Monitoring the feeding behavior of *Panulirus homarus* (Linnaeus, 1758) through artificial intelligence technology in a floating net cage in Pangandaran Regency

Rita Rostika, Mochhamad I. C. Utama, Lady A. S. Wijayanti

Department of Fisheries, Faculty of Fisheries and Marine Science, Universitas Padjadjaran, 45363 Jatinangor, Sumedang Regency, West Java, Indonesia. Corresponding author: R. Rostika, rita.rostika@unpad.ac.id

Abstract. Feeding behavior is a critical factor influencing the productivity and growth performance of green lobsters, *Panulirus homarus* (Linnaeus, 1758). Pangandaran, located on the southern coast of West Java, is recognized as one of the major centers for *P. homarus* aquaculture in Indonesia. This study aimed to analyze the feeding behavior of *P. homarus* juveniles, with particular emphasis on feeding time, feeding rate, and growth performance in floating net cage (FNC) systems. The experiment was conducted using a completely randomized design with 25 *P. homarus* per treatment over a 30-day culture period. Four dietary treatments were applied: Treatment A (80% anchovy feed), Treatment B (100% anchovy feed), Treatment C (80% shrimp feed), and Treatment D (100% shrimp feed). Key performance indicators measured included growth parameters, average daily gain (ADG), and survival rate (SR), as well as water quality parameters to ensure optimal rearing conditions. Observations indicated that *P. homarus* exhibited higher feeding activity during nighttime hours, as monitored using the AI Smart *P. homarus* Culture Version 1 system, which employed machine learning to track feeding behavior and optimize feeding strategies. Treatments B and D resulted in the highest ADG, whereas SR remained consistent across all treatments. Feeding behavior was assessed by recording the duration of specific activities: time spent observing the feed (0.44 minutes), approaching the feed (0.5 minutes), capturing the feed (0.82 minutes), and opening the mouth to ingest the feed (1.09 minutes). This study also highlights the potential of AI technology in monitoring FNC aquaculture systems.

Key Words: artificial intelligence, average daily gain, green lobster, survival rate.

Introduction. The advancement of effective and profitable green lobster, *Panulirus homarus* (Linnaeus, 1758) farming is necessary to achieve high survival and growth rates in *P. homarus* (Sapwan & Jalil 2024). Currently, it has been reported that *P. homarus* survival rate (SR) ranges from 40-50% in Lombok (Swastika et al 2008), primarily due to a mismatch between *P. homarus* nutritional requirements and the provided feed. A significant challenge remains in understanding the *P. homarus* feeding behaviour and addressing the shortcomings in submerged cage design in Indonesia. Rostika (2020) highlights that current floating net cage (FNC) designs lack effective water quality management for farmers, contributing to elevated *P. homarus* mortality rates. Consequently, modifications to submerged cage designs are being explored to enhance management practices and improve *P. homaru*'s growth conditions.

P. homarus farming is predominantly conducted in indoor ponds (Remani et al 2004; Radhakrishnan 2005; Amin et al 2022; Ilham et al 2023), where *P. homarus* are cultivated from juvenile stages until they reach approximately 30 g. Predictions of potential habitats for demersal fish typically rely on surface temperature and chlorophyll data. However, these methods do not apply to *P. homarus*, as they are primarily inhabiting healthy coral reefs in shallow waters with an abundance of natural food sources (Fadjar et al 2023). The adoption of indoor *P. homarus* farming is primarily driven by its efficient management practices and the ability to maintain water quality parameters that closely mimic natural marine conditions. However, it facilitates precise monitoring of *P. homarus* developmental stages, particularly during the molting process, which is critical for growth and survival. Indoor cultivation reduces mortality risks by minimizing the incidence of failed molting and cannibalistic behavior among *P. homarus* (James 2007; Prariska et al 2020). This study will elucidate farmers and stakeholders' understanding of the efficient and sustainable management of *P. homarus* resources, with a particular focus on maintaining optimal water quality parameters.

Farmers utilizing submerged cages, particularly those situated in the ocean ecosystem, encounter significant challenges in maintaining optimal water quality. High-quality water is essential for the success of *P. homarus* farming (Prariska et al 2020). Tackling various water quality issues requires continuous innovation, particularly through technological advancements. One promising approach is the integration of artificial intelligence (AI) to enhance aquaculture management and mitigate associated challenges (Briyan et al 2024; Ragab et al 2024). Effective AI implementation can optimize farming operations, improving both efficiency and productivity.

ReelData AI, a leading Canadian company in aquaculture technology, has made significant advancements in fish and *P. homarus* farming. Their technologies include ReelApetite, an AI-driven system that monitors and optimizes feed consumption and supply, and ReelBiomas, which provides precise estimation of biomass, including size and weight distribution (Ragab et al 2024). Additionally, Umitron Corporation, based in Tokyo, specializes in AI technology applications in aquaculture. Umitron's system utilizes real-time monitoring of fish swimming behavior to optimize feed timing and quantity, thereby enhancing efficiency and sustainability in aquaculture operations. These AI technological advancements play a vital role in optimizing aquaculture productivity (Ragab et al 2024). For instance, ReelApetite enables farmers to precisely calibrate daily feed allocations for fish, thereby eliminating the necessity for manual feeding and reducing the feed margin of error. Furthermore, AI technology allows for continuous assessment of fish growth rates relative to their developmental stage, facilitating the early detection and mitigation of growth anomalies.

To address water quality concerns, advanced underwater camera systems have been developed (Hung et al 2016). This camera technology is capable of capturing high-resolution images and videos in low-light and turbid environments, making them particularly advantageous for monitoring nocturnal *P. homarus* activity. Additionally, two-dimensional monitoring can be conducted using underwater cameras equipped with artificial lighting, strategically positioned at the bottom of the cages. This technology enables farmers to assess aquatic conditions without the need for water drainage, therefore, facilitating real-time health assessment and efficient management of potential cultivation challenges (Saberioon et al 2017).

The integration of AI technologies in Aquaculture significantly mitigates operational challenges faced by farmers (Rather et al 2024). By enhancing effectiveness and efficiency, AI facilitates the simultaneous management of critical aspects such as cage monitoring, feed distribution, and *P. homarus* health assessments, reducing reliance on manual labor. A strong understanding of AI-driven technology processes is essential to optimize these advancements, ultimately resulting in lower *P. homarus* mortality rates, improved harvest yields, and the sustainable fulfillment of market demand for *P. homarus*. The "Smart *P. homarus* Aquaculture Monitoring System Culture" version 1, developed at the Faculty of Fisheries and Marine Science, Universitas Padjadjaran, uses machine learning and computer vision to monitor *P. homarus* feeding behavior in real-time. This AI system tracks feed observation, approach patterns, feed handling, and consumption, optimizing feed distribution based on *P. homarus* behavior, which reduces waste and improves feeding efficiency. The AI's main benefit is in automatically adjusting feeding strategies to match the *P. homarus* natural feeding rhythms, resulting in better growth performance and SR. Further technical details are provided in the methods section.

The study aims to assess the average daily gain (ADG), SR, and water quality of green *P. homarus*, as well as evaluate the impact of AI on feeding times and speeds for *P. homarus* cultured 2 meters below the ocean surface.

Material and Method

Study location and tools. This research was carried out from August 2024 to November 2024 in Pangandaran, West Java, specifically in the coastal waters of Pangandaran Regency, located at coordinates 7°42'12.6"S, 108°39'42.9"E (Figure 1).

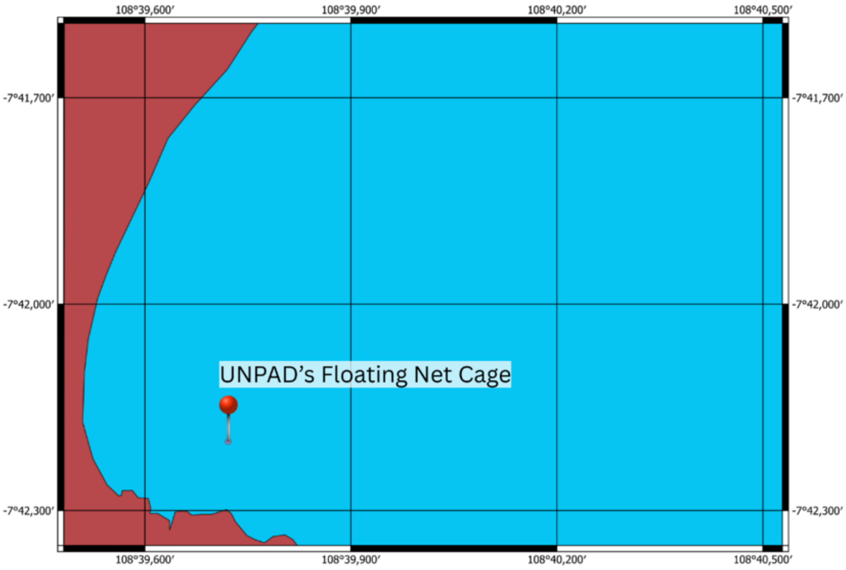


Figure 1. Research location map.

The *P. homarus* were maintained in submerged cages (Size M, diameter 111 cm, height 87 cm) at the FNC facility of the Faculty of Fisheries and Marine Science, Universitas Padjadjaran. These submerged cages were placed 2 meters below the ocean surface, where water quality parameters were continuously monitored to ensure optimal conditions for *P. homarus* growth. The equipment used in this study included the Smart *P. homarus* Culture Server, monitor, solar panel, underwater camera for real-time feeding behavior observation, digital scale, dissolved oxygen (DO) meter, thermometer, refractometer, pH meter, Secchi disk, millimeter block, plastic basin, smartphone camera, laptop, and notebook. The primary materials for this study consisted of *P. homarus* juveniles sourced from a hatchery (not wild-caught). For feeding treatments, anchovies (*Stolephorus* sp.) were used as the sole natural feed source, due to their high nutritional value, particularly omega-3 fatty acids, essential for *P. homarus* growth.

Cultivation treatment. The research procedure and treatment were conducted through six steps, including preparation of equipment and materials, setup of containers and *P. homarus* maintenance, seed stocking, seed care, feed provision, and data collection. The analysis was carried out using a quantitative experimental approach with a completely randomized design, involving four treatments and four replications. This design follows the method by Suriadi & Kurnia (2017) on the growth of *P. homarus*, where 100% natural feed is equivalent to 20% of their body weight. The treatments were designated as A: 80% anchovy feed, B: 100% anchovy feed, C: 80% shrimp feed, and D: 100% shrimp feed, respectively. In terms of feeding, the *P. homarus* were fed once daily with the feed constituting 20% of their body weight. The culture period lasted for 30 days, during which feeding behavior was monitored at four distinct times throughout the day: morning (09:00), afternoon (13:30), evening (16:00), and night (20:00). The feeding times and feeding behavior were recorded, and the data were analyzed based on time points (t0, t1, t2, t3) corresponding to the initial, middle, and final stages of the culture period.

Preparation of containers and maintenance media. The maintenance containers consisted of submerged cages of size M, with a diameter of 111 cm and a height of 87 cm. Before, the cages were sun-dried and cleaned of barnacles and algae. Any damaged cages were repaired before reuse as part of the maintenance protocol. The cages will be anchored with ropes at a depth of 2 meters. The tops are covered to prevent *P. homarus* from escaping, and each corner is reinforced with ropes to ensure stability. The cages were fitted with nets made of high-density polyethylene with a mesh size of 4 mm. After securing them to the floats, the cages submerged to a depth of 2 meters. According to Rostika et al (2023), a depth of 5 meters is ideal for promoting *P. homarus* growth, as it provides a stable temperature, moderate wind speeds, manageable wave heights, and a high presence of zooplankton (Mustafa 2013).

Panulirus homarus maintenance. The maintenance of *P. homarus* followed similar procedures described by Sunardi et al (2016), lasting 30 days with growth assessments occurring every 10 days. The objective of measuring *P. homarus* growth is to evaluate weight gain throughout the maintenance period. The growth parameters include ADG, SR, and water quality measurements taken every 10 days, which assess temperature, pH, DO, salinity, and turbidity (Sinaga et al 2021). In this study, *P. homarus* were fed once daily, with the feed constituting 20% of their body weight. Sampling to measure *P. homarus* growth was carried out every 10 days to monitor ADG and SR (Sunardi et al 2016; Sinaga et al 2021). Data collection spanned 30 days, involving measurements of *P. homarus* length, weight, water quality, and feeding habits every 10 days.

Observation measurement parameters. The research parameters were based on identifying shortcomings, addressing gaps, enhancing understanding, exploring existing data more thoroughly, and verifying the validity of previously established yet uncertain findings (Novarinda 2017). This study employs the following parameters:

Average daily gain (ADG). ADG is calculated using the following formula:

$$ADG = \frac{Wt-Wo}{t}$$

Where:
ADG = Average daily gain (%)
Wt = Average weight of the fish at the end of the maintenance period (individuals)
W0 = Average weight of the fish at the beginning of the maintenance period (individuals)
t = Duration of maintenance (days)

Survival rate (SR). The SR is determined using the formula established by Effendie (2002):

$$SR = Nt-No \times 100\ \%$$

Where:
SR = Survival rate (%)
Nt = Number of fish at the end of the study (individuals)
N0 = Number of fish at the beginning of the study (individuals)

Feeding habit. Feeding habits refer to the preferences of *P. homarus* regarding their eating behaviors, which include observing the feed provided, approaching it, taking it away, and consuming it. These behaviors were monitored through an underwater camera connected to a smartphone, capturing the *P. homaru*s feeding activities during four distinct feeding times: morning, afternoon, evening, and night. Each observation lasted 15 minutes, during which the duration of each activity (observing, approaching, handling, and consuming the feed) was recorded in seconds. Specifically, the open mouth to eat parameter refers to the time taken from when the *P. homarus* approached the feed to when it opened its mouth to begin consumption. Data were collected daily throughout the 30-day culture period, with three sessions per day to ensure accuracy and consistency. The analysis of this data helped to evaluate the feeding efficiency and preferences of the *P. homarus* at different times of day. As shown in Figure 2, the initial version of the Smart *P. homarus* Culture system.

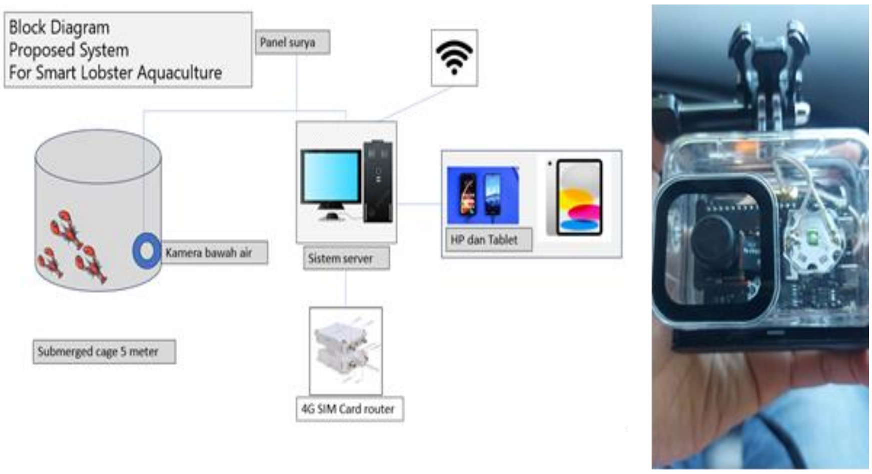


Figure 2. Block diagram of the initial version of smart *Panulirus homarus* culture (left); underwater camera connected to smartphone (right).

Water quality. Effective management of water quality in the cages entails cleaning the enclosures of any leftover feed and accumulated waste before feeding. Water quality parameters such as temperature, pH, salinity, and DO were measured using a Hanna Instruments HI98194 Portable Multiparameter Meter, which is a digital water quality checker. These measurements were cross-checked with real-time data from the Smart *P. homarus* Culture AI system, ensuring the consistency and accuracy of water quality monitoring. The AI system continuously recorded water conditions and correlated them with feeding behavior, providing a comprehensive overview of *P. homarus* health and environmental factors.

Data analysis. The data collected during the research were analyzed both statistically and descriptively, incorporating literature reviews and relevant supporting data. Water quality parameters and fish feeding habits will be presented descriptively using figures or tables. Data related to ADG and SR were analyzed statistically through Analysis of Variance (ANOVA). The statistical parameters will be assessed using Microsoft Excel 2010. Differences among treatments will be evaluated using Duncan's multiple range test with a 95% confidence interval (Susilawati 2015).

Results and Discussion

Average daily gain (ADG). The data presented below illustrates the weight gain across the four treatment groups (Figure 3). Figure 3 shows a noticeable increase in *P. homarus* muscle mass, attributed to the provided feed and optimal water quality. The natural feed, comprising anchovies and shrimp, was effectively digested and incorporated into the *P. homarus* body, leading to enhanced muscle development.

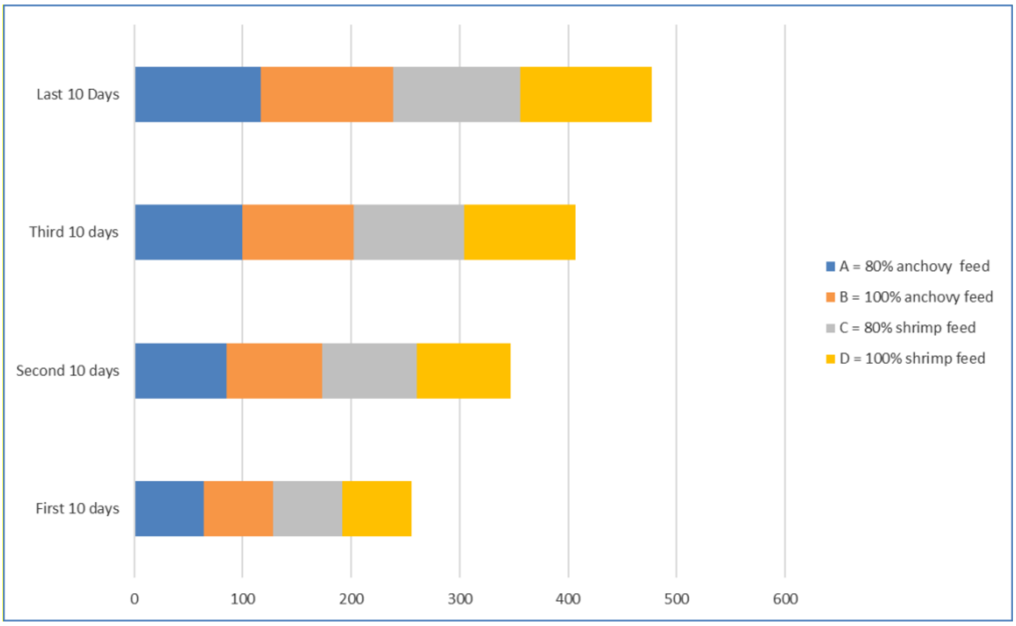


Figure 3. Weight gain of *Panulirus homarus* for each treatment during the study.

The ADG data, which reflects the daily weight increase for each treatment throughout the study, is summarized in Table 1. In Table 1, treatments B (100% anchovy feed) and D (100% shrimp feed) display significant differences compared to treatments A (80% anchovy feed) and C (80% shrimp feed), with averages of 0.65 g day^{-1}and 0.64 g day^{-1}, respectively. In contrast, the other treatments averaged 0.58 g day^{-1} and 0.59 g day^{-1}. This difference is expected, as treatments B and C utilized a higher percentage of feed (100%), which proved more effective than the 80% ratio used in the other treatments. The higher feed ratio of 100% likely provided more consistent and optimal nutrition, resulting in increased weight gain.

Additionally, B (100% anchovy feed) and D (100% shrimp feed) showed enhanced muscle development compared to the 80% feed treatments. This could be attributed to the higher energy intake, which supported faster growth. The feed's nutrient composition, particularly omega-3 fatty acids from anchovies and shrimp, contributed to better absorption and incorporation of essential nutrients into *P. homarus* tissues. These findings are consistent with previous studies indicating that a higher percentage of feed leads to improved growth performance and better health in *P. homarus*.

Table 1

Average daily gain for each treatment during the study

Time/Treatment	*A (g day^{-1})*	*B (g day^{-1})*	*C (g day^{-1})*	*D (g day^{-1})*
First 10 days	0.71	0.8	0.78	0.75
Second 10 days	0.48	0.49	0.48	0.55
Third 10 days	0.55	0.66	0.51	0.61
Average	0.58[a]	0.65[b]	0.59[a]	0.64[b]

Note: Different superscript letters in the *Average* row indicate significant differences among treatments according to one-way ANOVA followed by Duncan's multiple range test ($p < 0.05$); A = 80% anchovy feed; B = 100% Anchovy feed; P3 = 80% Shrimp feed; P4 = 100% shrimp feed.

Anchovies are rich in omega-3 fatty acids and are classified as oily fish (Kari et al 2022), similar to salmon, tuna, sardines, and mackerel (Wall et al 2010; Taşbozan & Gökçe 2017). The nutritional profile of anchovies (*Stolephorus* sp.) includes 70% protein, 5.30% fat, and 7.60% carbohydrates.

Additionally, anchovies are packed with essential vitamins and minerals beneficial for health (Swastawati et al 2020). This aromatic fish is particularly high in vitamin B3 (niacin), which aids in converting food into energy (Chand & Savitri 2016). They also contain substantial amounts of selenium (Yoshida et al 2012), a mineral important for heart health, thyroid function, immune support, and bone health (Triggiani et al 2009).

The protein and fat content of these two natural feed options aligns well with the nutritional requirements of *P. homarus*. This is corroborated by Rostika et al (2022), who found that the best weight gain in *P. homarus* occurs when fed natural feed compared to artificial alternatives. Moreover, Table 2 indicates that the growth rate of similarly sized *P. homarus* favored anchovies and shrimp over barnacles and golden apple snails (Rostika et al 2024).

Table 2

Growth rate of *Panulirus homarus* in floating net cages at 2 meters depth

Treatment	*Feed*	*Growth rate (g)*
A	Anchovies	1.944 ± 0.129450^{a}
B	Shrimp	1.743 ± 0.100566^{a}
C	Barnacles	1.069 ± 0.101154^{b}
D	Golden apple snail	0.903 ± 0.050632^{b}

Note: Values are mean ± SD. Different superscript letters indicate significant differences among treatments based on one-way ANOVA followed by Duncan's multiple range test ($p < 0.05$); A = anchovies feed; B = shrimp feed; C = barnacles feed; D =golden apple snail feed.

Survival rate. The data presented below outline the SR of *P. homarus* throughout the study (Table 3). The SR observed in the *P. homarus* did not correlate with the type of fresh natural feed provided. In all treatments (A, B, C, D), the SR was consistently 93%, indicating no significant difference between the types of feed (anchovies vs. shrimp) and feed ratios (80% vs. 100%).

Table 3

Survival rate of *Panulirus homarus* in the tube system, floating net cages

Treatment	*Feed*	*Survival rate (%)*
A	Anchovies 80%	93
B	Anchovies 100%	93
C	Shrimp 80%	93
D	Shrimp 100%	93

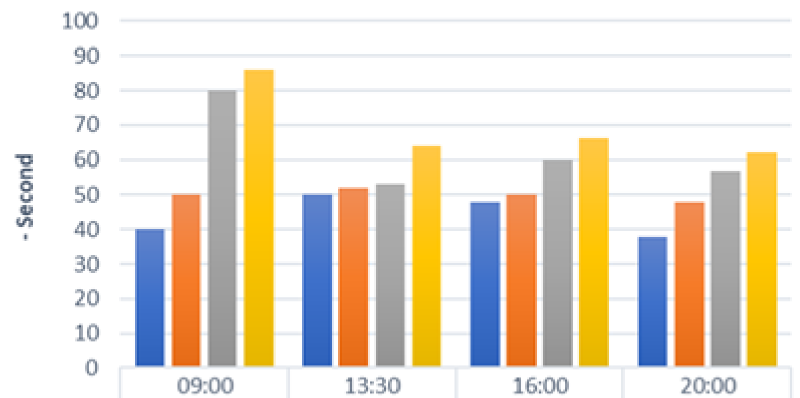
Note: A = 100% anchovy feed; B = 100% shrimp feed; C = 80% anchovy feed; D = 80% shrimp feed.

This consistent SR suggests that factors other than feed type may be influencing survival. Cannibalism, a common issue in juvenile *P. homarus*, is believed to be the primary cause of any potential mortality in *P. homarus*. However, in this study, the use of fresh feed in all treatments likely helped mitigate such behaviors. Juvenile *P. homarus* are naturally aggressive, and their predatory behaviors, including cannibalism, can be reduced by providing adequate and constant feed, as well as maintaining optimal population density in the cages. By reducing competition for food, these factors help prevent interactions that could lead to aggression and, subsequently, lower SR. Previous studies have reported that cannibalism is one of the main causes of mortality in juvenile *Panulirus* spp., particularly under conditions of limited feed availability and high competition (Smith et al 2009; Jones et al 2002).

In the present study, the use of fresh feed in all treatments likely contributed to reducing aggressive interactions and cannibalistic behavior. Adequate and continuous feed supply has been shown to lower predatory behavior in juvenile *P. homarus* by minimizing competition for food resources (Phillips et al 2013). Additionally, proper cage management and appropriate stocking density are known to play important roles in reducing stress and aggressive encounters, thereby supporting higher SRs (Cobb & Castro 2006).

Although solitary housing has been suggested as an effective strategy to further suppress cannibalism by limiting direct physical interactions among individuals (Wahle et al 2013), this approach was not applied in the present study. Nevertheless, the combination of sufficient feeding and suitable cage management appeared to be effective in maintaining a high SR, despite the naturally aggressive and territorial behavior of juvenile *P. homarus*.

Feeding habit. The feeding habits of *P. homarus* were examined, focusing on four specific behaviors: looking at feed, approaching feed, taking feed, and opening their mouths to eat. These behaviors were observed using the Smart *P. homarus* Culture Version 1, as illustrated in the following figure 4.



	09:00	13:30	16:00	20:00
looking at feed	40	50	48	38
approaching feed	50	52	50	48
take feed	80	53	60	57
open mouth to eat	86	64	66	62

Figure 4. Feeding habit of *Panulirus homarus* observed using Smart *P. homarus* Culture Version 1.

Feeding behavior plays a crucial role in optimizing the culture of the *P. homarus,* directly influencing feed efficiency and growth performance. Understanding their feeding response at different times of the day can provide valuable insights for enhancing feeding strategies.

Initial response to feed. The observation data reveal that *P. homarus* exhibited the fastest response in noticing feed during the night (20:00), with an average response time of 38 seconds. This was quicker than in the morning (40 seconds), midday (50 seconds), and the afternoon (48 seconds). Such differences suggest that *P. homarus* exhibits heightened feeding awareness under low-light conditions, a pattern consistent with previous studies indicating that nocturnal crustaceans demonstrate increased activity in reduced light environments.

Movement towards and consumption of feed, the time taken to approach feed was shortest at night (48 seconds), followed by the afternoon (50 seconds), morning (50 seconds), and midday (52 seconds). The fastest response in taking feed was observed in the afternoon and night (50 seconds), compared to midday (52 seconds) and morning (53 seconds). This suggests a higher feeding motivation during these periods, aligning with research by Wei-Ling et al (2023) and Lubis (2023), which found that *P. homarus* exhibits increased movement activity in the evening and nighttime.

The open mouth to eat parameter showed the slowest response in the morning (86 seconds), while the fastest was recorded at night (62 seconds). The afternoon and midday responses were 66 and 64 seconds, respectively. This suggests that *P. homarus* prefers to consume feed more actively at night, potentially due to natural foraging behavior in low-light conditions when predation risk is lower.

Implications for feeding strategy. These findings highlight the importance of optimizing feeding schedules in *P. homarus* aquaculture. The most efficient feeding time appears to be at night (20:00), as *P. homarus* exhibits the fastest responses in all behavioral indicators. This suggests that feed utilization and consumption rates are higher when provided during nocturnal periods, which is consistent with the nocturnal and crepuscular feeding behavior reported for spiny *P. homarus* (Phillips 2013; Smith et al 2009). Improved feed efficiency during nighttime feeding may help reduce feed waste and operational costs, making this period a preferred strategy for maximizing *P. homarus* growth.

Conversely, feeding in the morning (09:00) resulted in the slowest response, particularly for the open mouth to eat indicator, indicating less favorable physiological conditions for feeding. Previous studies on marine crustaceans have shown that metabolic activity is generally lower during morning hours and increases throughout the day, reaching peak levels in the evening and at night (Crear et al 2003; Phillips 2013). Therefore, allocating large feed portions in the morning may be less effective compared to feeding during periods of higher metabolic activity.

Feeding patterns observed during midday (13:30) and afternoon (16:00) were relatively similar, showing slightly delayed responses acrossall indicators compared to nighttime feeding. These periods could serve as secondary feeding times, ensuring that *P. homarus* receive adequate nutrition while maintaining feed efficiency. Implementing a split feeding strategy, where smaller portions are provided during the day and a larger portion is provided at night, may improve overall feed intake and utilization.

In addition to feeding schedules, environmental factors such as water temperature, dissolved oxygen levels, and social interactions among *P. homarus* also influence feeding behavior. Elevated daytime temperatures may suppress feeding motivation in crustaceans when approaching physiological tolerance limits, while high stocking densities can intensify competition for food and delay feeding responses (Jones et al 2002; Cobb & Castro 2006). Optimizing environmental conditions, including temperature regulation and appropriate stocking density, in alignment with natural feeding rhythms, can further enhance aquaculture efficiency and support *P. homarus* growth.

Recommendations for aquaculture practices based on the findings of this study, several recommendations can be made to improve *P. homarus* aquaculture:

1. Adjust feeding schedules to prioritize nighttime feeding, as *P. homarus* exhibit the highest feeding activity at this time.
2. Optimize feed quantity by reducing morning feeding portions and increasing nighttime feed allocation to match the natural feeding behavior of *P. homarus*.
3. Manage environmental factors such as lighting, water temperature, and stocking density to create conditions that support the *P. homarus* ' natural feeding behavior and improve overall aquaculture performance.

Water quality. Water quality parameters were monitored throughout the study to ensure that environmental conditions remained within the optimal range for *P. homarus* culture. Temperature, salinity, pH, DO, water clarity, and ammonia concentrations were measured regularly, and the results are summarized in Table 4. Overall, all measured parameters remained within the recommended ranges established by the Indonesian National Standard for *P. homarus* culture (NSAI 2015) and NSAI (2022), indicating that the rearing environment was suitable for *P. homarus* growth and survival.

Table 4

Optimal water quality parameters for *Panulirus homarus* based on NSAI (2015) and NSAI (2022)

No	*Parameter*	*Unit*	*Value*	*Observation result*
1	Temperature	^{o}C	25-30	28
2	Salinity	ppt	30-35	34
3	pH	-	7-8.5	8
4	DO	ppm	Minimum 4	6.5
5	Clarity	m	Minimum 2	2.5
6	Ammonia	mg L^{-1}	< 1	0.25

Temperature was maintained at approximately 28°C, which falls within the optimal range (25-30°C) for *P. homarus*. Temperature plays a critical role in regulating metabolic activity, digestion, and feeding behavior in crustaceans. Stable temperatures within this range support efficient feed utilization and reduce physiological stress, thereby contributing to consistent growth performance observed during the study. Similar optimal temperature ranges have been reported to enhance feeding efficiency and growth in spiny *P. homarus* and other decapod crustaceans (Crear et al 2003; Phillips 2013).

Salinity remained at 34 ppt, well within the optimal range (30-35 ppt). Appropriate salinity is essential for maintaining osmotic balance in *P. homarus* and supports normal physiological functions such as molting and metabolism. Deviations from optimal salinity can negatively affect appetite and increase stress, which may ultimately reduce growth and survival. Deviations from optimal salinity have been shown to reduce feeding activity and increase stress in marine crustaceans, potentially leading to reduced growth and survival (Cobb & Castro 2006; Phillips 2013).

The pH value recorded during the study was approximately 8, indicating slightly alkaline conditions that are favorable for marine *P. homarus*. Maintaining pH within the recommended range (7-8.5) is important for enzymatic activity, metabolic processes, and overall *P. homarus* health. Stable pH conditions also help prevent ammonia toxicity in aquaculture systems. Stable pH conditions also help prevent ammonia toxicity in aquaculture systems, which can otherwise impair feeding behavior and physiological performance (Boyd 2015).

DO levels averaged 6.5 ppm, exceeding the minimum requirement of 4 ppm. Adequate DO is crucial for aerobic respiration and directly influences feeding activity and growth. High DO levels support active feeding behavior, particularly during nocturnal periods when *P. homarus* exhibited increased feeding responses in this study. Higher DO levels have been associated with increased feeding motivation and metabolic efficiency, particularly during nocturnal periods when *P. homarus* exhibit heightened activity (Phillips 2013).

Water clarity, measured at 2.5 m, exceeded the minimum recommended value of 2 m. Good water clarity indicates low suspended solids and organic waste, which helps improve visual detection of feed and reduces stress. This condition may have contributed to the efficient feeding behavior observed using the AI-based monitoring system.

Ammonia concentrations remained low at 0.25 mg L^{-1}, well below the maximum threshold (< 1 mg L^{-1}). Low ammonia levels indicate effective waste dispersion and natural water exchange in the FNC system. Ammonia accumulation can suppress appetite and impair physiological functions in crustaceans; therefore, maintaining low ammonia concentrations is essential for sustaining high SR. Elevated ammonia concentrations are known to suppress appetite and impair physiological functions in crustaceans; therefore, maintaining low ammonia levels is essential for sustaining high SRs (Boyd 2015).

The integration of the Smart *P. homarus* Aquaculture Version 1.0 AI system enabled continuous monitoring of both *P. homarus* behavior and environmental conditions. By correlating water quality parameters with feeding activity, the AI system provides a valuable tool for early detection of suboptimal conditions and supports adaptive management decisions in real time (Figure 5).

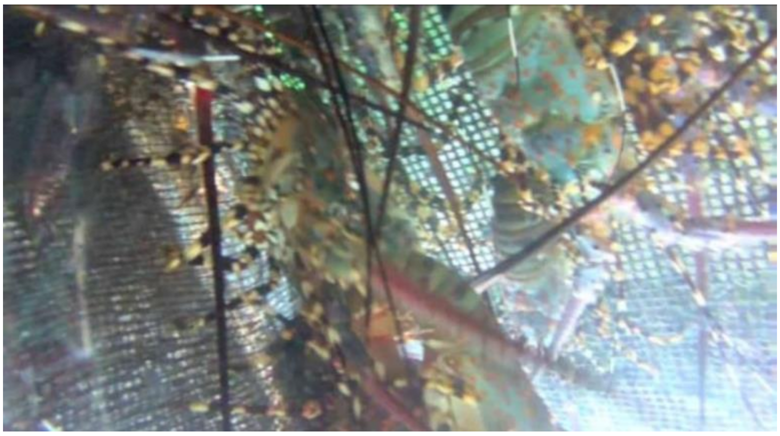


Figure 5. Results of AI observations from Smart *Panulirus homarus* Aquaculture Version 1.0 (2D). The figure shows *P. homarus* feeding behavior, including observing and consuming feed, recorded by the AI system.

In the future, AI can be leveraged to automate various tasks in aquaculture, including feed distribution, health monitoring of fish, and management of water quality. Additionally, AI can aid in developing new breeding programs aimed at producing *P. homarus* that are more resistant to disease and exhibit faster growth rates. The integration of AI in *P. homarus* farming has the potential to enhance the efficiency, sustainability, and profitability of the industry. As AI technology continues to evolve, it is likely to become an essential component of *P. homarus* aquaculture in the future.

Conclusions. The feeding behavior of *P. homarus* exhibits significant temporal variations, with nighttime (20:00) demonstrating the most efficient feeding response across all behavioral indicators. This suggests that nocturnal feeding aligns with the species' natural foraging patterns, leading to improved feed utilization and potential growth optimization. Conversely, morning feeding (09:00) resulted in the slowest response, indicating that metabolic and environmental factors may contribute to reduced feeding efficiency during this period. Midday (13:30) and afternoon (16:00) feedings showed intermediate responses, making them suitable as secondary feeding periods rather than primary feeding times.

These findings underscore the importance of strategic feeding schedule optimization in *P. homarus* aquaculture. Implementing a split feeding approach, where smaller portions are provided during the day and the majority at night, could enhance feeding efficiency while minimizing feed waste. Additionally, environmental factors such as water temperature, DO levels, and stocking densities must be carefully managed to ensure optimal feeding behavior and overall *P. homarus* productivity.

Future research should explore the integration of AI and automated feeding systems to refine feeding strategies based on real-time behavioral monitoring. By aligning feeding practices with natural behavioral rhythms, aquaculture systems can enhance both sustainability and profitability, contributing to the long-term viability of *P. homarus* cultivation.

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Authors:
Rita Rostika, Department of Fisheries, Faculty of Fisheries and Marine Science, Universitas Padjadjaran, Raya Bandung - Sumedang Km. 21, 45363 Jatinangor, Sumedang Regency, West Java, Indonesia, e-mail: rita.rostika@unpad.ac.id
Mochhamad Ikhsan Cahya Utama, Department of Fisheries, Faculty of Fisheries and Marine Science, Universitas Padjadjaran, Bandung - Sumedang Highway Km. 21, 45363 Jatinangor, Sumedang Regency, West Java, Indonesia, e-mail: mochhamad.ikhsan@unpad.ac.id
Lady Ayu Sri Wijayanti, Department of Fisheries, Faculty of Fisheries and Marine Science, Universitas Padjadjaran, Bandung - Sumedang Highway Km. 21, 45363 Jatinangor, Sumedang Regency, West Java, Indonesia, e-mail: Lady@unpad.ac.id

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