

Technological gaps and innovation needs assessment in recirculating aquaculture system for mangrove crab fattening in the Philippines

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Abstract. The recirculating aquaculture systems (RAS) are gaining popularity for mangrove crab (*Scylla* spp.) fattening in the Philippines. However, information on operators' perceptions, readiness, constraints, and adoption remains limited. This study assessed the technological gaps and innovation needs of RAS for mangrove crab fattening, with emphasis on operational practices, constraints, and adoption perspectives among Philippine crab growers. Data were gathered through key informant interviews, field observations, and technology assessments involving RAS adopters and conventional crab growers. The results showed that feeding practices relied heavily on manually administered trash fish, with no standardized rationing based on crab size or physiological stage, resulting in inefficiencies and seasonal cost instability. Water quality management depended largely on manual monitoring and basic filtration, with limited pathogen control and absence of automated data systems. Cleaning and maintenance were labor-intensive, while harvesting and handling practices induced stress and potential injury. Although mortality rates were generally low after acclimatization, high losses were observed when crabs were sourced from distant locations, highlighting transport-related stress. Energy demand was identified as a major constraint due to reliance on continuous power supply and high operational costs. Despite these challenges, growers recognized the potential of RAS to improve biosecurity, productivity, and year-round production. However, adoption was constrained by high capital investment, technical complexity, and limited access to training and localized system designs. The findings highlight the need for context-specific innovations, including optimized feeding strategies, automated monitoring, energy-efficient designs, and capacity-building interventions to enhance the sustainability and scalability of RAS for mangrove crab fattening.

Keywords: aquaculture, Bataan, crab growers, *Scylla serrata*, technology adoption.

Introduction. Mangrove crabs (*Scylla* spp.), locally known as alimango, are benthic crustaceans that inhabit mangrove-fringed estuarine and coastal ecosystems throughout the Indo–West Pacific. In the Philippines, the dominant cultured species include *Scylla serrata*, *Scylla olivacea*, and *Scylla tranquebarica* (Quinitio et al 2018; RAS Aquaculture 2020). These species contribute substantially to national aquaculture production, with output exceeding 20,000 metric tons and a total value of approximately PhP 9.4 billion, positioning mangrove crab as one of the country's top aquaculture commodities (PSA 2021; PSA 2023). Crab fattening is one of the production strategies among small-scale growers, involving the short-term rearing of underweight or soft-shelled crabs until they reach marketable condition and it allows rapid biomass gain and short culture period (Rahman et al 2017). This practice supports household income generation and serves as an important livelihood option in coastal communities (Molla et al 2009). In Bataan and in other coastal communities in Central Luzon, mangrove crab is a high-value fishery resource and an important livelihood source (Corpuz & Espaldon 2023).

Despite its economic importance, conventional crab fattening systems are constrained by several biophysical and management-related challenges. Open and semi-open pond systems are highly vulnerable to salinity fluctuations caused by rainfall and tidal exchange, which can disrupt molting and increase stress-induced mortality. Exposure to agricultural runoff, pathogens, and poor water quality further compromises

crab health, while cannibalism during molting remains a major cause of loss (Quinitio et al 2018). These risks are exacerbated by extreme weather events such as flooding and storm surges, which frequently affect pond-based operations (Catacutan et al 2003).

In response, recirculating aquaculture systems (RAS) have gained attention as a technology capable of improving environmental control and production efficiency. The RAS enables water reuse through mechanical and biological filtration, stabilizes key water quality parameters, and reduces dependence on external water sources (Ahmed & Turchini 2021; Rurangwa & Verdegem 2015). It also offers a controlled environment for intensive fattening and rearing by enabling continuous water treatment, solids removal, and nutrient control (RAS Aquaculture 2020). Such systems also support higher stocking densities, enhanced biosecurity, and reduced cannibalism through controlled rearing environments (Yulianto et al 2019; Martins et al 2010). However, despite these advantages, adoption of RAS for mangrove crab fattening in the Philippines remains limited (delos Reyes 2002). Moreover, there is a notable lack of empirical studies examining the perceptions, readiness, and constraints experienced by RAS adopters, highlighting a critical knowledge gap in the transition toward recirculating aquaculture systems for mangrove crab production.

The present study aimed to assess current practices and identify technological gaps in mangrove crab fattening with the goal of developing evidence-based recommendations for enhancement of RAS-based crab fattening for improved production efficiency and profitability. Moreover, the paper documented and analyzed key production components and practices as implemented by existing RAS adopters and mangrove crab fattening practitioners. Emphasis is placed on identifying constraints and adaptive strategies observed during system operation to inform practical technology refinement.

Material and Methods. The study employed a mixed qualitative–descriptive design to document current practices, identify operational gaps, and determine priority areas for enhancement in the application of RAS-based mangrove crab fattening. Data collection was carried out from September 2023 to July 2024, where face-to-face interviews and key informant interviews were conducted with trainees and adopters of the existing RAS-based mangrove crab fattening operations from Alfonso, Cavite (Southern Luzon) (Figure 1), and Magalang, Pampanga (Central Luzon). Respondents were selected purposively based on their direct involvement in the operation, management, or adoption of RAS for mangrove crab production. Specifically, technology adopters from Alfonso, Cavite and Magalang, Pampanga were chosen because they had actual experience in operating and managing RAS facilities. For the crab growers in Orani, Bataan, participants were selected based on their direct involvement in mangrove crab farming and their expressed interest in adopting RAS technology. This purposive approach ensured that respondents have the technical knowledge and practical insights necessary to provide relevant information regarding the operational challenges, adoption constraints, and technology needs associated with RAS.

A structured interview guide was used to obtain information on system configuration, stocking practices, feeding routines, water filtration, water quality monitoring, harvesting procedures, cleaning and disinfection protocols, mortality trends, and energy requirements. The guide also included open-ended questions to elicit perceived limitations, constraints, and potential improvements to the system. In addition to onsite interviews, follow-up discussions were conducted through online chat and voice calls with RAS adopters in Magalang, Pampanga to expand the geographic scope of the assessment and to capture variations in management practices and system performance. To provide a broader production context, select crab farmers from Orani, Bataan (Central Luzon) with prior experience in traditional pond-based fattening systems were interviewed (n=32). These interviews focused on comparative insights related to growth performance, survival rates, labor requirement, water use, disease occurrence, and overall production efficiency between pond-based and recirculating aquaculture systems. A survey instrument was administered to identify specific research gaps and technology needs associated with the use of RAS. The survey consisted of checklist and ranking items that covered biological, environmental, technical, and economic factors affecting

system performance. Responses from the interviews and focus group discussions were transcribed and analyzed using thematic analysis following the procedures of Braun & Clarke (2006). Initial coding was conducted through an inductive approach, wherein meaningful statements related to RAS adoption, operational challenges, perceived benefits, and research needs were identified and assigned preliminary codes. Similar codes were subsequently grouped into broader categories and refined into major themes through iterative review and comparison. A coding framework was developed to organize recurring concepts across respondents. To enhance the credibility and consistency of the analysis, two independent researchers coded the transcripts separately and compared their coding outputs. Discrepancies were discussed and resolved through consensus, resulting in the final set of themes. The frequency of occurrence of each theme was then quantified and ranked to identify the most frequently cited concerns, constraints, and priority areas for investigation and RAS improvement.

Descriptive statistics, including frequencies and percentages, were used to summarize the survey responses. The precision of each estimated proportion was assessed by calculating the corresponding 95% Wald confidence interval (%).



Figure 1. Mangrove crab fattening in vertical recirculating aquaculture system of Philippine Crab Aquaculture in Alfonso, Cavite, Philippines.

Results

RAS adopters. Table 1 summarizes the current practices, technology gaps, and areas for improvement for RAS-based mangrove crab fattening as perceived by key technology users. The assessment of an existing commercial RAS for mangrove crab fattening identified operational strengths and critical technological gaps that can be addressed through targeted system enhancement. Stocking currently relies on underweight crabs weighing approximately 100–300 g sourced from Southern Luzon (e.g. Quezon, Roxas City, Capiz, and Palawan). Their availability and price variability cause supply instability and increased procurement effort. These constraints highlight the need to explore the viability of juvenile mangrove crabs as an alternative stocking material to support sustainability and cost stability. Feeding was conducted manually twice daily using either chopped sardines, slipmouth, or mackerel scads, with feed adjustments based on observed biological cues related to appetite, molting, and shell separation. However, feeding protocols were not standardized according to crab size or age. Seasonal fluctuations in fish availability and cost, particularly during the rainy season, further highlighted the need for a standardized feeding guide and the development of locally sourced alternative diets. Moreover, weekly weighing of diet was recommended to refine ration calculations and improve feed conversion efficiency.

The water filtration system consisted of a sediment filter, ultraviolet sterilization, protein skimmer, and biofilters containing oyster shells for nitrification. Despite this configuration, no direct pathogen control mechanism was in place, and uneaten feed residues remained a recurring issue. The integration of live oysters and other live filter-feeding organisms as biological clarifiers was proposed in order to reduce bacterial load and organic sediments, together with periodic laboratory analyses recommended to assess pathogen dynamics during episodes of elevated mortality.

Table 1

Current practices, technology gap, and area for improvement for RAS-based mangrove crab fattening as perceived by key RAS adopters in the Philippines

<i>Area for assessment</i>	<i>Existing practice using RAS</i>	<i>Identified Technology gap / Problem</i>	<i>Area for system enhancement</i>
Stocking	Individual stocking of one underweight crab (100–300 g) per crab box; dependence on wild-caught thin crabs sourced from multiple provinces with fluctuating price and availability	Increasing cost and unstable supply of suitable underweight crabs; high variability in size and health condition	Limited empirical data on the performance of juvenile or hatchery-produced mangrove crabs in RAS fattening; need for trials on juvenile stocking density, growth, survival, and economic viability
Feeding management	Manual feeding twice daily using raw fish (slipmouth, sardines, or scad) at fixed quantities regardless of crab size or age; feeding adjusted subjectively based on visual observation	Absence of standardized feeding rates and size-specific rationing; reliance on seasonally variable and costly raw fish	Lack of validated feeding protocols for RAS-based crab fattening; need for feed ration models, weekly biomass-based feeding strategies, and development of nutritionally adequate, low-cost, local-based diets
Water filtration	Multi-stage filtration using sediment filters, protein skimmers, and biofilters including oyster shells; waste dominated by uneaten fish and shells	No active pathogen reduction component; accumulation of organic solids increases microbial load	Insufficient evaluation of pathogen control measures in crab RAS; need to assess UV sterilization efficiency and the use of live biofilters and bioindicators
Water quality testing and monitoring	Manual water sampling and use of commercial test kits for basic physicochemical parameters; records maintained in logbooks	No real-time monitoring, trend analysis, or microbial assessment	Lack of automated, continuous monitoring systems evaluated for crab RAS; need for integrated sensor-based monitoring, data logging, alert systems, and routine bacteriological testing
Harvesting and monitoring	Manual inspection of carapace width, weight, and maturity analysis through inspection of abdominal flap looseness and shape; individual crab coding for records	Frequent handling causes stress, claw loss, and labor inefficiency	Limited research on non-invasive monitoring tools for harvest readiness; need to test in-cage measurement guides and digital identification systems (e.g., QR-based profiling)
Cleaning and disinfection	Manual per-box cleaning during feeding; water replacement every two weeks; periodic system flushing	Labor-intensive cleaning; high cost of commercial biofilter media; inconsistent water renewal	Absence of low-cost biofilter alternatives and optimized cleaning schedules; need to identify locally available biofilter materials and evaluate increased water exchange frequency combined with UV treatment
Culture period	Fixed 30-day fattening period	No physiological or metabolic	Lack of studies on growth acceleration, metabolic

<i>Area for assessment</i>	<i>Existing practice using RAS</i>	<i>Identified Technology gap / Problem</i>	<i>Area for system enhancement</i>
		optimization to shorten culture duration	enhancers, or husbandry interventions to reduce fattening period and improve turnover and ROI
Mortality management	Low mortality after acclimatization; extremely high mortality when crabs are sourced from distant regions	Transport and acclimatization stress leading to mass mortality	Limited validation of transport, anesthesia, and acclimation protocols for mangrove crabs in RAS; need for stress mitigation and biosecurity studies
Molting management	Molting monitored visually; feed reduced when pre-molt signs appear; no environmental control for molting	Unpredictable molting, stress-induced mortality, molting failure due to suboptimal conditions	Research on molting physiology, environmental cues (salinity, temperature, photoperiod), and dietary supplements to regulate molting
Power requirement and energy use	Continuous operation of high-capacity pumps; dependence on grid electricity; system failure during prolonged outages	High operational cost and vulnerability to power interruption	Lack of economic and technical evaluation of alternative energy systems; need to assess hybrid power solutions, solar integration, and energy-efficient pump configurations

Water quality monitoring was conducted manually using commercial test kits to measure pH, ammonia, nitrate, and nitrite, with results recorded in logbooks without systematic analysis. Proposed improvements included automated, continuous monitoring with real-time data visualization and SMS alerts for abrupt parameter changes. Microbiological assessment, including the detection of pathogenic indicator microorganisms was also recommended to strengthen preventive health management. Harvesting practices involved manual inspection of carapace width, body mass, and inspection of abdominal flap (pleon or apron) shape and looseness to evaluate the maturity of crab after a 3-week culture period (immature individuals have a narrow, tightly closed apron, whereas sexually mature females possess a broader, fully expanded abdominal flap; mature males retain a narrow, elongated T-shaped apron).

Frequent handling induced stress and physical injury. The installation of internal measurement guides and a QR code-based individual tracking system was proposed to minimize handling and improve data accuracy. Cleaning procedures were conducted manually during feeding and required several hours (approximately 2 h for 120 crab boxes), revealing inefficiencies linked to costly commercial biofilter media and periodic sediment and organic waste accumulation. Increased water exchange frequency, and identification of locally sourced biofilter materials were recommended to enhance system resilience. The culture period of 20-30 days was perceived to have potential for reduction through physiological or metabolic interventions to improve economic returns. Mortality remained low at 5–10% following acclimatization; however, crabs sourced from distant regions exhibited considerable higher mortality, likely due to transport and environmental stress. The use of anesthesia during transport was proposed to mitigate these effects.

Energy demand was substantial, relying on three 3-hp pumps and continuous grid electricity, rendering operations vulnerable to power interruptions. The integration of a diesel generator for emergency backup and a solar-powered system for long-term energy efficiency was recommended to ensure operational stability and reduce overall costs. Collectively, these findings provided a basis for scientific investigation aimed at improving the productivity, sustainability, and economic viability of RAS for mangrove crab culture.

Insights of crab growers. The surveyed crab growers were all male, predominantly middle-aged, with most respondents falling within the 35–55 age range. The majority belonged to low- to middle-income households, with annual incomes largely derived from small- to medium-scale aquaculture operations supplemented by seasonal fishing or

other informal livelihoods. In terms of educational background, most growers had completed secondary education, while a smaller proportion attained vocational or college-undergraduate level, often in non-agriculture-related fields. Formal training in aquaculture was limited, with technical knowledge primarily acquired through experiential learning, peer-to-peer knowledge exchange, and informal training programs provided by local government units or extension agencies.

From the perspective of crab growers practicing conventional pond- or box-based fattening, RAS were generally perceived as technologically advanced but difficult to adopt under prevailing farm conditions. Approximately 78.12% (25 out of 32; 95% CI: 63.80 to 92.45%) of respondents recognized that RAS can stabilize water quality by controlling salinity, temperature, and waste accumulation, thereby reducing mortality associated with environmental fluctuations. About 71.87% (23 out of 32; 95% CI: 56.30 to 87.45%) acknowledged that RAS could lessen dependence on tidal exchange and rainfall, while 65.62% (21 out of 32; 95% CI: 49.20 to 82.08%) believed that controlled systems could improve growth uniformity and shorten the fattening period. In addition, 62.50% (20 out of 32; 95% CI: 45.73 to 79.28%) perceived that RAS could improve production planning through more predictable harvest schedules and reduced environmental risk. Despite these perceived advantages, adoption remains limited. Around 59.37% (19 out of 32; 95% CI: 42.36 to 76.39%) of growers expressed hesitation toward RAS implementation due to the absence of direct experience or practical exposure to operational systems. Notably, 43.75% (14 out of 32; 95% CI: 26.56 to 60.94%) reported that they had never personally observed a functioning RAS facility for mangrove crab fattening, while 37.50% (12 out of 32; 95% CI: 20.73 to 54.27%) indicated uncertainty in system operation, maintenance, and troubleshooting. High capital investment and energy requirements were identified as major constraints by 62.50% (20 out of 32; 95% CI: 45.73 to 79.27%) of respondents, reinforcing concerns over financial risk and system sustainability. Moreover, approximately 56.25% (18 out of 32; 95% CI: 39.06 to 73.44%) of growers reported that their awareness of RAS originated primarily from social media platforms, online videos, and television features, particularly during the COVID-19 pandemic when digital content consumption increased. While these sources raised interest and curiosity, growers emphasized that such information was often promotional and lacked practical and site-specific guidance. Consequently, limited exposure to hands-on demonstrations and locally validated performance data has contributed to cautious attitudes toward adoption.

The major constraints affecting adoption of RAS-based mangrove crab fattening as perceived by local crab growers are illustrated in Figure 2. When respondents were asked to identify the major constraints limiting the adoption of RAS, the most frequently cited barrier was high capital investment.

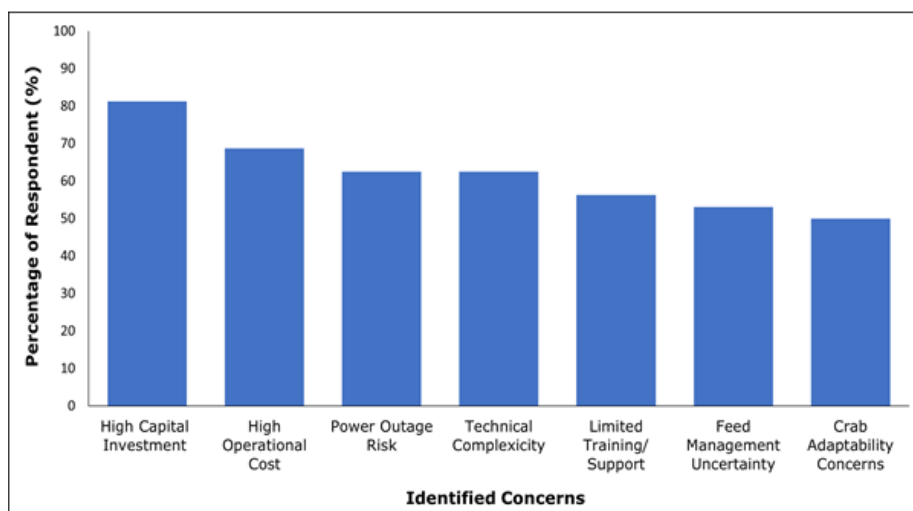


Figure 2. Perceived constraints of local crab growers limiting the adoption of recirculating aquaculture systems in mangrove crab fattening.

Approximately 81.25% (26 out of 32; 95% CI: 67.73 to 94.77%) of respondents indicated that the cost of tanks, filtration units, pumps, sensors, and backup power systems was prohibitive when compared with traditional pond-based operations that rely largely on natural water exchange. In addition, 68.75% (22 out of 32; 95% CI: 52.69 to 84.81%) expressed concern over recurring operational expenses, particularly electricity consumption and routine system maintenance. Power instability was viewed as a critical risk, with 62.50% (20 out of 32; 95% CI: 45.73 to 79.27%) of respondents emphasizing that even short-term power outages could result in total stock loss, a risk perceived as greater than mortality experienced in conventional ponds. Technical complexity also emerged as a major limitation. Similarly, 62.50% of growers reported that RAS requires a level of technical knowledge beyond their current capacity, particularly in water chemistry management, biofilter operation, and disease control. Most respondents rely on experiential knowledge rather than sensor-based monitoring or data-driven decision-making. Furthermore, 56.25% (18 out of 32; 95% CI: 39.06 to 73.44%) indicated limited access to hands-on training, technical support, or locally validated RAS designs specifically adapted for mangrove crab fattening, which reduces confidence in system adoption. Feed management was another recurring concern. Approximately 53.12% (17 out of 32; 95% CI: 35.83 to 70.42%) of respondents expressed uncertainty about replacing low-cost trash fish with formulated feeds, questioning whether commercial diets could sustain growth and profitability under RAS conditions. In addition, 50% (16 out of 32; 95% CI: 32.68 to 67.32%) of growers were skeptical about the ability of wild-caught crabs to adapt to confined and highly controlled environments, particularly during the molting phase, which they considered a high-risk stage for stress-related mortality.

Discussion. The application of RAS for mangrove crab fattening represents a significant technological transition from traditional pond- or cage-based operations to intensive, controlled environments with the potential to improve productivity and profitability (Hashimi et al 2025; Lu et al 2025). Compared with water exchange systems, RAS can maintain lower concentrations of nitrogenous wastes, more stable water quality, and reduced water use, which are key determinants of survival and growth in mangrove crab culture (Flo et al 2024). For example, RAS has been shown to improve larval viability and reduce ammonia and nitrite compared with conventional water exchange systems, indicating that microbial community management and water quality stabilization are central benefits of RAS (Lu et al 2025). Existing research also demonstrates that RAS adaptations, such as polychaete-assisted biofilters, improve reproductive performance and water quality parameters in broodstock, highlighting the capacity of engineered systems to enhance physiological outcomes relative to non-RAS controls (Van Calunod et al 2025). Mangrove crab farming in many Central Luzon provinces often relies on water sources with high microbial loads, contributing to water quality challenges in traditional pond systems (Rabadon & Corpuz 2021; Rabadon et al 2022); the adoption of RAS offers improved microbial control by treating and recirculating water, thereby reducing the influence of contaminated source water on culture conditions.

Despite these advantages, fundamental problems constrain the effective adoption of RAS in mangrove crab fattening. One critical challenge arises from stress and immune dysfunction associated with transport and initial acclimatization of wild-caught stock. The RAS designed with clear water alone may not suffice to mitigate stress and pathogen proliferation following extended transport, suggesting that environmental complexity and habitat-mimicking design features are required to support physiological recovery and survival (Manliclic et al 2018; Nivas et al 2025). This underscores a broader gap in understanding the interaction between system design, microbial ecology, and animal health. RAS inherently promotes a closed microbial community, which can improve water quality, but it also necessitates precise management of microbial dynamics to prevent dysbiosis and outbreaks of opportunistic pathogens, such as *Vibrio* spp., implicated in high mortality events under suboptimal conditions (Villarías et al 2025).

Feeding practices in RAS also present constraints. Traditional reliance on raw fish and unstandardized feeding schedules can compromise water quality and increase labor without necessarily optimizing growth or feed conversion. While studies in related

systems indicate that trash fish at defined proportions of body weight can yield adequate growth and feed efficiency, the relative merits of diversified feeds and formulated diets remain insufficiently evaluated for intensive RAS fattening (Diamahesa & Rahmadani 2024) Optimizing feed type and feeding frequency is important for system performance because overfeeding directly affects water quality parameters central to RAS operation (Mayzuri et al 2025).

Infrastructure and operational complexity pose additional problems. The RAS require continuous energy input for pumping, aeration, and filtration, which increases operating costs and creates vulnerability to power disruptions. High initial capital and technical knowledge barriers further impede adoption by small- and medium-scale producers, which is consistent with broader observations that RAS, while resilient to external climatic fluctuations, are costly and require sophisticated management (Ahmed & Turchini 2021). While crab growers generally acknowledge the theoretical advantages of RAS including improved water quality, reduced water consumption, and more stable production, its practical adoption in the Philippines remains constrained. Similar to findings in other aquaculture sectors, high capital investment and elevated operational costs are consistently identified as primary barriers, particularly for small- and medium-scale producers (Badiola et al 2012; Martins et al 2010). These financial challenges are compounded by the technical complexity of RAS, which requires competencies in water chemistry, biofilter management, and system maintenance that are often beyond the traditional skill set of smallholder farmers (d'Orbcastel et al 2009).

Crab growers also express uncertainty regarding profitability and return on investment, especially given the vulnerability of RAS to power interruptions and mechanical failure. Such risks increase perceived production uncertainty and discourage adoption among risk-averse farmers, a trend similarly observed in fish production systems where technology-intensive systems face low uptake despite biological advantages (d'Orbcastel et al 2009; Badiola et al 2012; Badiola et al 2018). In contrast, adoption of RAS has been more evident in regions where water scarcity, environmental regulation, or biosecurity pressures justify higher capital inputs (Martins et al 2010). Overall, although RAS offers clear technical benefits, economic constraints, skill requirements, and uncertainty in performance outcomes continue to limit its widespread adoption in conventional mangrove crab farming systems.

Conclusions. The RAS offer a promising pathway to improve productivity, biosecurity, and environmental control in mangrove crab fattening. However, adoption remains constrained by high capital costs, energy dependence, and technical complexity, particularly for small-scale producers. Biological challenges such as stress, molting-related mortality, and feed inefficiencies further affect system performance. Findings highlight the need for locally adapted RAS designs, cost-efficient energy solutions, and improved feeding and health management strategies. Strengthening farmer capacity through training and evidence-based system optimization is essential. Addressing these gaps can enhance economic viability and support the sustainable integration of RAS into Philippine mangrove crab production systems.

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

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