, 15*(3), 944-946.
Wang, C., Guo, Y., Gu, X., Elisee, N., Jiang, B., & Zhao, B. (2026). Water quality and sediment microbial community differences between sea urchin monoculture and sea urchin-shrimp IMTA systems. *Water, 18*(2), 268.

Received: 23 May 2026. Accepted: 12 July 2026. Published online: 17 August 2026.
Authors:
Wiwin Kusuma Atmaja Putra (WKAP), Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Agatis street, 16680 Bogor, Indonesia, e-mail: wiwin_putra@apps.ipb.ac.id,
Irzal Effendi (IE), Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Agatis street, 16680 Bogor, Indonesia, e-mail: irzalef@apps.ipb.ac.id,
Tatag Budiardi (TB), Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Agatis street, 16680 Bogor, Indonesia, e-mail: tatagbu@apps.ipb.ac.id,
Iis Diatin (ID), Department of Aquaculture, Faculty of Fisheries and Marine Science, IPB University, Agatis street, 16680 Bogor, Indonesia, e-mail: iisd@apps.ipb.ac.id
Luky Adrianto (LA), Department of Aquatic Resource Management, Faculty of Fisheries and Marine Science, IPB University, Agatis street, 16680 Bogor, Indonesia; e-mail: lukyadrianto@apps.ipb.ac.id

How to cite this article:
Putra, W. K. A., Effendi, I., Budiardi, T., Diatin, I., Adrianto, L. (2026). Bioeconomic implications of solid aquaculture waste generation in hybrid grouper nursery systems under different stocking densities. *AACL Bioflux, 19*(4), 1911-1930.