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Original Research Articles

The current situation and sustainable development of *Penaeus monodon* in South China: A Review

Zhiwei Sun[1a], Yunchuan Cai[2b], Xinyu Qi[1], Jieyi Wang[1], Falin Zhou[1], Jianzhi Shi[1], Junchao Ming[1c], Song Jiang[1d]

[1] South China Sea Fisheries Research Institute, Chinese Academy of Fishery Sciences/Key Lab. of South China Sea Fishery Resources Exploitation and Utilization, Ministry of Agriculture and Rural Affairs, Guangzhou, 510300, P.R. China, [2] Agriculture Technology Extension Centre of Guangdong Province, Guangzhou, 510000, P.R. China

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The three provinces of Guangdong, Hainan, and Guangxi in South China are the primary production areas for *Penaeus monodon* aquaculture. The combined coastline of these three provinces spans 7,552.74 kilometers, accounting for 23.60% of China,s total coastline length. Compared to Southeast Asia and India, where *P. monodon* farming is declining due to disease outbreaks and competition with *Litopenaeus vannamei*, South China remains a key producer by leveraging intensive pond systems and government-supported breeding programs. In 2022, the aquaculture production of *P. monodon* in these provinces reached 91,200 metric tons, representing 79.79% of the national total; by 2023, this figure increased to 104,200 metric tons, comprising 81.12% of the national output. Currently, the aquaculture area for *P. monodon* in South China spans approximately 300,000 mu (about 20,000 hectares), with 50,000 mu (about 3,333 hectares) dedicated to high-level pond systems. Statistics indicate that the *P. monodon* industry supports employment for over one million residents across these provinces. Consequently, the sustainable development of *P. monodon* aquaculture is critical to both the economic growth and livelihoods of South China. However, the industry faces challenges such as frequent disease outbreaks, low-quality seedling rates, and high farming risks. To investigate the current status, existing issues, and sustainability of *P. monodon* aquaculture, this study was conducted. It aims to provide a concise overview of the *P. monodon* industry in South China and offer reference for policy formulation by global aquaculture sectors and relevant government agencies.

INTRODUCTION

Production of crustaceans culture in China reached 2055 tons in 2023 and of that, 85.95% was contributed by shrimp species.[1] Of all penaeids, the black tiger shrimp *Penaeus monodon* is among the largest penaeid species and the second most produced penaeids species after white leg shrimp *Litopenaeus vannamei*, with almost 81.12% being cultured in Guangdong Province, Guangxi Province, Hainan Province, the three provinces of South China.[1] So that the culture and intensive production of *P. monodon* support not only the livelihood of coastal communities but also the economic growth of many aqua-farmers.[2,3] At a point in shrimp farming, *P. monodon* was the most widely farmed species in South China due to its rapid growth rate,high market value and potential for larger size attainment than other species that were mostly cultured.[4-6] However, the occurrence and prevalence of diseases such as white spot syndrome(WSSV) and vibriosis in *P. monodon* farms and the introduction of *L. vannamei* to China have led to the shift from *P. monodon* to *L.vannamei* among shrimp farmers.[7-10] In order to explore the current situation of *P. monodon* farming and the existing problems, as well as the sustainability of farming, we conducted this study to introduce the

a These authors contributed equally to this work

b These authors contributed equally to this work

c Corresponding author:
Junchao Ming. 231 Xingang Road West, Haizhu District, Guangzhou City, Guangdong Province, 510300, PR China. E-mail address: mjc0312@126.com

d Corresponding author, Song Jiang. 231 Xingang Road West, Haizhu District, Guangzhou City, Guangdong Province, 510300, PR China. E-mail address: tojiangsong@163.com

P. monodon industry in South China Provinces briefly, and provide some reference for the worldwide *P. monodon* aquaculture industry and the policy-making of relevant government departments.

MATERIALS AND METHODS

MATERIALS

Relevant statistical data were sorted, literature and reports were consulted. A structured questionnaire was designed to collect data on farming practices, economic performance, and sustainability perceptions. The survey targeted 500 shrimp farms across 20 main production areas in Guangdong, Guangxi, and Hainan provinces, selected through stratified random sampling to ensure representation of small-, medium-, and large-scale operations (sample size determined by Cochran's formula with a 95% confidence level and 5% margin of error) Ethical approval was obtained from the South China Sea Fisheries Research Institute Ethics Committee, and informed consent was secured from all participants.

METHODS

Using multiple stratified and random sampling, status of system workshop, Google Earth random partitioning, SPSS and Excel software were used for data statistics.

RESULTS

DISTRIBUTION OF AQUACULTURE MODELS IN THE THREE PROVINCES

Survey results reveal five primary aquaculture models for *P. monodon* in the three provinces of South China: Pond, High-level pond, Large water surface, Small shed, and Industrialized farming (Figure 1). Among these, Pond aquaculture dominates with a share of 49.40%, followed by High-level pond at 24.00%. Notably, the proportion of industrialized farming in Hainan Province (5.00%) exceeds that of Guangdong Province (2.67%) and Guangxi Province (1.00%).

AQUACULTURE SPECIES ACROSS DIFFERENT FARMING MODELS IN THE THREE PROVINCES

Survey results indicate that among the *P. monodon* aquaculture models in the three provinces of South China, Pond, High-level pond, Small shed, and Industrialized farming models are exclusively monocultures of *P. monodon*. In contrast, the Large water surface model involves polyculture with other economically valuable species. Specifically, yellowfin seabream (*Sparus latus*) and rabbitfish (*Siganus* spp.) dominate the polyculture system, accounting for 65.26% and 17.89% of the total, respectively (Figure 2).

OPERATIONAL STATUS OF P. MONODON AQUACULTURE ENTERPRISES/FARMS IN 2023

In 2023, 77.80% of surveyed *P. monodon* aquaculture enterprises/farms were profitable. Among small-scale farms, 77.97% achieved profitability, accounting for 36.80% of all profitable farms. However, small-scale farms also represented a high proportion (64.58%) of loss-making farms. In contrast, only 1.43% of large-scale farms incurred losses, likely due to factors such as excessively high stocking densities and relatively higher farming risks in small-scale operations (Figure 3).

SUSTAINABILITY FACTORS IN P. MONODON AQUACULTURE

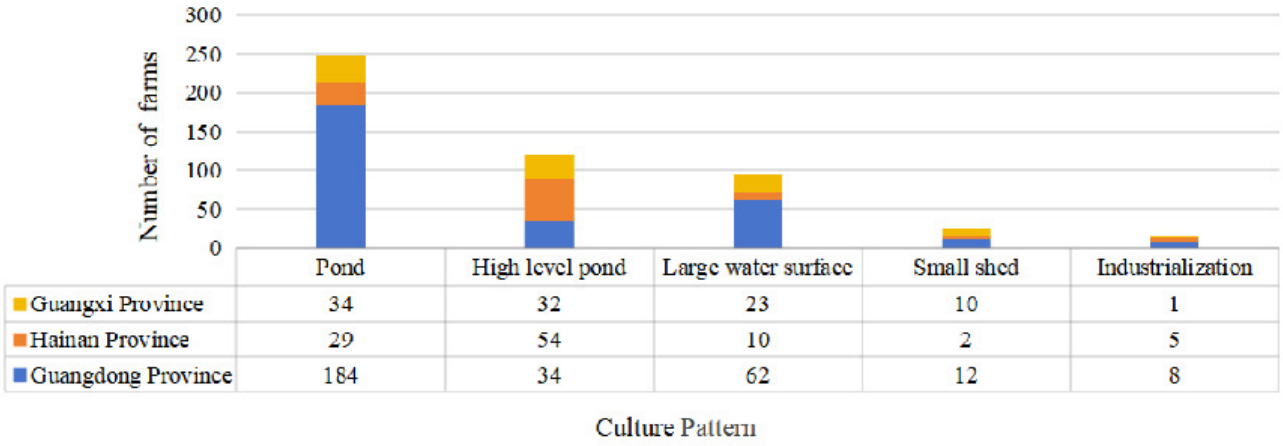
We surveyed aquaculture farmers to identify factors influencing the sustainable development of *P. monodon* farming, with respondents quantitatively ranking the proposed indicators. Results showed that seedling supply, seedling quality, aquaculture management, water quality control, and government policies/regulations were regarded as the top positive drivers for sustainable development. These findings align with the subsequent discussion on seed fraud and policy gaps, highlighting the need for centralized quality control. A minority of respondents identified factors such as enterprise import-export grading and input costs as uncertain elements. The most highly ranked negative factors included product pricing, weather conditions, input costs, and disease control (Figure 4).

TRENDS IN DEVELOPMENT OF AQUACULTURE ENTERPRISES WITH DIFFERENT SCALES AND FARMING MODELS

The investigation results reveal that the development of *P. monodon* aquaculture has exhibited a relatively stable growth trend. Between 1991 and 2020, newly established aquaculture enterprises ranged from 35 to 63 per five-year interval. The small-scale High-level pond culture model primarily expanded between 1996 and 2020, while enterprises adopting Small shed culture systems and industrialized farming models only gradually emerged after 2016. This progression aligns with the broader shift toward precision farming, automated systems, and sustainable practices observed in modern aquaculture development (Figure 5).

PARENTAL ATTITUDES TOWARD OFFSPRING ENGAGING IN P. MONODON AQUACULTURE

The survey reveals that across all farm scales, 43.00% of respondents expressed unwillingness to encourage their offspring to pursue careers in *P. monodon* aquaculture. This sentiment was unevenly distributed among farm sizes: 26.80% of respondents from small-scale farms held this view, compared to 11.20% in medium-scale and 5.00% in large-scale operations. The primary reason cited was the perception of the industry as overly labor-intensive and technically undemanding, which aligns with broader concerns about occupational sustainability and skill develop-



	Pond	High level pond	Large water surface	Small shed	Industrialization
Guangxi Province	34	32	23	10	1
Hainan Province	29	54	10	2	5
Guangdong Province	184	34	62	12	8

Figure 1. Distribution of Aquaculture Models in the Three Provinces

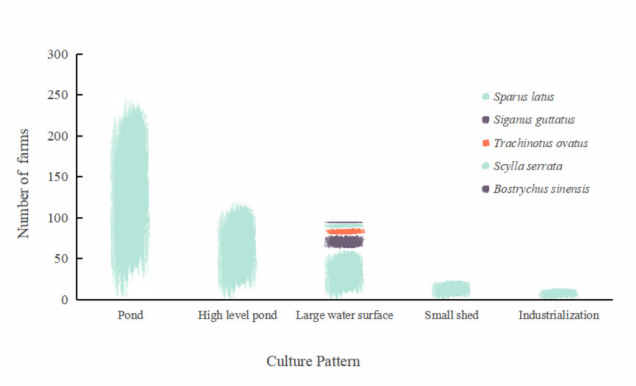


Figure 2. Aquaculture Species Across Different Farming Models in the Three Provinces

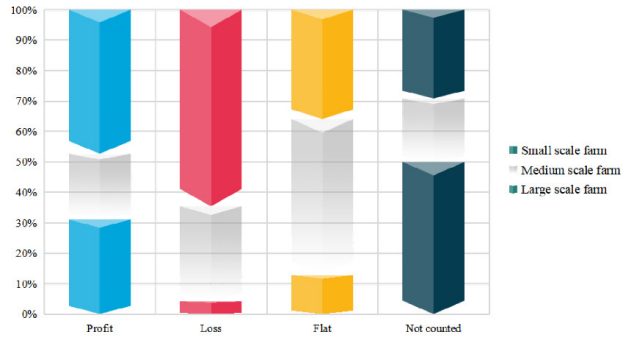


Figure 3. Operational Status of *P. monodon* Aquaculture Enterprises/Farms in 2023

ment in aquaculture. Notably, this indicates that nearly half of the respondents in the three southern provinces of China hold negative perceptions regarding the sustainable development prospects of the *P. monodon* aquaculture sector (Figure 6).

DISCUSSION

Based on the survey findings and identified challenges in *P. monodon* aquaculture across three provinces of South China, this study employs a comprehensive set of indicators spanning economic, environmental, and social dimensions to systematically evaluate the sustainability of shrimp farming practices in the region.

ECONOMIC DRIVERS AND TRADE-OFFS

PROFITABILITY TRENDS AND INDUSTRIALIZATION

The three South China provinces possess a coastline spanning 7,552.74 km, accounting for 23.60% of China's total coastal length.[1] Their expansive shallow tidal flats, abundant harbors, and unique geographical advantages have fostered a thriving *P. monodon* aquaculture industry.[11] As a high-value commodity in international aquatic trade, *P. monodon* has emerged as a flagship cultivated species, establishing a comprehensive industrial chain with an annual output value of 80 billion CNY. This sector generates 500,000 direct employment opportunities and supports over 2 million livelihoods.[1] The region leads nationally in seven key metrics: aquaculture area, postlarval production, shrimp yield, feed output, processing capacity, export volume, and the operation of China's largest specialized shrimp trading market.[1]

Small shed and Industrialized farming aquaculture systems have gained prominence in Guangdong and Hainan provinces. Characterized by standardized infrastructure and mechanized operations, these systems integrate seawater disinfection technologies and modern bio-based water purification methods, effectively curbing pathogen

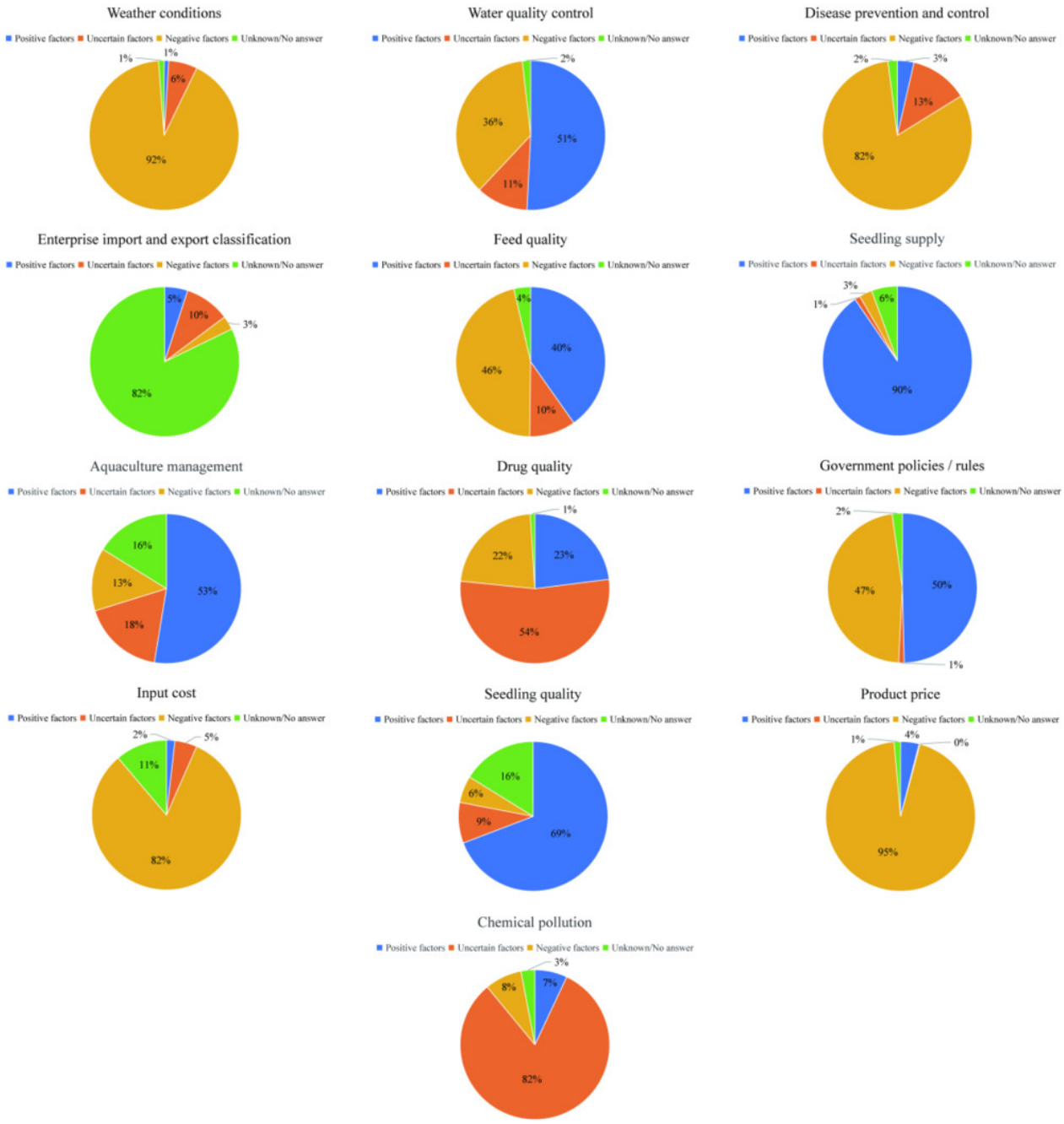


Figure 4. Sustainability Factors in *P. monodon* Aquaculture

transmission. This innovation has significantly enhanced *P. monodon* survival rates and yield, driving transformative upgrades in sustainable shrimp farming practices.[12]

COST PRESSURES AND MARKET DYNAMICS

From the perspective of domestic and international markets, production costs-including pond rentals, feed, and pharmaceuticals-are rising. In Zhanjiang, Guangdong Province, some small-scale farms have shifted to high-density, high-input, and high-pollution *P. monodon* aquaculture practices to accelerate cost recovery, thereby constraining sustainable development. The Waste water treatment cost increase makes the transformation window period of sustainable technologies such as circulating water system rapidly narrow, and the sustainable development of the industry is facing a critical point challenge.

According to reports, the periodic sedimentation rate of shrimp pond substrates has reached nearly 200 t ha^{-1}.[13] Sediments discharged from shrimp farms into adjacent environments after harvest can cause globally significant environmental impacts.[14] Studies have demonstrated that polyculture of *Penaeus chinensis* with *Perinereis aibuhitensis* or *Crassostrea gigas* can reduce pollutants in pond substrates and effectively improve shrimp survival rates.[15] Oyster filter-feeding has been shown to decrease bacterial concentrations in water bodies, mitigate pollutant levels in shrimp ponds, and reduce eutrophication.[16] Consequently,

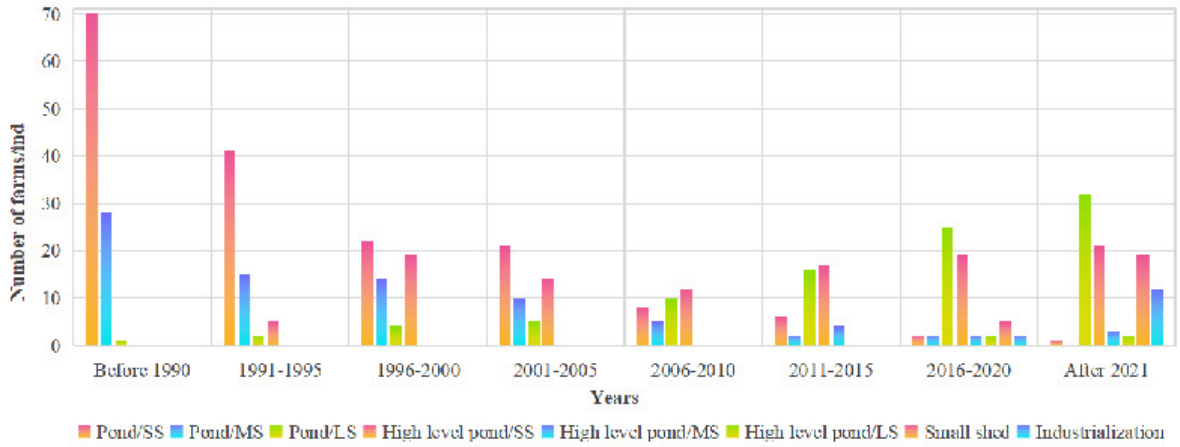


Figure 5. Trends in Development of Aquaculture Enterprises with Different Scales and Farming Models

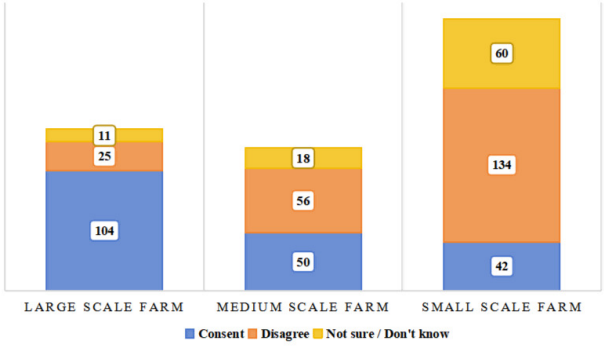


Figure 6. Parental Attitudes Toward Offspring Engaging in *P. monodon* Aquaculture

the high-level pond aquaculture model requires further standardization and innovation. For example, integrating bivalve cultivation and optimizing facility layouts within farming zones to achieve regulated water intake and drainage systems. This approach aims to establish a novel aquaculture model characterized by ecological stability, resource efficiency, environmental compatibility, and resilience to external risks.

ENVIRONMENTAL CHALLENGES AND INNOVATIONS

CURRENT SITUATION OF ENVIRONMENTAL POLLUTION

The rapid expansion of high-density, large-scale *P. monodon* aquaculture has led to the overloading of coastal waters, resulting in a progressive decline in disease resistance and frequent disease outbreaks among cultured shrimp.[17] In our investigation, it was observed that currently, coupled with the aging of high-level ponds and the discharge of untreated wastewater from *P. monodon* aquaculture by small-scale farmers with poor environmental awareness directly into the sea. In recent years, some farms even releasing wastewater directly into ponds, the coastal waters have experienced increasing eutrophication, accompanied by the accumulation of sediments and pathogens.

REGULATORY IN CHEMICAL USE

Indiscriminate use of antibiotics and other chemicals in some aquaculture facilities has disrupted microbial ecosystem balance, promoting the emergence of antibiotic-resistant pathogens. Additionally, antibiotic residues accumulated in shrimp tissues pose significant risks to export quality and food safety.[18] Microbial agents are gaining increasing favor among aquaculture facilities, and their widespread application has become a trend toward ecological and sustainable *P. monodon* farming.[19-22] Our survey revealed that some feed manufacturers provide phototrophic bacteria free of charge at a fixed ratio when supplying feed to farms. Although farmers' environmental awareness is gradually improving, the use of probiotics remains sporadic—often applied only when farmers recall or when shrimp exhibit abnormalities—leading to expired or ineffective microbial agents due to unplanned usage. This highlights the necessity for targeted training and technical guidance to enhance farmers' participation in standardized aquaculture practices and resource optimization.

SOCIAL PERCEPTIONS AND LABOR DYNAMICS

POLICY INTERVENTIONS FOR DEVELOPMENT

The fragmented household contract system, characterized by small-scale operations, low industrialization levels, limited technological integration, poor market responsiveness, and weak risk resilience, demonstrates significant misalignment with modern economic demands.To address these challenges, the *P. monodon* industry should undergo consolidation and restructuring to establish large-scale, efficient enterprises with robust market expansion capabilities, including vertically integrated operations spanning production, supply, and marketing. Simultaneously, optimizing human resource allocation and enforcing strict

quality control in water intake, seed procurement, and farming practices are critical. Strategic alliances across upstream and downstream sectors could further foster market-oriented production systems aligned with global and domestic demand.

With the promotion of domestically bred shrimp varieties, seed quality has significantly improved, and the domestic supply of new seed strains now meets market demands. However, some companies have been reported selling second-generation shrimp larvae as first-generation products, exploiting farmers' limited capacity to distinguish between them. This issue stems from high-profit margins in seed production, low technical barriers, and inconsistent technician qualifications. To address this, provincial governments should establish a mandatory seed certification program, enforced through third-party audits and blockchain traceability systems. Collaboration between feed companies and research institutions could standardize probiotic application protocols, while subsidies for automated water treatment systems would reduce small-scale farmers' reliance on antibiotics. Additionally, increased investment in broodstock and seed technology alongside the establishment of commercial seed brands could reduce reliance on imported or wild caught broodstock, thereby securing greater autonomy in *P. monodon* aquaculture.

INTERGENERATIONAL WORKFORCE ATTITUDES

Nearly half of the respondents expressed negative attitudes toward encouraging their children to engage in *P. monodon* aquaculture. To address this, governments should intensify promotional efforts to disseminate the principles of ecological and sustainable aquaculture models and highlight the industry's future prospects. Strengthening supportive policies, such as stabilizing shrimp prices and implementing measures to secure farmers' confidence in the sector which is also critical to fostering intergenerational continuity in the industry.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

AUTHORS' CONTRIBUTION

ZWS, YCC, JCM and SJ designed the study. QYX, JZS and JYW took part in the execution of study. SJ, and FLZ implemented the study and involved in sampling as well as testing. ZWS, YCC and JCM drafted the manuscript. All the authors read and accepted the final manuscript before submission.

ETHICAL APPROVAL

The whole experiment was conducted according to the guidelines established by the National Institutes of Health.

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