

## Effects of Different Feeding Strategies on the Production Performance of Pacific White Shrimp

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**Abstract** Pacific white shrimp (*Litopenaeus vannamei*) is one of the most economically important aquaculture species worldwide, and feed management plays a crucial role in determining production efficiency and profitability. Different feeding strategies can significantly influence shrimp growth performance, feed utilization, water quality, and overall economic returns. This paper reviews the nutritional requirements and feeding characteristics of Pacific white shrimp and systematically evaluates the effects of various feeding strategies, including fixed-time and fixed-quantity feeding, multiple small-meal feeding, and intelligent precision feeding. The impacts of these strategies on growth rate, survival rate, feed conversion ratio, environmental conditions, and disease management are analyzed. In addition, their economic implications, such as feed costs, production efficiency, and return on investment, are discussed. A comparative case study is presented to illustrate the practical performance of different feeding approaches in commercial shrimp farming systems. The findings indicate that optimized feeding management can improve feed utilization efficiency, enhance shrimp health, reduce environmental impacts, and increase farm profitability. Furthermore, the integration of intelligent feeding technologies offers promising opportunities for sustainable and precision aquaculture. This review provides valuable insights for researchers, aquaculture practitioners, and policymakers seeking to improve the productivity and sustainability of Pacific white shrimp farming.

**Keywords** Pacific white shrimp; Feeding strategy; Feed utilization efficiency; Aquaculture economics; Precision feeding technology

### 1 Introduction

The Pacific white shrimp *Litopenaeus vannamei* has become the dominant farmed crustacean worldwide and a cornerstone of the global seafood market, contributing a large share of aquaculture production and animal protein supply. Its commercial success is driven by fast growth, high survival, and tolerance to a wide range of environmental conditions and high stocking densities, making it attractive for intensive and super-intensive systems in both coastal and inland areas (Qiao et al., 2023). At the farm level, intensive pond and tank operations routinely achieve several thousand kilograms per hectare per cycle with favorable financial indicators, highlighting the strong economic potential of this industry when production is efficiently managed (Farkan et al., 2024).

Despite these advantages, the sustainability and profitability of *L. vannamei* culture are tightly constrained by feed costs and feeding efficiency. Feed typically accounts for more than half of the operating or variable costs in shrimp farming, and in some cases approaches 60%-68% of total variable expenses. Surveys of commercial farms similarly show that large feed inputs and resulting feed conversion ratios are key determinants of economic performance, with higher FCRs negatively affecting farm profitability. Beyond economics, excessive feed inputs are a primary source of nutrient loading, deteriorating water quality and generating nitrogen and phosphorus-rich effluents that accumulate in pond water and sediments, increasing environmental risks and reducing long-term sustainability. Consequently, optimizing feed use is central not only to reducing production costs, but also to improving ecological performance and resource efficiency in intensive shrimp aquaculture (Chaikaew et al., 2019; Da Silva et al., 2023).

Within this context, feeding strategy—encompassing ration level, feeding frequency, delivery method, and integration with natural food or biofloc—has emerged as a critical lever for improving production performance of Pacific white shrimp. Evidence from pond and tank trials under semi-intensive and intensive conditions shows that modifying feed amounts, frequencies, or the use of automatic and demand-feeding systems can significantly alter

growth, final weight, and economic returns without necessarily compromising survival or FCR. In biofloc and integrated multi-trophic systems, reduced feeding rates or minimum table-based rations have been shown to maintain acceptable growth while markedly improving FCR and lowering feed costs, indicating that natural productivity and microbial flocs can partially substitute formulated feed when feeding regimes are carefully adjusted (Gonçalves et al., 2024). Other studies emphasize the importance of aligning feeding rates and frequencies with shrimp behavior and physiology, demonstrating that strategies such as more frequent small meals, optimal feeding frequencies with automatic feeders, or moderate feed restrictions can enhance growth, feed utilization, antioxidant capacity, and profitability, while avoiding overfeeding and unnecessary nutrient loading.

Nevertheless, despite growing recognition that feeding management strongly shapes growth, feed efficiency, environmental footprint, and economic outcomes, information on optimal feeding strategies for Pacific white shrimp across different culture systems and intensities remains incomplete, especially under commercial-scale conditions. There is a clear need to systematically evaluate how different feeding strategies influence production performance—such as growth rate, survival, FCR, and economic returns—under realistic farming scenarios, including ponds, recirculating systems, and biofloc-based operations. The present study, titled “Effects of Different Feeding Strategies on the Production Performance of Pacific White Shrimp,” aims to address this gap by comparing alternative feeding regimes designed to adjust ration level and feeding pattern, and by quantifying their impacts on growth performance, feed utilization, and production economics. By identifying feeding strategies that balance high productivity with reduced feed inputs and environmental loading, this research seeks to provide practical guidance for farmers to enhance profitability and sustainability in Pacific white shrimp aquaculture.

## **2 Nutritional Requirements and Feeding Characteristics of Pacific White Shrimp**

### **2.1 Nutritional requirements at different growth stages of pacific white shrimp**

Protein is a primary driver of growth in Pacific white shrimp, but the optimal level shifts with body size and developmental stage. Feeding trials across juvenile, sub-adult, and adult stages indicate that crude protein requirements for maximum growth generally fall around 32%-36%, with slightly higher levels for smaller shrimp and modest reductions as shrimp grow larger. In larvae, diets containing about 35% protein have produced superior weight gain and protein efficiency, suggesting that early life stages also benefit from moderately high but not excessive protein inputs (Elfeky, 2022).

Energy supply through lipids must be balanced with protein so that protein is used for growth rather than as an energy source. Studies combining different protein and lipid levels in juvenile shrimp identify an optimal protein-energy ratio around 340 g/kg protein with moderate lipid (about 75 g/kg), which maximizes growth, protein efficiency, and feed efficiency without excessive fat deposition. For postlarval shrimp, graded lipid trials suggest an optimal dietary lipid level near 118-124 g/kg when both growth and stress tolerance are considered, highlighting that very young stages may tolerate or require higher lipid levels to support rapid growth and resilience (Xie et al., 2019).

### **2.2 Feeding behavior and influencing factors**

Feeding behavior in Pacific white shrimp is strongly shaped by environmental conditions, especially temperature. Experimental work shows that at cooler temperatures (around 24 °C-28 °C), juveniles feed slowly on the tank bottom, with long gut-filling and evacuation times and substantial uneaten feed remaining after meals. As temperature rises to 30 °C-34 °C, shrimp swim actively while feeding, fill their guts within 15-20 minutes, and consume nearly all the offered pellets, indicating a sharp temperature-dependent acceleration of intake and digestion. Parallel growth trials confirm that growth rate and feeding rate increase with temperature, but the optimal temperature for fastest growth declines as shrimp size increases, implying that feeding strategies should be adjusted to both size and thermal regime.

Beyond temperature, social and environmental context also modifies feeding behavior and efficiency (Figure 1). Behavioural studies show that stocking density and dominance hierarchies affect how long individuals spend on the feeding area and how feed is partitioned; at higher densities, shrimp show greater relative feed consumption but

share limited feeding space, while dominance-related differences in feeding time are reduced (Bardera et al., 2021). Turbidity alters group-level responses, with higher turbidity increasing feed intake and reducing distances between individuals, suggesting that commercial ponds with naturally turbid conditions may promote more cohesive and intense feeding bouts than clear-water tanks (De Tailly et al., 2025).

### Mechanistic diagram of the effects of temperature gradient on the feeding behavior of *Litopenaeus vannamei*

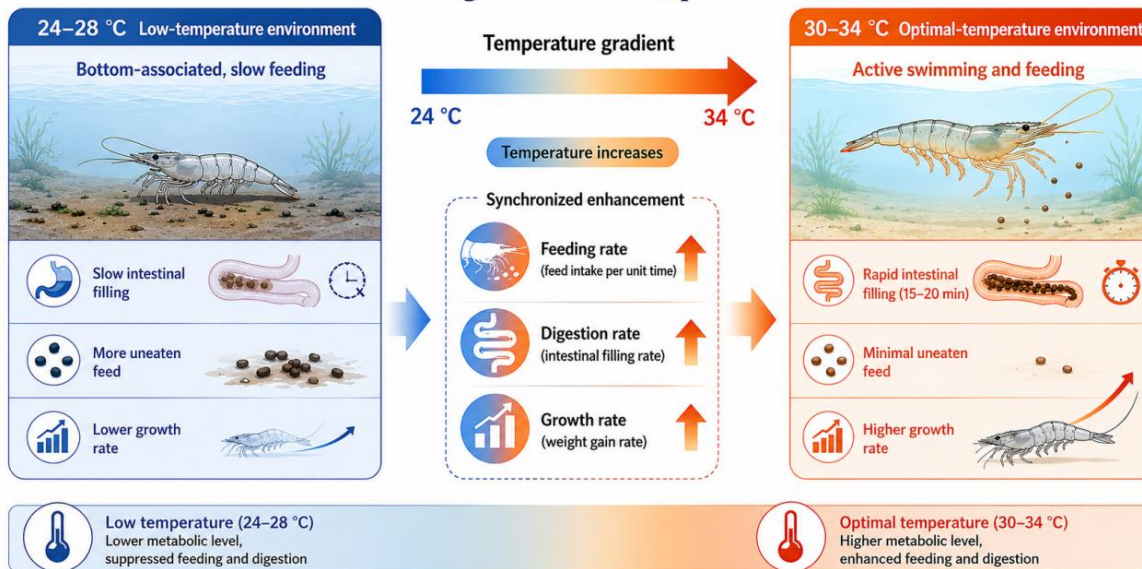


Figure 1 Effects of water temperature on feeding behavior, digestive activity, and growth performance of Pacific white shrimp (*Litopenaeus vannamei*)

Note: Shrimp reared at 24 °C-28 °C exhibit slower feeding activity, prolonged gut-filling and evacuation times, and increased feed residues, whereas individuals maintained at 30 °C-34 °C show rapid feed consumption, accelerated digestion, and enhanced growth

### 2.3 Relationship between feed utilization efficiency and growth performance

Feed utilization efficiency, commonly expressed as feed conversion ratio (FCR), is tightly linked to growth performance and is influenced by diet formulation and feeding rate. In intensive systems, increasing feeding rates above a standard schedule leads to higher final weights, but FCR worsens and growth approaches a plateau, revealing an inflection point near 100%-101% of the standard feeding rate where additional feed yields diminishing returns. Trials manipulating feeding frequency in juveniles similarly show that moderate automatic feeding (around 6-8 meals per day) improves FCR, final weight, and antioxidant status compared with less frequent manual feeding, indicating that spreading the same ration into more meals can enhance nutrient utilization (Liang et al., 2025).

Dietary interventions that improve digestion or metabolic efficiency can reduce FCR while supporting growth. Supplementation of low-fishmeal, low-lipid diets with small amounts of lysophospholipids increases final body mass, growth rate, and protein deposition, while lowering FCR and enhancing digestive enzyme activities and intestinal health, demonstrating how additives can “unlock” feed efficiency under cost-saving formulations (Li et al., 2026). Similarly, nanoemulsified curcumin in olive oil has been shown to improve specific growth rate, FCR, and protein efficiency ratio, alongside better digestive enzyme secretion and antioxidant capacity, linking enhanced physiological status to more efficient feed use (El-Bab et al., 2024).

## 3 Common Feeding Strategies and Their Characteristics

### 3.1 Fixed-time and fixed-quantity feeding strategy

In many commercial farms, shrimp are fed at fixed times and fixed daily rations based on biomass estimates or standard feeding tables. This approach is simple to implement and relies on scheduled distributions (for example, two to four meals per day) with predetermined quantities that are adjusted periodically as shrimp grow. Semi-intensive pond trials using standard feeding protocols (SFP) show that applying a fixed ration close to a

reference curve can support good growth and survival under both tank and pond conditions. In these studies, reducing or increasing feed input around the SFP (for example, 90%-110% of the table) had limited effect on feed conversion ratio, suggesting that fixed-ration strategies can be robust when biomass estimates are reasonable (Van et al., 2017).

However, strictly fixed rations may fail to match real-time appetite, especially as natural food availability and environmental conditions fluctuate. In intensive biofloc systems, experiments that applied several discrete feeding levels (30%-150% of a standard rate) revealed that growth increases with higher feed inputs but feed conversion worsens once a threshold is exceeded, indicating a trade-off between maximum biomass gain and feed efficiency under fixed-rate feeding. These results highlight that while fixed-time and fixed-quantity strategies are practical, they require careful calibration to avoid underfeeding, which limits growth, or overfeeding, which raises costs and nutrient loading (Weldon et al., 2021).

### 3.2 Multiple small-meal feeding strategy

Shrimp have small stomachs and naturally ingest many small meals, so distributing the daily ration into multiple small feedings aims to better align with their feeding behavior. Controlled studies comparing low (1-2 meals) and higher frequencies (4-6 meals or more) show that more frequent feeding can improve growth and, in some cases, water quality when total ration is maintained. For example, juveniles in biofloc systems fed three, six, or twelve times daily with the same daily ration displayed higher final weight, yield, and protein deposition as frequency increased, while feed conversion ratio decreased (Xu et al., 2020). Similar trials with extruded diets found that once- or twice-daily daylight feeding promoted growth but at the expense of water quality and FCR, whereas higher frequencies reduced ammonia and nitrite levels, indicating environmental benefits of spreading meals (Espinoza-Ortega et al., 2023).

Multiple small-meal strategies can be implemented manually or via automatic feeders and may be particularly valuable when diet formulation or system design constrains performance. Using a low-fish-meal, amino-acid-supplemented diet, offering ten meals per day via automatic feeders enhanced survival, body weight, and FCR compared with two or four manual meals, illustrating that more frequent feeding can compensate for lower fish-meal inclusion by improving intake and nutrient use. On farms, observations of pond management practices similarly emphasize dividing rations into several daily feedings and monitoring consumption, supporting more even distribution and reducing cannibalism, which are key practical characteristics of multiple small-meal feeding (Andriani and Pratama, 2023).

### 3.3 Intelligent precision feeding strategy

Intelligent precision feeding integrates automatic devices and real-time feedback or predictive models to dynamically adjust feed delivery according to shrimp demand and biomass. On-demand acoustic systems such as AQ1 release feed in response to feeding sounds, allowing shrimp to “request” feed within programmed limits. Pond trials comparing acoustic demand feeding with fixed-schedule timer feeders and standard protocols demonstrate that AQ1 systems consistently produce larger shrimp, higher yields, and greater crop value, without worsening FCR or survival, indicating more precise matching of feed input to appetite. Follow-up work under semi-intensive conditions similarly found that automatic feedback systems operating in real time outperformed standardized timer-based schedules, reinforcing the performance advantage of demand-driven feeding (Reis et al., 2020).

Beyond behavior-based feedback, recent developments incorporate machine-learning biomass prediction into intelligent feeders. In recirculating systems, data-driven models using water-quality and management data can predict shrimp biomass with high accuracy, enabling feeders to calculate appropriate ration sizes and stabilize water quality. Automated feeding trials that varied the number and distribution of meals show that when combined with optimized schedules, these systems improve growth and FCR compared to manual feeding, while also reducing labor costs and enabling higher feeding frequencies (Liang et al., 2025). Overall, intelligent precision strategies are characterized by continuous or high-frequency feed delivery, sensor or acoustic feedback, and algorithm-guided ration adjustment, aiming to maximize growth and profitability while minimizing waste.

## 4 Effects of Different Feeding Strategies on the Growth Performance of Pacific White Shrimp

### 4.1 Effects on weight gain and specific growth rate

Feeding rate and rationing strategy have clear impacts on weight gain and specific growth rate (SGR) of Pacific white shrimp. In high-density biofloc systems, increasing feeding rates above a reduced baseline progressively increased final weight and weekly growth, but gains tended to plateau as rates exceeded the level needed to approach maximum growth. Similarly, in biofloc grow-out systems, a moderate 25% reduction in feeding rate unexpectedly produced the highest final weight, biomass, and weight gain, indicating that natural food sources can compensate for reduced formulated feed while still supporting rapid growth and high SGR (Kusmiatun et al., 2025).

Feeding frequency and delivery method also shape weight gain and SGR, even when the total daily ration is similar. In ponds, increasing daily feedings from two to six times using timer or acoustic demand systems significantly raised final individual weights compared with twice-daily protocols, showing that distributing feed more evenly enhances growth performance. Recirculating tank trials with automatic feeders further highlight that feeding 6-8 times per day optimizes final body weight and SGR compared with both lower-frequency manual feeding and higher-frequency automatic schedules, suggesting that there is an optimal feeding frequency window beyond which additional meals do not improve, and may even impair, growth (Liang et al., 2025) (Figure 2).

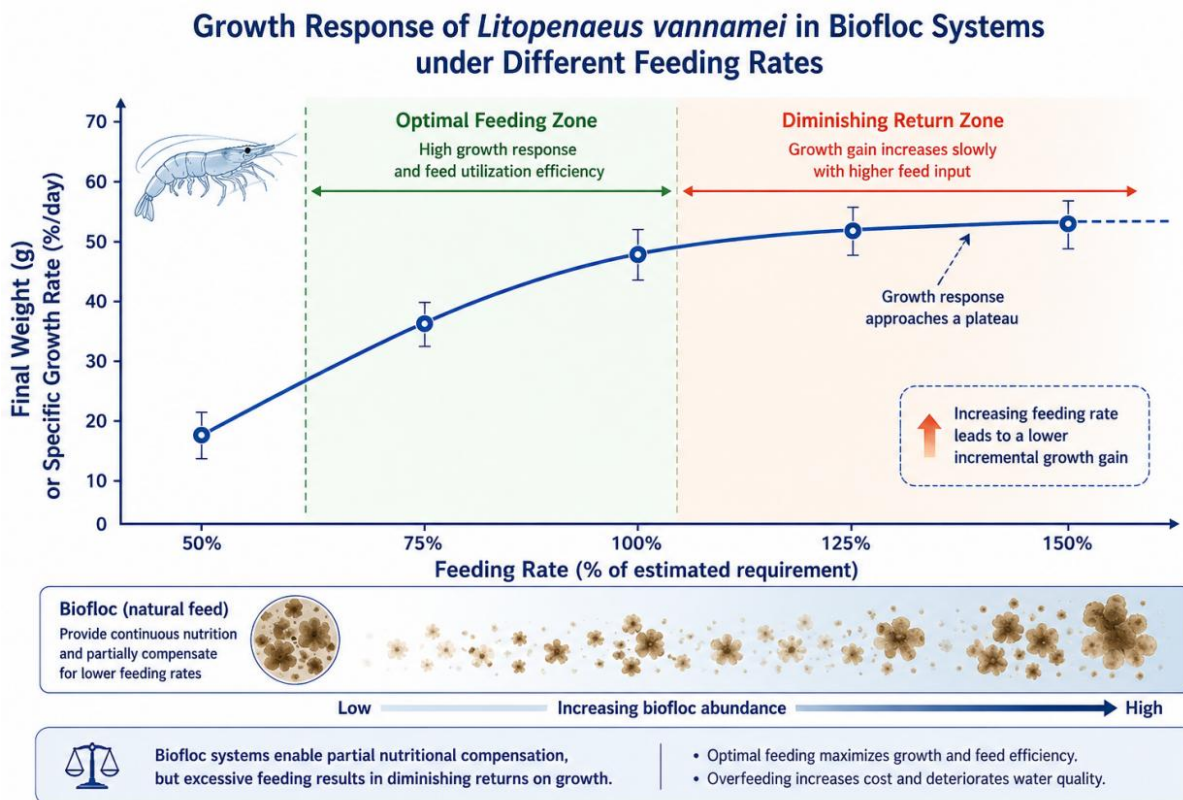


Figure 2 Conceptual relationship between feeding rate and growth performance of Pacific white shrimp (*Litopenaeus vannamei*) cultured in biofloc systems

### 4.2 Effects on survival rate and culture duration

Many feeding strategies that alter ration level or delivery pattern can maintain high survival while modifying growth trajectories, which has implications for culture duration. In intensive biofloc systems exposed to a wide range of feeding rates, survival remained consistently high (around 94%-97%) across treatments, indicating that shrimp tolerate substantial variation in feed inputs over a 63-day cycle without major mortality effects. Nursery-phase biofloc studies similarly reported no significant differences in survival or feed conversion ratio when feeding frequency was reduced from six to one meal per day over 40 days, suggesting that survival in early nursery stages is relatively robust to feeding frequency adjustments under good water quality (Wasielesky et al., 2020).

Under integrated multi-trophic systems, survival outcomes can even improve under adjusted feeding regimes. In tanks co-culturing shrimp with the macroalga *Caulerpa lentillifera*, survival and yield at 75%-100% of the control feed ration were significantly higher than in monoculture controls over 45 days, despite reduced formulated feed inputs. Biofloc-based studies cutting feed by 25% also maintained good survival while shortening effective time to marketable size through higher SGR, implying that optimized feed reductions in enriched systems may sustain or improve survival while potentially reducing culture duration required to reach target weights (Kusmiatun et al., 2025).

#### **4.3 Effects on size uniformity within shrimp populations**

Feeding strategies influence how evenly feed is distributed among individuals, thereby affecting size uniformity. Experiments manipulating pellet (diet) size showed that larger pellets prompted more aggressive feeding behavior, with some shrimp obstructing others and monopolizing feed; this “selfish” behavior was suggested as a mechanism leading to considerable size variation and potentially higher mortality among smaller individuals as they grow to market size. Practical feeding recommendations from field observations similarly stress that even feed distribution in ponds is essential to promote proportional growth, indicating that unequal spatial delivery of feed can exacerbate within-cohort size differences (Andriani and Pratama, 2023).

Feeding frequency and access time also interact with social dynamics to influence size dispersion. Studies of stocking density and dominance in *L. vannamei* showed that density and social rank affect time spent feeding, with dominant individuals securing more feeding opportunities under certain conditions. Automatic or demand-based feeding systems that provide more continuous access to feed throughout the day can partially mitigate competitive exclusion by extending feeding windows, which likely contributes to the improved growth observed with acoustic demand feeders compared with limited twice-daily hand feeding in ponds (Ullman et al., 2018).

### **5 Effects of Different Feeding Strategies on Feed Utilization Efficiency**

#### **5.1 Effects on feed conversion ratio (FCR)**

Feed conversion ratio is highly sensitive to how much and how often shrimp are fed, with both restrictive and excessive rations altering efficiency. In high-density biofloc systems, varying feed inputs from 30% to 150% of a standard rate showed that increasing feed above about 100% raised final weight but caused FCR to increase, indicating diminishing returns in growth relative to feed supplied. Regression analysis also identified an inflection near 101% of the standard rate where feed utilization declined rapidly, emphasizing that overfeeding directly worsens FCR even when growth continues to rise (Weldon et al., 2021).

Feed restriction and the use of natural productivity can conversely improve FCR when carefully managed. In a symbiotic pond system, partial feed restriction reduced FCR from 0.59 under full feeding to 0.30 under restricted feeding while still allowing total compensatory growth, showing that lower rations can markedly increase efficiency if environmental food is available. Similarly, in biofloc tanks, a 25%-50% reduction in feeding rate produced the lowest FCR values (0.90-0.71) compared with standard rations in clear water or biofloc, illustrating that biofloc-based strategies can substantially enhance FCR under reduced feed inputs (Kusmiatun et al., 2025).

#### **5.2 Effects on dietary protein utilization efficiency**

Feeding strategies that alter protein intake and ration size strongly affect protein retention and utilization. In a green-water recirculating system, combinations of 25%-40% dietary protein and two feeding rates produced significant differences in apparent net protein retention (49%-66%), with lower protein intake treatments achieving the highest retention despite slower growth (Araujo et al., 2025). This indicates that high feeding and protein levels favor growth but can dilute protein efficiency, whereas more modest protein supplies improve retention per unit intake.

Biofloc-based feeding reductions can simultaneously improve growth and protein utilization when natural food supplements the diet. In a 30-day biofloc trial, a 25% feed reduction produced the highest final protein content and protein retention (18.94%) compared with standard feeding in clear water or biofloc, demonstrating more effective

conversion of ingested protein into body tissue under moderate restriction (Kusmiatun et al., 2025). Cyclical fasting-feeding regimes also improved protein efficiency ratio in juveniles, suggesting that intermittent restriction can enhance protein use while maintaining compensatory growth.

### 5.3 Effects on production efficiency and resource use

At the farm scale, FCR is closely tied to economic and environmental performance, so feeding strategies that lower FCR directly improve resource use. Nutrient-budget analysis on an intensive farm showed that feed contributed 80% of nitrogen inputs, with an overall FCR of 2.0; modeling a reduction to 1.8 FCR indicated the farm could cut 147 kg of feed, saving over US\$1000 per crop and reducing nitrogen and phosphorus loading to ponds and effluents. Global assessments of embodied resources in shrimp feeds further suggest that reducing FCR by 0.1 across major cultured species would save large amounts of energy, land, freshwater, and wild fish, underscoring the broader sustainability gains from efficient feeding.

Within biofloc and synbiotic systems, feed-restriction strategies can maintain or even improve production efficiency while lowering operational inputs. In synbiotic ponds, partial feed restriction halved FCR and reduced total operating costs by about 20%, yet both restricted and unrestricted treatments showed positive profitability, indicating that lower feed input strategies can be economically viable (Gonçalves et al., 2024). Complementary work in biofloc systems found that feeding according to minimum table values yielded better FCR, survival, and lower waste production than maximum table rates or FCR-based rationing, highlighting that conservative, well-calibrated feeding tables can improve both resource use and system cleanliness (Da Silva et al., 2023).

## 6 Effects of Different Feeding Strategies on Culture Environment and Health Management

### 6.1 Effects on water quality parameters

Feeding rate and delivery method directly affect nutrient loading and key water quality variables in shrimp culture systems. In semi-intensive ponds, increasing feed inputs raised nitrogen and phosphorus concentrations, elevating total ammonia nitrogen and nitrite, particularly when demand feeders allowed higher daily feed loads than hand feeding or timer-based protocols. In indoor recirculating systems, sharp increases in feed load led to spikes in total ammonia nitrogen up to 24.2 mg/L, coupled with oxygen depletion and large mortality events, underscoring how overfeeding can overwhelm biofiltration capacity and destabilize water quality (Mohammed et al., 2024).

Feeding strategy can also modify suspended solids and organic matter dynamics in pond water. Comparisons between ponds using feeding trays and mechanical feed blowers showed that tray feeding generated lower ammonia and particulate organic solids loads per kilogram of shrimp, even though total suspended solids were slightly higher, suggesting tighter control of uneaten feed. In biofloc and zero-exchange systems, adjusting feeding levels interacts with microbial floc to influence ammonia; for example, nursery tanks with lower feeding rates showed significantly reduced ammonia compared with higher-fed controls, reflecting the role of feed load management in maintaining acceptable nitrogen levels (Khanjani et al., 2016).

### 6.2 Effects on pond sediment conditions and organic loading

Uneaten feed and feces are major contributors to sediment organic loading, and their accumulation is closely linked to feed management intensity. Field analysis of different shrimp culture intensities showed that estimated organic waste (total suspended solids) derived from feed rose from about 488 kg TSS/ha in traditional plus systems to over 9,228 kg TSS/ha in intensive ponds, reflecting higher feed use at greater stocking densities (Mhr, 2022). Nitrogen budget studies in penaeid ponds, although not specific to *L. vannamei*, similarly indicate that up to 38.4% of nitrogen entering as feed and inflow may accumulate in sediments, with waste generation per kilogram of shrimp increasing strongly with stocking density and associated feed inputs.

Sedimentation rates of nutrients and particulates also respond to management history and feed loading intensity. In *L. vannamei* earthen ponds, treatments associated with higher initial inputs for dense greenhouse phases showed significantly elevated early sedimentation of nutrients and particulate matter, indicating rapid deposition of feed-derived solids. In polyculture ponds with tilapia and shrimp, ponds classified as high feed-loading exhibited

sediment accumulation rates around 35.5 cm/year and markedly higher carbon burial than low-loading ponds, suggesting that persistent overfeeding accelerates pond infilling and long-term organic enrichment of sediments (Kunlapasuk et al., 2019).

### 6.3 Effects on disease risk and immune status

Feeding strategies interact with health management by shaping both environmental stressors and the nutritional support for immunity. Excess feed inputs elevate ammonia and nitrite, which can compromise shrimp condition and increase susceptibility to disease; high TAN associated with an 81.2% increase in feed load was linked with 40% mortality in a recirculating system, demonstrating how feed mismanagement can directly trigger health crises (Mohammed et al., 2024). Broader analyses of shrimp aquaculture wastewater identify excess feeding as a major source of organic and nutrient pollution, and recommend careful feed control as part of preventive health and environmental management to avoid eutrophication and related disease risks (Iber and Kasan, 2021).

Conversely, diet composition and functional feed additives within a given feeding strategy can enhance immune status and disease resistance. Probiotic-supplemented diets, such as those containing *Lactobacillus plantarum* Ep-M17 or *Pediococcus acidilactici*, improved growth, lowered feed conversion ratio, and significantly reduced mortality after *Vibrio parahaemolyticus* or *Fusarium solani* challenges, reflecting strengthened immune and antioxidant responses under routine feeding schedules. Similarly, herbal or functional additives such as artemisinin and lysozyme-based supplements enhanced antioxidant capacity, immune enzyme activities, and resistance to *Vibrio* infections, indicating that appropriately formulated and scheduled feeding can be a key tool in integrated health management strategies (Figure 3).

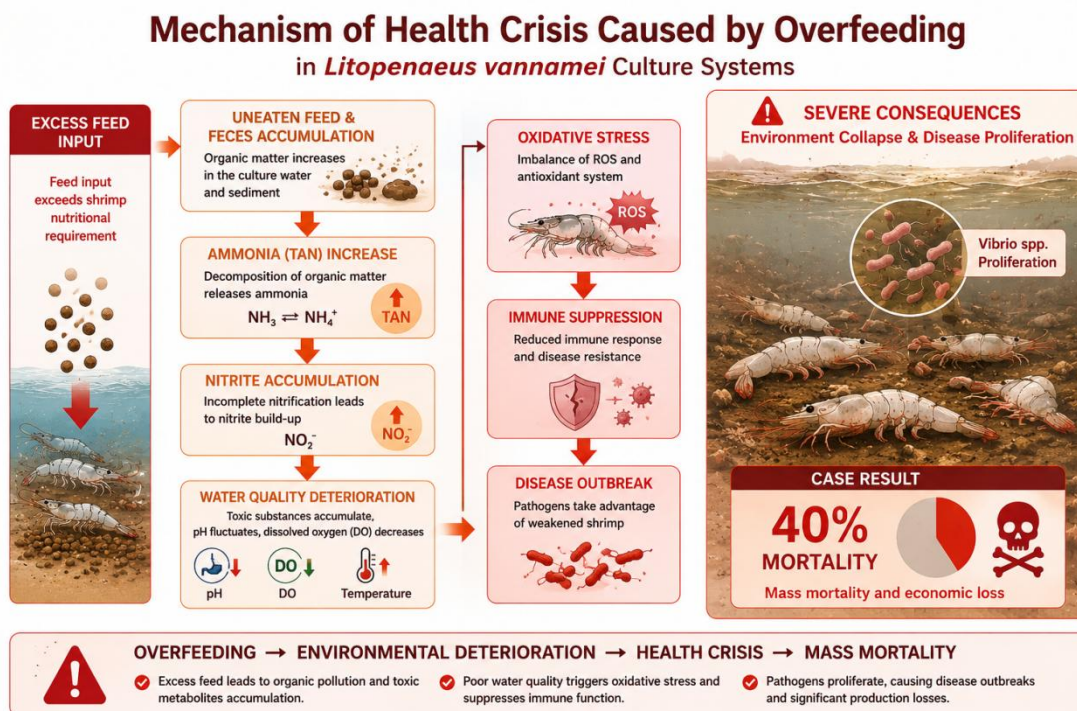


Figure 3 Mechanistic pathway linking excessive feeding to environmental deterioration and disease risk in Pacific white shrimp (*Litopenaeus vannamei*)

## 7 Effects of Different Feeding Strategies on Economic Benefits of Shrimp Farming

### 7.1 Analysis of feed costs and production costs

Feed is consistently identified as the largest component of variable production costs in Pacific white shrimp culture, so feeding strategy directly shapes overall cost structure. In Indian farms, feed accounted for about 69% of total variable costs, greatly exceeding other inputs such as seed, energy, and labor, which together represented less than one-third of variable expenditure. Similar analyses comparing *L. vannamei* and *P. monodon* across intensification

levels in India showed that feed alone represented about 70% of variable costs in whiteleg shrimp farms, underlining that small changes in feed use or price translate into large changes in total production cost per hectare (Nisar et al., 2021).

Because feed is such a dominant cost, strategies that reduce ration without harming growth can markedly lower total and operating costs. In a synbiotic pond system, partial feed restriction cut FCR by roughly half and reduced effective operating costs by 21.8% and total operating costs by 20.2%, with feed volume being the only cost component differing between treatments (Gonçalves et al., 2024). Under semi-intensive pond conditions, modest feed reductions (to 90% or a staged 80%-90%-100% of standard tables) produced similar growth and economic returns to full rations, while slightly decreasing feed cost per kilogram of shrimp, indicating that careful ration control can improve cost efficiency without sacrificing performance.

### 7.2 Comparison of yield and economic returns

Feeding technologies and strategies that raise growth and yield generally increase gross revenue and shrimp value per hectare. In a 16-week pond trial comparing four feed-management techniques, timer feeders and acoustic demand feeding significantly increased final weights, and the AQ1 acoustic system more than doubled shrimp value to about US\$21,198/ha relative to standard twice-daily protocols (Ullman et al., 2019). A separate study with higher stocking density similarly found that AQ1 demand feeding raised yield to 7430 kg/ha and shrimp value to US\$65,587/ha, clearly outperforming timer and standard feeding while maintaining comparable FCR and survival (Ullman et al., 2018).

Diet formulation, when coupled with appropriate feeding management, can also shift revenues through changes in yield and size distribution. Under commercial conditions, a fishmeal- and fish-oil-free “F3” diet produced higher biomass, better FCR (1.03 vs. 1.15), and larger shrimp, leading to an 11.8% higher sales revenue compared with a commercial reference feed. On-demand feeding with different protein levels showed that although a 40% protein diet was more expensive, it did not improve biomass or economic outcomes relative to 30%-35% protein diets, indicating that overly rich diets may not yield proportional revenue gains when demand feeding is used (Strebel et al., 2023).

### 7.3 Evaluation of return on investment and economic sustainability

Economic analyses that integrate feed inputs, yields, and market prices show how feeding choices influence return on investment (ROI) and long-term financial viability. In a commercial pond trial comparing conventional and marine-resource-free feeds, the F3 diet yielded higher growth and revenue, resulting in ROI values of 89.8% versus 64.5% for the commercial diet, while all other non-feed costs remained similar between treatments (Tran et al., 2022). Business analyses from Indonesian farms likewise report R/C ratios above 1 and very short payback periods (around 0.5-2.9 years) for intensive *L. vannamei* operations, suggesting that when feed is managed efficiently the sector is highly profitable (Farkan et al., 2024).

Feeding and management strategies also interact with intensification to determine economic sustainability and resource use efficiency. Comparative studies across intensity clusters in India showed that more intensive *L. vannamei* farms achieved higher net returns (about US\$41,641/ha/year) and lower cost per ton, provided feed and other inputs were used efficiently. (Nisar et al., 2021). Multi-country analysis of intensification in Vietnam and Thailand further found that higher-intensity clusters had lower costs per metric ton and greater profitability, reinforcing that feeding strategies which support high yields while controlling feed costs are central to economically sustainable shrimp farming.

## 8 Case Study: Comparative Evaluation of Different Feeding Strategies in Pacific White Shrimp Farming

### 8.1 Performance analysis of traditional manual feeding practices

Traditional manual feeding remains a common baseline strategy in pond and tank culture, typically using standard feeding tables and two to four meals per day. Semi-intensive tank and pond trials applying a standard feeding

protocol (SFP) and slight variations ( $\pm 10\%$ - $20\%$ ) showed similar survival, FCR, and economic returns across treatments, indicating that well-calibrated manual tables can support satisfactory growth and profitability without high feed surpluses. At nursery scale in biofloc systems, reducing manual feeding frequency from six to one meal per day did not significantly affect final weight, survival, or FCR, suggesting that in early stages, growth performance can be maintained even with relatively simple manual schedules when water quality is stable (Wasiolesky et al., 2020).

Nevertheless, comparative trials consistently show that manual feeding underperforms more intensive or automated strategies in terms of growth and yield. In intensive tanks, a manually fed control group at six meals per day achieved lower final body weight and poorer FCR than groups fed at similar frequencies with automatic feeders, underscoring the limitations of human-timed delivery in matching shrimp appetite patterns (Liang et al., 2025). Large-pond comparisons of manual hand feeding versus automatic timer and acoustic systems also showed the lowest average daily growth, final body weight, and yield under manual regimes, even though survival remained comparable, highlighting that manual feeding is robust but less efficient for maximizing production.

### 8.2 Production benefits of multiple small-meal feeding regimes

Case studies comparing low versus high feeding frequencies demonstrate clear production gains from multiple small meals. In recirculating systems, automatic feeding 6-12 times per day, with the same total ration as a manual six-meal control, significantly increased final body weight and specific growth rate, while improving FCR; regression analysis indicated an optimal automatic frequency around 7.8 meals per day (Liang et al., 2025). Similarly, post-larval trials showed that feeding six times daily yielded higher final weights than two or four meals, confirming that distributing the ration more finely better matches the shrimp's continuous feeding behavior.

Pond-scale work reinforces these findings by linking increased feeding frequency to higher growth and crop value. In a 16-week pond trial, moving from two daily feedings under an SFP to six feedings via timer feeders raised final individual weights and improved economic returns, even though overall FCR and survival remained similar (Ullman et al., 2019). Subsequent studies in semi-intensive ponds confirmed that higher numbers of meals allow greater total feed inputs and higher yields, with growth responses linked more strongly to the number of meals than to the specific day-night schedule, emphasizing that multiple small meals are a key lever for enhancing production efficiency.

### 8.3 Economic and environmental assessment of intelligent automatic feeding systems

Intelligent automatic systems—including timer feeders, acoustic demand feeders, and model-based “smart” feeders—offer both economic and environmental advantages over traditional methods. In pond case studies, acoustic demand systems (AQ1) produced the highest final weights, yields, and crop values compared with standard twice-daily SFP and timer-based protocols, while maintaining similar FCR and survival, thereby increasing revenue per hectare without extra feed cost per kilogram of shrimp. Another semi-intensive trial similarly found that on-demand AQ1 feeding yielded larger shrimp and higher production than several fixed over-SFP timer regimes, demonstrating that real-time feedback can outperform pre-set schedules in economic terms (Reis et al., 2020).

Environmental and labor-cost benefits arise from more precise control of ration size and timing. Water-quality monitoring in ponds fed by hand, timers, and AQ1 showed that the acoustic system achieved the greatest yield but also higher late-season ammonia and nitrite, indicating that automated strategies must be matched to system nutrient-processing capacity to avoid water-quality deterioration. In recirculating systems, intelligent feeders using machine-learning biomass prediction can calculate appropriate feed amounts from sensor data in real time, supporting stable water quality while reducing waste and labor, and IoT-linked solar feeders further cut long-term labor and energy costs, achieving large percentage reductions in annual and 10-year operating expenses compared with manual feeding (Boonraksa and Boonraksa, 2025).

## 9 Conclusions and Future Perspectives

Across culture systems, feeding strategies can be viewed along a spectrum from fixed schedules and ration tables to fully intelligent, sensor-driven control. Fixed-time, fixed-ration approaches remain the backbone of many farms

because they are simple and compatible with standard commercial feeds and protein formulations. They can support good growth and acceptable feed conversion when carefully calibrated, especially when diet quality is high and protein levels match shrimp requirements. At the same time, such strategies are vulnerable to errors in biomass estimation and cannot react to short-term variations in appetite or environmental conditions. More dynamic strategies, including multiple small meals, feed restriction in biofloc or green-water systems, and automated delivery, offer important gains in feed utilization and growth. Studies with reduced feeding rates in biofloc show that moderate restriction can improve both growth and feed efficiency by leveraging natural productivity, while high-protein diets and functional additives further enhance performance. Increasing feeding frequency and using automatic or acoustic demand feeders improves growth and economic returns without compromising survival, indicating that closer matching of feed supply to shrimp demand is a core principle of effective feeding strategies. Intelligent precision approaches based on biomass prediction and IoT platforms are beginning to unify these elements into integrated feeding systems.

Despite substantial progress, existing research on feeding strategies for Pacific white shrimp has several limitations. Many trials are relatively short in duration, focus on a single production phase, or are conducted in experimental tanks and small ponds rather than full commercial farms. This constrains understanding of long-term impacts on pond ecology, sediment dynamics, and multi-cycle sustainability. Moreover, most studies evaluate one dimension at a time—such as protein level, ration size, or feeding frequency—rather than systematically exploring their interactions across different culture intensities and environments. There are also gaps in the evaluation of emerging intelligent and automated technologies. Machine-learning-based biomass prediction and IoT-enabled feeders have demonstrated technical feasibility and good prediction accuracy, but evidence on their robustness across seasons, farm scales, and management styles remains limited. Economic analyses often emphasize feed cost and gross revenue without fully accounting for capital expenditure, maintenance, training, or data-management requirements. In addition, much of the AIoT literature is fish-focused, with relatively fewer shrimp-specific applications, leaving questions about model transferability, behavior-based appetite detection in crustaceans, and integration with health and disease-monitoring systems.

Intelligent precision feeding is poised to become a central pillar of precision aquaculture for Pacific white shrimp. Future systems are likely to couple real-time water-quality sensing, computer vision or acoustic monitoring of feeding activity, and data-driven biomass models to continuously adjust ration size, timing, and spatial distribution. Shrimp-specific machine-learning models that integrate environmental, nutritional, and behavioral data can refine estimates of appetite and growth potential, allowing automatic feeders to minimize overfeeding while sustaining rapid weight gain. As IoT hardware and cloud platforms mature, these tools are becoming more accessible, including for small and medium-scale farms. At a broader scale, intelligent feeding will be increasingly linked to farm-level and even regional management. Integration with AIoT farm-management systems can align feeding decisions with energy use, aeration control, and disease-risk forecasting, improving resilience and lowering environmental footprints. Advances in precision aquaculture point toward multimodal sensor fusion, digital twins, and explainable AI, which could help farmers understand and trust automated recommendations while optimizing FCR, nutrient retention, and economic returns. To realize these prospects, future work must address challenges of cost, interoperability, data quality, and capacity building, ensuring that intelligent precision feeding contributes not only to higher productivity, but also to long-term economic and ecological sustainability of shrimp farming.

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### **Conflict of Interest Disclosure**

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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