Research Article

Bioeconomic Evaluation of Feeding Tray Strategies for Pacific White Shrimp (*Litopenaeus vannamei*) in Sea Floating Cages

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Abstract | The growth of Pacific white shrimp (*Litopenaeus vannamei*) in sea floating cage systems is attracting increasing attention as a promising new approach to sustainable aquaculture. However, feed management efficacy remains one of the key challenges that hinder productivity and business profitability. The present study's objective was to analyze the impact that the quantity of feeding trays exerted on the bioeconomic and biological performance of *Litopenaeus vannamei* cultivation. The study was performed over 105 days employing a completely randomized treatment design for the number of feeding trays per cage comprised of 1 feeding tray (A), 2 feeding trays (B), 3 feeding trays (C), and 4 feeding trays (D) units with 3 replicates each. Data were analyzed using one-way ANOVA followed by the LSD test. The results indicated that treatments C and D had the highest final weight and biomass (17.43 - 18.02 g, 3.60 - 3.62 kg m^{-2}, respectively). The best bioeconomic performance was achieved by treatment C, with IRR: 10.56%, ROI: 6.72%, NPV: 500,720 IDR. With treatment D, most of the production was turned into a net profit, but it also offered a relatively modest increase in yield relative to the added inputs. The findings of this paper are that three feeding trays represent the most bioeconomically efficient configuration for vannamei shrimp farming in sea floating cages.

Keywords | Bioeconomics, Sea floating cage, *Litopenaeus vannamei*, Feed management, Feeding tray

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INTRODUCTION

Pacific white shrimp (*Litopenaeus vannamei*) or vannamei shrimp are among the most important economic resources owing to extremely high demand and ability to survive intensive farming operations (Supono and Rivaie, 2025; Almeida *et al*., 2022). However, traditional shrimp farming along the coast is becoming less and less economically sustainable due to a lack of space, environmental impact and pressure (Tran *et al*., 2025). The aforementioned limitations have stimulated the development of novel techniques for farming, such as using sea floating cages to maximize the space for producing aquaculture sustainably (Millatina *et al*., 2025; Mardiana *et al*., 2023; Marsela *et al*., 2023).

The sea floating cages system provides several benefits, such as enhanced water circulation, a reduction in conflicts regarding coastal area utilization, and an increase in production capabilities in open waters (Troell *et al*., 2009; Gentry *et al*., 2017). From both technological and economic standpoints, feed management in open-sea shrimp farming is particularly challenging (FAO, 2020; Kumar and Engle, 2016). The cost of feeding the shrimp is the most expensive aspect of shrimp aquaculture operations (Hasan, 2007; Tacon and Metian, 2015). Utilizing the incorrect practices can result in reduced growth, make it more challenging to transform feed into shrimp, deteriorate the quality of the water, and have a negative impact on the financial line of the company (Jory *et al*., 2001; Martinez-Cordova *et al*., 2015).

Feeding trays are widely used to monitor shrimp feeding behaviour, adjust feed rations, and reduce feed waste. Despite this, empirical methods and practical experience continue to be the most important factors in deciding the application of feeding trays, particularly when it comes to selecting the number of trays that are utilized (Ullman *et al*., 2017). In sea floating cage aquaculture systems, the dynamics of currents, stocking density, and geographical distribution differ from those in pond systems (Wen *et al*., 2025; Holmer, 2010). As a result, there is a limited scientific understanding of the effectiveness of feeding trays and the ideal arrangement of these trays (Ma and Qin, 2024; Cheng *et al*., 2021).

In aquaculture operations, the number of feeding trays is frequently selected without statistically addressing the relationship between feeding tactics, the biological response of shrimp, and the implications for the economy (Shinji *et al*., 2019). The presence of the uncertainty in determining the appropriate number of feeding trays can lead to inefficient feed utilization, higher operational costs, and reduced production efficiency in shrimp farming systems (Eggink *et al*., 2024; Wafi and Ariadi, 2024). Few studies integrate biological and economic analyses concurrently, particularly for shrimp farming in sea floating cages (Shinji *et al*., 2019; Wafi and Ariadi, 2024). Meanwhile, scientific research related to shrimp feed management often concentrates on pond systems and emphasizes solely on biological elements (Skretting, 2022; Ambasankar *et al*., 2025).

This study conducts a bioeconomic evaluation of feeding tray strategies for vannamei shrimp in sea floating cage systems. The physiological and economic optimum feeding tray arrangement will be established using biological indices and economic evaluation. This study hypothesized that increasing the number of feeding trays would improve biological performance and feed utilization efficiency up to an optimal threshold, beyond which the additional operational costs would outweigh the economic benefits. The results are therefore expected to provide supporting evidence for evidence-based management decision making and sustainable marine shrimp farming methods based on the principles of the blue economy.

MATERIALS AND METHODS

Time and place of research

The investigation was carried out for 105 days on a sea floating cage system at the Sea Farming Center, Center for Coastal and Marine Resources Studies (CCMRS), IPB University on Semak Daun Island, Seribu Islands. The study area consisted of open seawater, which corresponded to offshore shrimp farming conditions with dynamic marine environmental conditions.

Experimental design

The research employed a completely randomized design (CRD) with four feeding tray number treatments per cage unit. There were treatment A (1 feeding tray per floating cage), treatment B (2 feeding trays per floating cage), treatment C (3 feeding trays per floating cage), and treatment D (4 feeding trays per floating cage). There were 12 experimental units because each treatment was done three times. All cage units had uniform size, stocking density, and maintenance conditions to minimize the influence of non-treatment factors. The experimental design and layout of the sea floating cage system used in this study are presented in Figure 1.

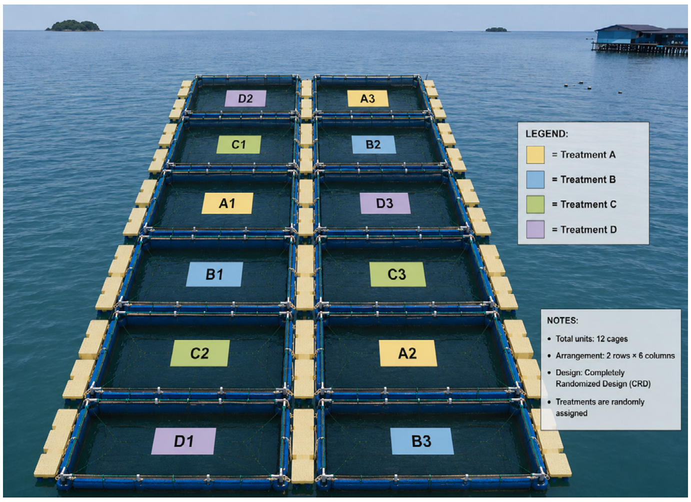

Figure 1: Experimental layout of sea floating cage system used for shrimp culture.

Research procedure

The research was conducted using HDPE sea floating cages measuring 3 m × 3 m × 3 m (27 m^3) equipped with two layers of netting. The outer layer of netting had a mesh size of 2.5 cm, while the inner layer had a mesh size of 0.5 cm. Vannamei shrimp (*Litopenaeus vannamei*) with an average weight of 0.4 g were stocked into floating cages at a density of 400 shrimps m^{-2} or equivalent to 3,600 shrimps per cage unit. Although cage volume (27 m^3) was used as the structural unit, stocking density was expressed on an area basis (m^{-2}) rather than a volumetric basis (m^{-3}). This is because vannamei shrimp is a benthopelagic species that predominantly occupies the bottom substrate of the cage during resting, feeding, and moulting activities, making the floor area (9 m^2) the ecologically relevant spatial unit for density calculation. The study utilized 12 sea floating cages as experimental units, with a total stocking of 43,200 vannamei shrimps distributed among the cages.

The feeding trays used were 80 cm × 80 cm × 10 cm, with frames made of 0.5-inch diameter pipes and 0.5 mm mesh. The shrimp were raised for 105 days and fed commercial feed (32% protein, 6% fat, and 4% fiber) at 1.5 - 10% of their biomass per day. The feed ration was calculated at 10% of shrimp biomass, reducing to 1.5% of biomass by the time the cultivation period ended. Calculation of rations was done after every ten days using the biomass of shrimps obtained from sampling. The feed was placed on each feeding tray according to the treatment and given four times a day, namely at 06:00, 11:00, 16:00, and 21:00.

Feeding trays were used to monitor feeding response and manage feeding throughout the entire experimental period. The feed trays were inspected after every feeding session to identify the feeding response of the shrimp and the amount of feed consumed. The amount of leftover feed was calculated, which assisted in identifying feed residue and regulating the rate of feeding. Depending on the reaction of the shrimps towards feeding and the feed residue, more or fewer feeds were provided. The feeding trays were equal in all treatments. Each tray was placed 10 cm above the cage net bottom in order to make sure that the feed was easily accessible to the shrimp without any unnecessary wastage of the feed due to its falling from the tray through the mesh.

Monitoring of water quality throughout the entire experiment period was performed through the determination of important physical and chemical parameters such as temperature, pH, dissolved oxygen (DO), and salinity. Measurements were conducted weekly at 07:00, 12:00, 17:00, and 21:00 using a multiprobe water quality meter at 1 m depth within each cage, from the beginning until the end of the study to ensure that environmental conditions remained within acceptable ranges for shrimp culture.

Observation parameters

The collection of data for determining the weight of the shrimps was done at an interval of 10 days in the cultivation period. Randomly, twenty shrimps from each floating cage were chosen and their weights recorded using digital scales (with an accuracy of 0.01g). Shrimps with visible disease, deformities, or injuries were excluded from sampling. The biological performance measures included final weight, average daily gain (ADG), absolute growth, feed efficiency, feed conversion ratio (FCR), survival rate, and biomass production.

Bioeconomic analysis framework

The bioeconomic analysis framework is described. An economic feasibility analysis was performed on biological data from the experiment and based on a standard set of investment criteria (net present value, internal rate of return, return on investment, payback period, and revenue-cost ratio), the biological and economic efficiency of vannamei shrimp farming in sea floating cage systems under individual feeding tray treatments was analyzed. This involved the combination of the important biological variables, such as growth performance, feed conversion ratio (FCR), survival rate (SR), and biomass production, with economic variables including feed cost, operation cost, income, profit, and economic efficiency.

The study aimed at analyzing how each treatment conducted under similar culture conditions, but with different levels of feeding tray, affected economically. This economic influence of each treatment was based on the production data collected during the 105 days of culture. The cost of operation included the following: (1) feed (20,000 IDR kg^{-1}); (2) seed (100 IDR per shrimp); (3) labor (500,000 IDR per cage); and (4) tray depreciation (35,000 IDR per unit).

The market price of shrimp was assumed to be 100,000 IDR kg^{-1}, reflecting the prevailing market price consistently observed in Indonesian shrimp markets for premium shrimp produced from sea floating cage culture systems. A discount rate of 12% was used for the economic evaluation. Economic viability and production efficiency were then compared among different treatment groups in order to determine which feeding tray setup made the optimal balance between biological and economical aspects.

The biological performance parameters were calculated using the following equations:

$$ADG = \frac{W_t - W_0}{t}$$

Where; ADG = average daily gain (g day-1); Wt= final weight (g); W_0= initial weight (g); t= culture period (days).

$$AG = W_t - W_0$$

Where; AG= absolute growth (g), W_t= final weight (g), W_0= initial weight (g).

$$\text{Feed Conversion Ratio (FCR)} = \frac{F}{B_t - B_0}$$

Where; F= total feed consumed (kg), B_t= final biomass (kg), B_0= initial biomass (kg).

$$FE\ (\%) = \frac{B_t - B_0}{F} \times 100$$

Where; FE= feed efficiency (%), B_t= final biomass (kg), B_0= initial biomass (kg), F= total feed consumed (kg).

$$\text{SR}\ (\%) = \frac{N_t}{N_0} \times 100$$

Where; SR = Survival rate (%), N_t= final number of shrimp harvested, N_0= initial number of shrimp stocked.

$$BP = \frac{B_t}{A}$$

Where; BP = biomass production (kg m^{-2}), B_t= total harvested biomass (kg), A= culture area (m^2).

Economic performance was evaluated using the following formulas:

$$\text{Net Profit} = TR - TC$$

Where; TR= total revenue (IDR), TC= total production cost (IDR).

$$\text{Net Present Value (NPV)} = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t}$$

Where; B_t= benefit or revenue in year t, C_t= cost in year t, i= discount rate, n= project lifetime.

$$\text{Net B/C Ratio} = \frac{\sum \frac{B_t}{(1+i)^t}}{\sum \frac{C_t}{(1+i)^t}}$$

$$\text{Return on Investment (ROI, \%)} = \frac{\text{Net Profit}}{\text{Total Investment (IDR)}} \times 100$$

$$\text{Payback Period (PP)} = \frac{\text{Initial Investment}}{\text{Annual Net Profit}}$$

To standardize economic evaluation, financial performance from the 105-day culture cycle was annualized. Thus, cash inflows and outflows from the experimental cycle were converted into equivalent annual values, and NPV was estimated using a one-year time horizon.

The internal rate of return (IRR) was estimated as the discount rate at which the NPV equals zero, “NPV”=0. project was considered economically feasible when NPV > 0, Net B/C > 1, and IRR exceeded the prevailing discount rate. The treatment combining optimal biological performance and economic efficiency was identified as the optimal bioeconomic strategy for offshore shrimp aquaculture. The purpose of this approach was to provide a practical evaluation of feed management options to enable production efficiency development and sustainability support for marine shrimp farming.

Data analysis

The results were evaluated using analysis of variance (ANOVA) to determine the impact of feeding tray number on biological parameters, production performance, and economic indicators. When significant differences among treatments emerged, the analysis was performed using the Least Significant Difference (LSD) test at 95% confidence. Normality and homogeneity of variance (Levene’s test) were verified prior to ANOVA. Statistical analyses were conducted to evaluate differences in growth performance, feed conversion ratio (FCR), survival rate, biomass production, and economic parameters between treatments.

The economic data obtained from each treatment were used to quantitatively analyze the financial feasibility of the cultivation system applied for different feeding tray configurations. It aimed to evaluate the differences between treatments related to production-related expenses and income generated by shrimp harvests. A per-cycle comparison of cost and revenue data was performed to assess variations in economic performance related to feeding tray utilization.

Financial feasibility of investment was evaluated based on a variety of investment assessment options: net present value (NPV), internal rate of return (IRR), return on investment (ROI), payback period, and the revenue-cost (R/C) ratio. These analytical results compared treatment economic feasibility and identified the optimal feeding tray selection method for the sustainable and profitable feeding of vannamei shrimp farming in sea floating cage production systems.

RESULTS

Growth performance, feed utilization, and survival rate

Table 1 shows the results of the growth performance and feed utilization of Pacific white shrimp (*Litopenaeus vannamei*) in sea floating cages exposed to different feeding tray configurations. One-way ANOVA results revealed that feeding tray number significantly impacted on final weight, average daily gain (ADG), absolute growth and biomass production (P < 0.05). However, feed conversion ratio (FCR), feed efficiency and survival rate were not significantly different (P > 0.05). Collectively, these findings indicate that increasing feeding trays from three to four optimized shrimp growth performance and biomass production in sea floating cage culture without compromising feed utilization efficiency or survival.

Bioeconomic performance

The bioeconomic performance of vannamei shrimp under different feeding tray configurations is presented in Table 2. From the one-way ANOVA results, there were statistically significant differences among the treatments on all feasibility criteria (P<0.05), which implied that the number of feeding trays had a considerable impact on the economic efficiency of sea cage farming. Net profit was progressively increased through the increasing number of feeding trays, as treatments C and D showed significantly better profitability than A and B (P<0.05). On the contrary, there was a clear difference in NPV, as the C and D treatments had positive NPV while A and B had negative NPV.

Both the Internal Rate of Return (IRR) and Net B/C Ratio showed similar trends, where treatments C and D performed very well compared to treatments that received lower trays. Importantly, the IRR for treatments C and D were above the minimum acceptable rate that is used as a discount rate for judging viability in aquaculture investments, while for treatments A and B, they were far below the threshold. The Return on Investment (ROI) was also the highest for treatments C and D, which significantly outperformed treatments A and B (P<0.05).

Table 1: Growth performance, feed utilization, and survival rate of *Litopenaeus vannamei* under different feeding tray treatments.

Parameters	Treatments			
	A (1 feeding tray)	**B (2 feeding trays)**	**C (3 feeding trays)**	**D (4 feeding trays)**
Biological input				
Initial weight (g)	0.32 ± 0.093	0.37 ± 0.133	0.33 ± 0.062	0.38 ± 0.089
Final weight (g)	13.30^{c} ± 0.63	14.85^{b} ± 0.90	17.43^{a} ± 0.52	18.02^{a} ± 0.66
Average Daily Gain (g day^{-1})	0.12^{c} ± 0.01	0.14^{b} ± 0.01	0.16^{a} ± 0.01	0.17^{a} ± 0.01
Absolute growth (g)	12.98^{c} ± 0.56	14.49^{b} ± 0.96	17.10^{a} ± 0.57	17.64^{a} ± 0.58
Feed Conversion Ratio	1.37^{a} ± 0.34	1.88^{a} ± 0.13	1.72^{a} ± 0.09	1.70^{a} ± 0.08
Feed efficiency (%)	72.99^{a} ± 17.05	51.13^{a} ± 3.51	51.90^{a} ± 7.90	50.74^{a} ± 2.84
Survival rate (%)	57.81^{a} ± 1.25	56.44^{a} ± 6.06	60.27^{a} ± 1.38	60.40^{a} ± 1.15
Biomass production (kg m^{-2})	3.08^{b} ± 0.14	3.35^{ab} ± 0.34	3.60^{a} ± 0.11	3.62^{a} ± 0.15

Note: Values are presented as mean ± SD. Different superscript letters in the same row indicate significant differences (P < 0.05) based on LSD test.

Table 2: Summary of bioeconomic performance across treatments.

Parameters	Treatments			
	A (1 feeding tray)	**B (2 feeding trays)**	**C (3 feeding trays)**	**D (4 feeding trays)**
Biological input				
Stocking density (shrimp m^{-2})	400	400	400	400
Feed Conversion Ratio (FCR)	1.37	1.88	1.72	1.70
Survival Rate (%)	57.81	56.44	60.27	60.40
Biomass Production (kg m^{-2})	3.08	3.35	3.60	3.62
Feasibility analysis				
Net Profit (IDR)	296,041^{b} ± 144,578	131,619^{b} ± 133,775	695,755^{a} ± 58,679	765,918^{a} ± 128,915
Net Present Value (NPV) (IDR)	-9,735,770^{b} ± 3,702,570	-13,946,548^{b}±3,425,917	500,720^{a} ±1,502,735	2,297,565^{a}±3,301,462
Internal Rate of Return (IRR) (%)	5.08^{b} ± 0.02	2.52^{b} ± 0.02	10.56^{a} ± 0.01	11.43^{a} ± 0.02
Net B/C Ratio	0.73^{b} ± 0.10	0.61^{b} ± 0.10	1.01^{a} ± 0.04	1.06^{a} ± 0.09
Return on Investment (ROI) (%)	2.86^{b} ± 1.40	1.27^{b} ± 1.29	6.72^{a} ± 0.57	7.40^{a} ± 1.25
Payback Period (PP) (year)	10.43^{b} ± 1.46	12.52^{b} ± 2.03	7.37^{a} ± 0.30	7.05^{a} ± 0.60

Note: Values are presented as mean ± SD. Different superscript letters in the same row indicate significant differences (P < 0.05) based on LSD test.

Table 3: Minimum and maximum values of water quality parameters recorded during the experimental period.

Water quality parameter	Treatment A	Treatment B	Treatment C	Treatment D
Temperature (°C)	28.1 - 32.2	28.1 - 32.2	28.1 - 32.4	28.1 - 32.0
pH	8.0 - 8.3	8.0 - 8.3	8.0 - 8.3	8.0 - 8.3
Dissolved oxygen (mg L^{-1})	3.0 - 7.5	3.0 - 7.3	3.0 - 7.5	3.0 - 7.8
Salinity (ppt)	33.6 - 37.0	33.7 - 37.1	33.7 - 37.1	33.6 - 37.1

For Payback Period (PP), the treatment D had the lowest investment recovery period, which was followed by treatment C, while treatments A and B had much higher investment recovery period that even exceeded a decade.

All of this together shows that the use of three or four feed trays constitutes an economically viable and economically advantageous system of cultivation for vannamei shrimp in sea floating cages. It can be concluded that the feed tray management is of crucial importance for the biological efficiency of shrimp cultivation and its economic sustainability.

Water quality parameters

Water quality variables measured through the entire duration of the experiment remained constant and within permissible limits in all treatments, as shown in Table 3. Water temperature was kept constant within the established thermoneutral range for the vannamei shrimp, while the pH values indicated stability within the alkaline marine environment, which is suitable for proper physiological activities of penaeid shrimp. Oxygen concentrations were maintained above the critical limit for vannamei shrimp for the entire culture period, while the salinity was typical of open oceanic environment. Most importantly, the similarity in water quality parameters between all treatments indicated that no environmental interference had occurred as a result of the manipulation of number of feeding trays. The overall stability and suitability of these parameters further validate sea floating cages as a reliable and environmentally consistent production system for vannamei shrimp in small-island marine environments (Ariadi *et al*., 2019; Harlina *et al*., 2022; Sievers *et al*., 2021).

DISCUSSION

Growth performance and feeding tray configuration

The results of the study indicate that the number of feeding trays has a significant effect on the growth performance of vannamei shrimp reared in sea floating cage system. Based on analysis of variance (ANOVA), the treatment involving the number of feeding trays had a significant effect ($P < 0.05$) on final weight, average daily gain (ADG), absolute growth, and biomass production.

Final shrimp weight increased as the number of feeding trays increased. The single feeding tray treatment yielded a final weight of 13.30±0.63 g, increasing to 14.85±0.90 g in the two feeding trays treatment. A more significant increase occurred in the three feeding trays treatment with a final weight of 17.43±0.52 g, while the four feeding trays treatment reached 18.02±0.66 g. Post-hoc LSD test results showed that the three and four feeding tray treatments were in the same group and significantly different from the one feeding tray treatment.

A similar pattern was observed in ADG values. The one and two feeding tray treatments yielded ADGs of 0.12±0.01 g day^{-1} and 0.14±0.01 g day^{-1}, respectively, while the three and four feeding tray treatments reached 0.16±0.01 g day^{-1} and 0.17±0.01 g day^{-1}. This growth increase indicates that more even feed distribution via additional feeding trays improves shrimp feed access to feed and reduce competition among individuals within the cage (Villarreal, 2023).

Ambasankar *et al.* (2025) indicated that in intensive aquaculture systems, especially in sea floating cage systems, where the water currents can impair feed availability, uneven feed distribution is a critical factor. Such effects result in decreased growth performance and increased waste, as uneven distribution of feed can hinder animal growth and increase the amount of wasted feed. The optimal water quality observed during the culture period likely contributed to the enhanced growth performance of Litopenaeus vannamei, as suitable environmental conditions support normal physiological functions and shrimp health (Widigdo *et al*., 2019; Prasetyo *et al*., 2024).

Feed trays enable direct observation of feed intake and improve feed management efficiency (Zeigler and Horton, 2015; Tacon, 2002). Therefore, an increase in the number of feeding trays might promote shrimp growth due to efficiency in feed distribution, which aligns with findings that optimized feeding strategies reduce competition and improve feed utilization in shrimp aquaculture (Ambasankar *et al*., 2025).

The variations in growth performance and biomass between treatments can also be explained through an analysis of the feeding behaviour of *Litopenaeus vannamei* in relation to feed availability, intraspecific competition and feed distribution in the cage environment. As reported by Bardera *et al.* (2021), Pacific white shrimp demonstrate feeding behaviour that is highly competitive where dominant individuals control the feeding area and consume larger amounts of feed than their conspecific counterparts who are systematically excluded from feed areas and have constant limited access to feed. The occurrence of feeding competition among individuals in shrimp farming cages is highly influenced by population density and intraspecific competition, where at higher population densities, feeding competition is high and reduces the efficiency of feeding and causes variation in growth performance of the organisms (Bardera *et al.*, 2021). In this case, the number of the feeding trays served as an important factor which determined the amount of feeding space available for each individual. Fewer trays treatments (A and B) offered a small number of feeding points in proportion to the population density in the cage, leading to increased competition among the individuals while feeding.

Conversely, increasing the number of feeding trays in treatments C and D expanded the total feeding surface area available within the cage, enabling a greater proportion of the shrimp population to access feed concurrently and reducing the intensity of intraspecific competition during each feeding session. This mechanism aligns with the well-established principle that feed delivery point spatial distribution directly mediates individual feeding equity in high-density aquaculture systems (Darodes de Tailly *et al.*, 2025; Liang *et al.*, 2025). In addition, the use of feeding trays within sea cages, which would have caused rapid dispersion of the food due to tidal currents but for the provision of a feeding area that was constant, made the feed available long enough for subordinate animals to access it. The above behavioural pattern offers a biological basis for the significantly better final body weight, average daily gain, absolute growth, and biomass production of treatments C and D despite there being no significant difference in FCR and survival rate among the different treatments since the improved access to feed enabled uniform growth and not change in feed conversion and mortality rate.

Balancing feed efficiency and biomass production

A prominent finding of this study is the negative relationship between feed efficiency and biomass production, which is well known in the field of intensive aquaculture (Martinez-Porchas and Martinez-Cordova, 2012). Treatment A (one feeding tray) had the lowest FCR (1.37) and highest feed efficiency (72.99%), yet produced the lowest biomass (3.08 kg m^{-2}). This aligns with studies indicating that feed control increases efficiency, although overall yield decreases accordingly (Boyd *et al.*, 2022). On the contrary, treatments C and D exhibited greater biomass production with high FCR values (1.72-1.70) which indicates the dilemma between producing the greatest amount of biomass and having high feed conversion rate (Ambasankar *et al.*, 2025). Although there was no statistical difference in terms of FCR, the tendency for increased FCR values due to greater trays deserves further study.

This trade-off demonstrates that the optimal feed does not necessarily mean the optimal production. Low tray situation indicates that feed intake will be controlled; hence, efficiency of feed use and minimizing of feed loss will both be achieved. Limited food access can delay the growth due to the presence of competition (Davis, 2015). More feeding trays indicate an increase in feed access and growth capacity, but it can cause feed loss and lack of uniformity in the process. This reflects evidence that feeding strategies must balance biological efficiency with production targets, as Asche *et al.* (2021) showed through their investigation. Decision making in intensive aquaculture systems should balance production goals against biological efficiency, a common trade-off (Anderson *et al.*, 2017).

Treatment A showed the lowest FCR (1.37), even though it used only one feeding trough. This finding is misleading and is not due to good feed conversion physiology. The mechanism underlying this outcome is feed restriction induced by fierce competition for food among individuals at one feeding trough for 3,600 shrimps (Bardera *et al.*, 2021). Competition excluded access to feed during feeding episodes on a regular basis, which means that feed consumption by individuals was low in absolute terms compared to biomass gain and thus reduced the FCR number (Liang *et al.*, 2025). This finding is in line with the paradoxical effect of feed restriction on FCR under intensive penaeid shrimp culture conditions, which is well described in literature (Ambasankar *et al.*, 2025). Therefore, FCR must not be interpreted as a standalone performance indicator. It should always be evaluated alongside biomass production and survival rate to accurately assess the productive efficiency of an aquaculture system.

Bioeconomic performance and financial feasibility

The findings of the bioeconomic analysis presented in this current study indicate that the economic feasibility of sea cage shrimp farming cannot be based on growth performance alone but through the relationship among biomass production, cost structures, and the number of feeding trays used. Although the final body weight of the two treatments (C and D) was not different from each other in comparison to those of treatments A and B, the harvested biomass greatly varied among treatments due to the variations in the survival rate, ranging from 56.44% for treatment B to 60.40% for treatment D (Table 2). In economic modelling in aquaculture, total revenue depends directly on harvested biomass, thus small increases in the survival rate at the stocking density of 400 ind m^{-2} will result in great changes in total revenue (Wafi and Ariadi, 2024). Biomass in treatments C and D (3.60 and 3.62 kg m^{-2}, respectively) was higher than that in treatment A (3.08 kg m^{-2}). This harvested biomass difference directly translated into a larger total revenue base per production cycle. In treatments C and D, the revenue generated was sufficient to exceed the threshold required to recover both fixed and operational costs. In contrast, the lower biomass yields observed in treatments A and B produced inadequate revenue to achieve cost recovery within the defined investment period. This explains the significant NPV disparity between treatments A/B and C/D, despite their seemingly comparable individual shrimp growth trajectories (Garlock *et al*., 2024).

Figure 2 illustrates the relationship between revenue and operating costs, demonstrating that the use of a greater number of feeding trays substantially increases business revenue. Improved feeding management enhances feed utilization and growth performance in aquaculture systems (Hernández-Llamas *et al*., 2025). Profit increased proportionally with biomass production, as indicated with treatment C and treatment D, demonstrating that an optimal feed strategy effectively translates into a higher yield and profitability (Huang *et al*., 2025). However, an increase in operating costs also occurred due to the greater demand for feed and feeding equipment, reflecting the economic trade-offs commonly reported in intensive aquaculture practices (Li *et al*., 2022). While treatment D created marginally more revenue than treatment C, its higher operating costs did not lead to greater economic efficiency ,illustrating the principle of diminishing marginal returns, where additional inputs yield progressively smaller gains in output (Saha *et al*., 2022).

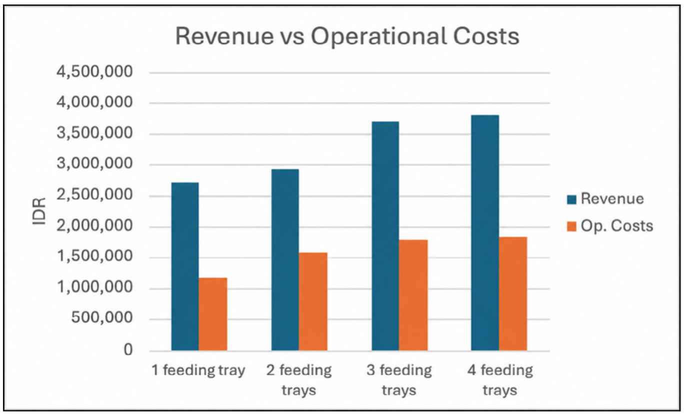

Figure 2: The relationship between revenue and operational costs.

These results indicate that the profitability of an aquaculture system is determined not only by high biological production but also by the balance between revenue and production costs, as demonstrated in bioeconomic studies that integrate biological and economic outcomes for aquaculture decision-making (Hernández-Llamas *et al*., 2025). Therefore, bioeconomic perspective is important for the effective and sustainable aquaculture strategies that were developed, which align with the more recent frameworks highlighting sustainability and circular economy concepts in aquaculture (Masi *et al*., 2024; Nagarajan *et al*., 2024).

According to findings, three feeding trays provide the optimal combination of shrimp development, biomass output, and feed utilization efficiency. Adding a fourth feeding tray did not result in a significant increase in production, implying the presence of a bioeconomic optimum in this aquaculture system and supporting the theory that marginal returns diminish as input levels increase (Asche *et al*., 2022).

This optimization notion is consistent with bioeconomic theory in aquaculture, which asserts that higher production inputs do not always result in proportional increases in output (Anderson *et al*., 2017; Asche *et al*., 2022). As a result, determining the ideal input level is critical for increasing production efficiency and the sustainability of the aquaculture system.

Identification of bioeconomic optimum

This study fundamentally contributes by determining an ideal bioeconomic feeding tray arrangement, an approach increasingly applied to link biological production with commercial viability (Domínguez-May *et al*., 2024a; Wijayanto *et al*., 2014). Treatment C was ideal in providing the best growth, biomass yield, efficiency of the investment, and economic viability. The treatment had a biomass yield of 3.60 ± 0.11 kg m^{-2} and an IRR and ROI of 10.56±0.01% and 6.72±0.57%, respectively. All the above are sustainable profitability standards for intensive shrimp aquaculture (Martínez-Cordero and Leung, 2004).

Treatment D yielded a slightly higher net profit and biomass than that of treatment C. But it should be noted that those increments were relatively low compared to the extra investment made in treatment D. It is common knowledge in aquaculture economics that when the amount of production inputs rises above a certain threshold, the returns are very minimal (Rola and Hasan, 2007). In other words, the marginal benefit of adding a fourth feeding tray did not justify the marginal cost.

The principle behind the bioeconomic approach in aquaculture is the fact that any additional input in terms of production will have to be taken in consideration from both economic efficiency and sustainability perspectives. In this case, the increase in the number of feeding trays above three was not directly proportional to the economic gains achieved. According to Nauta *et al*. (2025), sustainable aquaculture systems should take into consideration the profitability as well as other ecological and operational factors. Based on the above, three feeding trays seem to be the best configuration for vannamei shrimp sea floating cage aquaculture. The biological performance, especially in terms of growth and biomass production, seemed to influence economic performance greatly. Nevertheless, this experiment was not meant to prove any causal link between the number of trays and certain biological processes such as intraspecific competition reduction.

To provide stronger quantitative support for the selection of treatment C as the optimal configuration, a marginal return analysis and incremental cost-benefit analysis were conducted based on the bioeconomic data presented in Table 2. The marginal return from adding a fourth feeding tray (treatment D vs. treatment C) yielded only a marginal increment in biomass production of 0.02 kg m^{-2} (+0.56%) and an additional net profit of 70,163 IDR per production cycle, despite requiring a 33.3% increase in feeding tray input. To quantify input-use efficiency, a per tray productivity metric was computed by dividing net profit by the number of feeding trays in each treatment. This analysis revealed that treatment C achieved the highest net profit per tray (231,918 IDR $tray^{-1}$), outperforming treatment D (191,480 IDR $tray^{-1}$), treatment A (296,041 IDR $tray^{-1}$, though economically nonviable due to negative NPV), and treatment B (65,810 IDR $tray^{-1}$). Similarly, biomass yield per tray was highest in treatment C (1.200 kg m^{-2} $tray^{-1}$) compared to treatment D (0.905 kg m^{-2} $tray^{-1}$), confirming that the marginal productivity of each additional tray declined substantially beyond three units. Consistent with Domínguez-May *et al*. (2024b) and Samat *et al*. (2024), this pattern reflects the principle of diminishing marginal returns, wherein additional production inputs beyond an optimal threshold yield progressively smaller output increments relative to the cost incurred.

Thus, the optimization criterion adopted in this study is one that comprises the following three factors: (1) biological performance (biomass generation and growth); (2) financial gains (positive NPV, IRR >10%, net B/C ratio > 1, and ROI); and (3) efficiency of input use (net profit and biomass per feeding tray). It is clear within such a multicriteria system that treatment C always constitutes the optimal solution, since it obtains biological productivity and financial gains that are statistically equal to those of treatment D using less input. This conclusion aligns with the principle of economic efficiency in sustainable aquaculture management (Domínguez-May *et al*., 2024b; Garlock *et al*., 2024).

Implications for the development of sustainable shrimp farming

The results of this study have important implications for the development of marine shrimp farming based on offshore aquaculture, as the offshore systems are increasingly recognized for their potential to expand production while reducing environmental pressures in coastal zones (Gentry *et al*., 2017). Optimization of feeding management has been proven to promote productivity and maximize both productivity and profitability of shrimp farming, supporting results of evidence on the efficacy of optimal feeding in achieving high growth performance and profit in penaeid shrimp culture) (Rafael *et al*., 2018).

A method of applying an optimal number of feeding trays can be considered a technical strategy for enhancing production efficiency, reducing the risk of loss in profitability and ensuring more sustainable operation of marine shrimp farming on coastlines and small islands, aligning with studies that suggest that technological innovations provide a cost-effective and stable solution to stabilize yields in shrimp aquaculture (Rola and Hasan, 2007). Additionally, the bioeconomic approach used in this study can also help form the basis for making adaptive, long-term sustainable management decisions, reflecting principles upon which ecological resilience and economic feasibility in aquaculture development are built (Masi *et al*., 2024).

This study was limited to a single production cycle under specific environmental conditions. Consequently, the generalization of the results is limited. Hernández-Llamas *et al*. (2025) noted that multi-cycle validation is an important part of developing a trustworthy aquaculture bioeconomic model. As a result, future research could include such a design. The inclusion of the analysis of the influence on prices and the evaluation of the effect on the environment will increase the applicability of the bioeconomic model. Concerning this, Martínez-Cordero and Leung (2004) pointed out that it is vital to evaluate economic risks and ecological sustainability in aquaculture system planning. Taken together, these directions will contribute to a more robust and applicable bioeconomic model for marine shrimp cage farming.

CONCLUSIONS

The number of feeding trays significantly affected growth and biomass production, and consequently influenced the economic returns of Pacific white shrimp (*Litopenaeus vannamei*) cultivation in sea floating cage systems. The use of three feeding trays per cage optimized the balance between production and profitability. Although treatment D produced higher absolute profits (765,918 vs 695,755 IDR) and a shorter payback period (7.05 vs 7.37 years), treatment C achieved these outcomes with 25% fewer trays, representing better efficiency per input unit. On marginal return criteria, three trays per cage are the recommended configuration. Thus, the use of three feeding trays is recommended as the most efficient and sustainable feed management strategy in offshore aquaculture based vannamei shrimp farming.

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NOVELTY STATEMENT

This research is the first study to determine the optimal number of feeding trays for *Litopenaeus vannamei* under open-sea floating cage systems through the use of the bioeconomic approach. Performance parameters, such as growth, FCR, survival rate, and biomass production, were analyzed together with economic measures, including NPV, IRR, ROI, and payback period, which are important in investment decisions. In previous literature on the subject, either biological or financial parameters have been the focus. This study was done based on offshore marine environment conditions at Semak Daun Island, Thousand Islands, Indonesia. This condition represents the hydrodynamic characteristics of small island aquaculture. The bioeconomic threshold was determined by this research. Three feeding trays were found to be the optimum, while the fourth one added to the cost of operation but not the yield output. This research provided an applicable tool that could be applied in the decision-making process of managing feed in offshore shrimp farming. The research also gave concrete contribution to the sustainable development of aquaculture based on blue economy in islands or coastal areas.

AUTHORS' CONTRIBUTION

RRH: Conceived the study, supervised all research stages, and led the writing, revision, and final approval of the manuscript. Y: Conducted water quality monitoring and environmental assessment, and contributed to the relevant sections of the manuscript. BW: Managed field operations including feed management and shrimp observation, and contributed to the methods section. RK: Designed the experimental methodology, performed statistical analyses, and contributed to the results section. DI: Conducted the bioeconomic and financial feasibility analyses, and led the writing of the bioeconomic discussion.

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Generative AI and AI-assisted technology statement

Generative AI was used to assist with language editing and clarity. The authors manually reviewed and edited the manuscript to produce the final version.

Conflict of interest

The authors declare that there are no conflicts of interest among the authors in the preparation of this manuscript. All authors have contributed to the research and approved the final manuscript for publication.

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