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Effects of Different Farming Systems on Growth Performance and Survival of Chinese Sea Bass (*Lateolabrax maculatus*)

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Abstract As an important commercial marine fish species for aquaculture in my country, the growth performance and survival rate of the spotted sea bass (*Lateolabrax maculatus*) depend heavily on the type of culture system and its capacity for environmental control. This paper reviews and compares the mechanisms by which pond culture, net-pen culture, and recirculating aquaculture systems (RAS) influence growth performance and survival rates. The results indicate significant differences among these systems regarding water quality stability, dissolved oxygen supply, ammonia-nitrogen accumulation, and stocking density management, leading to variations in growth rates and feed conversion ratios (FCR). Among them, RAS typically demonstrates superior growth efficiency and lower mortality due to robust water quality control and stable environmental conditions; pond systems are significantly affected by natural environmental fluctuations, resulting in less stable growth and survival; net-pen systems fall between the two but are susceptible to the effects of water exchange and seasonal changes. Comparative analysis further reveals that environmental stability and nutrient utilization efficiency are key determinants of aquaculture performance. Additionally, the incidence of disease and stress responses intensifies under high-density culture conditions. Based on this comparative analysis, the paper proposes optimized culture models and environmental management strategies to enhance the sustainability and productivity of spotted sea bass aquaculture.

Keywords Spotted sea bass; Culture system; Recirculating aquaculture system (RAS); Growth performance; Survival rate

1 Introduction

Chinese sea bass (*Lateolabrax maculatus*) has become an increasingly important aquaculture species in China over the past two decades, with the industry expanding rapidly and contributing substantially to the national fishery economy (Huang et al., 2025). This development is closely linked to the species' favorable biological characteristics, especially its rapid growth rate and strong adaptability to a range of environmental conditions, which have supported its broad culture potential and increasing industrial relevance. At the same time, progress in Chinese sea bass aquaculture has depended on advances across multiple fields, including breeding, seed production, nutrition, and disease management, indicating that further gains in production will likely require continued integration of biological and farming technologies. Despite these achievements, the industry still faces important constraints, including low profitability and insufficient risk management relative to other major farmed fish sectors, which highlights the need for research that can support higher-quality and more efficient development.

Among the major factors shaping aquaculture productivity, the choice and optimization of farming system is especially important because production environment directly influences fish growth, health status, resource use, and overall economic return (Li et al., 2023). Comparative work on Chinese sea perch culture systems has shown clear differences in ecological-economic performance among pond farming, offshore cage culture, and cage culture, with offshore cage culture identified as the most sustainable among the current main marine fish farming systems in China (Zhang et al., 2021). More broadly, research on modern recirculating aquaculture systems indicates that controlled land-based production can reduce water use, improve water quality, lower disease risk, and strengthen waste management, all of which are directly relevant to improving production efficiency and survival in intensive fish culture (Gupta et al., 2024). These findings suggest that farming-system design is not only a management issue but a central biological and economic determinant of aquaculture performance.

Evidence from other cultured fish further supports the view that system optimization can markedly alter growth and survival-related outcomes. In grass carp, the recirculating pond aquaculture system produced lower concentrations of ammonia, nitrite, and nitrate nitrogen than traditional ponds, while also improving growth rate and feed conversion, indicating that better environmental control can translate into more efficient production (Xu et al., 2025). In largemouth bass, a funnel-shaped recirculating aquaculture system generated significantly higher body weight and stronger antioxidant capacity than a traditional pond system, suggesting that improved hydrodynamics and water treatment can enhance both growth and physiological condition (Xu et al., 2025). Similar trends have also been reported in hybrid grouper, where fish reared in a recirculating aquaculture system showed better growth performance and lower *Vibrio* concentrations in tissues than fish in a simulated pond system, linking farming mode to both productivity and health protection. Although these studies involve species other than Chinese sea bass, they provide a strong comparative basis for expecting measurable effects of farming systems on growth performance and survival.

Against this background, evaluating the effects of different farming systems on Chinese sea bass is both scientifically necessary and practically valuable. Chinese sea bass aquaculture has advanced substantially, but the lack of integrated system-level assessment remains a barrier to the industry's high-quality development and to clearer identification of future goals (Huang et al., 2025). Experimental evidence in spotted sea bass already shows that environmental conditions characteristic of different systems, such as flow velocity, can shift growth, lipid metabolism, and oxidative stress responses, demonstrating that production settings can create biological trade-offs rather than simple uniform benefits (Li et al., 2023). Therefore, the present study aims to compare different farming systems for L. *maculatus* by focusing on growth performance and survival, with the broader goal of clarifying which culture conditions are more favorable for efficient and sustainable production. The scope of this study is to provide an evidence-based basis for farming system optimization in Chinese sea bass aquaculture and to contribute to the ongoing transition of the industry toward greater productivity, resilience, and environmental compatibility.

2 Biological Characteristics and Growth Requirements of *Lateolabrax maculatus*

2.1 Growth performance and feeding behavior characteristics

Lateolabrax maculatus is widely regarded as a promising aquaculture species because it combines rapid growth with broad farming applicability across marine and low-salinity systems (Huang et al., 2025). Growth performance in this species is strongly shaped by nutritional composition, especially dietary protein and lipid balance. Under controlled feeding trials, juveniles reared at 27 °C achieved their highest weight gain when diets contained about 47% crude protein, and feed conversion improved as protein level increased up to that point. Growth is also sensitive to dietary energy partitioning, because optimal protein-to-energy ratios differed with temperature, indicating that efficient tissue deposition depends on both feed formulation and the rearing environment rather than nutrient level alone (Lu et al., 2020).

Feeding behavior in Chinese sea bass shows a clear link to growth efficiency. Juveniles fed to apparent satiation two or three times daily displayed higher weight gain, specific growth rate, feed efficiency, and protein efficiency ratio than fish fed less frequently, while performance was not meaningfully improved beyond twice-daily feeding. Feed quality further modifies this response. Diets with an n-3/n-6 polyunsaturated fatty acid ratio near 0.66 produced the highest final body weight, weight gain, specific growth rate, and protein efficiency ratio, together with the lowest feed conversion ratio (Dong et al., 2023). Recent neuroendocrine evidence also indicates that feeding and growth are physiologically integrated, with temperature- and salinity-responsive stress pathways activating anorexigenic and growth-inhibitory signals that ultimately suppress intake and growth under unfavorable conditions (Li et al., 2023).

2.2 Environmental adaptability and stress response

Chinese sea bass is a euryhaline species with unusually broad salinity tolerance, which explains its suitability for culture in seawater cages, brackish environments, and freshwater ponds (Zhu et al., 2023). Available evidence indicates that the species can survive from freshwater to high-salinity seawater conditions, although growth is not equally supported across that entire range. Earlier work identified an optimal salinity around 16-17 ppt, and long-term acclimation experiments showed that growth remained stable at 0, 12, and 30 ppt but was significantly inhibited at 45 ppt (Li et al., 2023). Salinity challenge therefore demonstrates both strong environmental plasticity and a measurable cost when osmotic demand becomes excessive.

The stress response of L. *maculatus* is similarly environment-dependent. Moderate salinity elevation to 24 psu appears to improve protein utilization, whereas salinity stress also alters Na^+/K^+-ATPase activity, oxidative damage markers, and the expression of genes involved in energy metabolism, immunity, and osmoregulation (Hu et al., 2024). Temperature is another major regulator. Growth after 30 days was 2.76-3.22 times better at 21 °C than at 14 °C or 28 °C, showing that both low and high temperature can constrain performance even in an adaptable species (Li et al., 2023). At the molecular level, environmental stress activates coordinated defense pathways, including heat shock protein responses under thermal challenge and broad gill transcriptomic remodeling under salinity or alkalinity stress, confirming that adaptability depends on active cellular compensation rather than passive tolerance alone (Zhu et al., 2023).

2.3 Physiological constraints on survival and development

Despite its adaptability, Chinese sea bass faces clear physiological constraints that limit survival and normal development under chronic or acute stress. Early life stages occur in estuarine nursery habitats where temperature and salinity fall within relatively defined ranges, indicating that successful larval development depends on suitable brackish-water conditions rather than unrestricted environmental tolerance. In juveniles, thermal stress sharply increases vulnerability. Larger juveniles experience higher oxidative stress, more severe liver damage, and greater mortality than smaller individuals under acute heat exposure, suggesting that body size influences thermal resilience during culture (Qin et al., 2023). These findings show that survival is shaped not only by the external environment but also by ontogenetic stage and internal physiological capacity.

Long-term heat exposure imposes even broader constraints on organ function and whole-animal survival. At 35 °C, juvenile Chinese sea bass showed increased mortality together with oxidative damage, inflammation, apoptosis, and strong induction of heat shock proteins, indicating that compensatory defenses are activated but are insufficient to fully prevent injury (Yang et al., 2025). Prolonged high temperature also caused gill remodeling, liver vacuolization, reduced and broken intestinal villi, depressed digestive enzyme activities, and weakened nonspecific immune capacity, which together reduce oxygen uptake, digestion, tissue repair, and disease resistance. Survival can also decline rapidly during handling-related stress: during 9 h of simulated waterless transport, survival dropped markedly and major biochemical disturbances developed, indicating that confinement and impaired homeostasis are important non-growth constraints in production chains (He et al., 2020).

3 Overview of Different Farming Systems

3.1 Pond culture systems

Pond culture is one of the principal farming modes used for *Lateolabrax maculatus* in China, and it remains especially representative in the Bai Jiao production area of Guangdong because local hydrological conditions favor this model (Huang et al., 2025). In practice, pond systems are semi-enclosed and usually depend on tidal exchange, which makes them relatively easy to manage because of their smaller water volume, but also ties production performance closely to surrounding water conditions (Zhang et al., 2021). This basic structure supports both extensive and semi-intensive production. Extensive ponds rely more on natural productivity and lower external inputs, whereas semi-intensive ponds use greater feed input, higher stocking densities, and more active water management to raise output while still retaining the operational simplicity of earthen or coastal pond infrastructure.

The main strengths of pond systems are flexibility and comparatively straightforward husbandry, but their biological performance depends strongly on density control and water quality stability. In intensively managed earthen ponds for seabass, survival did not differ significantly among tested stocking densities, yet fish stocked at 6 fish/m^2 achieved significantly greater final weight and daily weight gain than those stocked at 10 fish/m^2 (Nhan et al., 2022). Pond environments also influence fish health through their microbial conditions, because sea bass ponds with high mass mortality showed bacterial community structure and function that differed significantly from low-mortality ponds (Deng et al., 2021). These findings indicate that pond farming can support strong production, but as semi-intensive management increases, growth and survival become more sensitive to ecological imbalance, crowding, and deterioration of the pond environment.

3.2 Cage and net pen aquaculture systems

Cage and net pen aquaculture is the other major farming system for Chinese sea bass, and it is widely used in sheltered marine waters where open-water exchange can support intensive fish production (Zhang et al., 2021). In these systems, fish are confined within mesh enclosures while surrounding water flows freely through the cage, which facilitates feeding, observation, and harvesting while also helping to maintain water quality and disperse wastes. This makes cage farming attractive for carnivorous, high-value fish such as sea bass. However, the same openness that improves exchange also exposes stocks and infrastructure to waves, currents, temperature shifts, and other external stressors, so site selection and engineering design are central to production success.

Performance in cage culture depends heavily on stocking density, hydrodynamics, and structural stability. In open-sea floating net cages, *Asian seabass* stocked at 10 fish/m^3 showed the best overall growth and production metrics, indicating that moderate density can outperform both lower and higher loading under offshore conditions (Figure 1) (Mostofa et al., 2024). At the same time, cage systems are mechanically sensitive because nets bear most hydrodynamic load, can deform under waves and currents, and thereby reduce culture space and water exchange, both of which affect fish welfare. Environmental modeling for deep-sea sea bass cages in the Yellow Sea further suggests that water-column quality can remain acceptable, although organic wastes may still accumulate in underlying sediments, highlighting the need for careful layout and environmental monitoring in offshore expansion.

3.3 Recirculating aquaculture systems and industrialized systems

Recirculating aquaculture systems (RAS) and other industrialized land-based systems represent a more controlled farming strategy in which water is repeatedly reused after mechanical and biological treatment (Lindholm-Lehto, 2023). These systems are increasingly promoted because they reduce water consumption and environmental discharge while allowing farmers to regulate key production variables more precisely than in ponds or sea cages (Li et al., 2023). As a result, RAS and industrialized systems are particularly relevant where biosecurity, standardized production, and year-round environmental control are priorities. Their technological basis also aligns with the broader trend toward more intensive and mechanized aquaculture development in China and elsewhere.

The main advantage of RAS is continuous environmental control, but this benefit depends on effective treatment and monitoring because wastes can accumulate rapidly in closed-loop systems. Hazardous substances such as particulate matter, ammonia, nitrite, and nitrate can build up from feeding and excretion and directly threaten fish safety and system operation if treatment performance declines (Li et al., 2023). Evidence from integrated land-based recirculating production shows that water-quality variation within the system is reflected in final weight, survival, specific growth rate, and yield, confirming that fish production responds directly to the success of recirculation management. Modern RAS therefore offers strong potential for improving growth consistency and survival of Chinese sea bass, but its practical value depends on reliable biofiltration, oxygenation, and real-time monitoring rather than on water reuse alone.

4 Effects of Farming Systems on Growth Performance

4.1 Growth rate differences across culture systems

Growth performance differs across culture systems because ponds, cages, and recirculating systems expose fish to distinct combinations of flow, salinity, density, and environmental stability. In Chinese sea bass, pond aquaculture and marine net-cage aquaculture remain the two dominant production modes, and recent industry review evidence notes that desalinated fish in pond-based production can grow about one-third faster than those reared in seawater, although high-density freshwater pond farming can reduce product quality (Huang et al., 2025). At the same time, offshore cage culture appears more favorable than conventional cage culture in ecological-economic performance, suggesting that differences among open-water systems are also biologically and operationally meaningful rather than merely structural (Zhang et al., 2021). System-specific hydraulic conditions further help explain these differences. Experimental work designed to mimic land-based RAS and deep-sea cage flow regimes showed that higher flow velocities enhanced growth performance relative to low-flow conditions in L. *maculatus*, while a separate velocity trial found the best specific growth rate and weight gain at a moderate flow of 1.14-1.56 body lengths/s rather than at still water or the highest velocity (Fei et al., 2025).

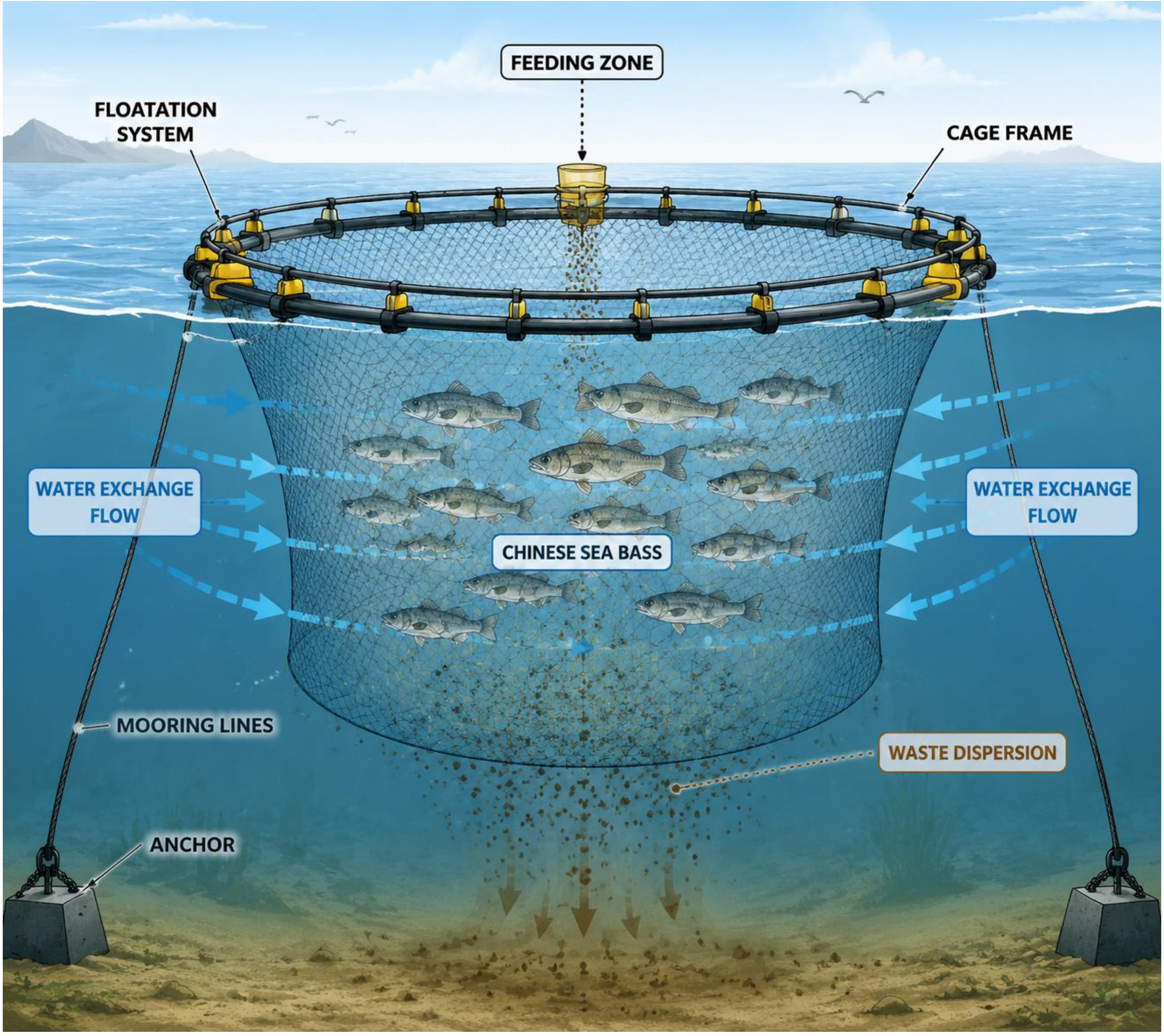

Figure 1 Schematic representation of a marine cage and net pen aquaculture system used for Chinese sea bass culture

Evidence from other cultured bass supports the same pattern: systems that provide more stable and better-controlled rearing conditions often produce faster growth, but only within appropriate density and engineering limits. In largemouth bass, a funnel-shaped recirculating system produced significantly higher body weight than a traditional pond system, indicating that industrialized water treatment and circulation can improve growth outcomes over conventional pond culture (Xu et al., 2025). In European sea bass net pens, growth rate increased linearly with cage volume, reaching 0.68 g/day in large cages versus 0.56 and 0.32 g/day in medium and small cages, respectively, showing that even within cage farming, physical scale can materially affect growth. Recirculating systems also have density thresholds. In tank-based RAS for sea bass, daily feed intake and specific growth rate were maintained up to 70 kg/m^3, but growth declined above that level, with specific growth rate about 14% lower at 100 kg/m^3. Taken together, the evidence indicates that no farming system guarantees superior growth on its own; performance depends on how well each system controls the specific environmental factors that constrain growth.

4.2 Feed conversion efficiency and nutrient utilization

Feed conversion efficiency is a central indicator of farming performance, but it should be interpreted together with broader nutrient-use metrics. In aquaculture, FCR is defined as feed administered divided by weight gained, and it remains the most widely used measure of production efficiency. However, FCR alone does not capture feed composition, edible yield, or nutrient quality of harvested fish, so nutrient retention offers an important complementary perspective when comparing farming systems or feeds. For Chinese sea bass, diet-quality studies show that feed utilization is highly responsive to nutritional balance. A dietary n-3/n-6 PUFA ratio of 0.66 produced the highest final body weight, weight gain, specific growth rate, and protein efficiency ratio, together with the lowest FCR, indicating that system performance depends partly on whether the culture environment allows efficient use of a biologically appropriate diet (Dong et al., 2023). Thus, comparisons among farming systems should consider not only how much feed is consumed, but how effectively environmental conditions translate that feed into growth and retained nutrients.

System conditions can improve or impair feed utilization by altering oxygen availability, crowding, digestion, and activity level. A broad endocrine review shows that low dissolved oxygen reduces growth, feed intake, and overall fish performance, and that FCR is inversely related to dissolved oxygen, making water-quality control a direct determinant of feed efficiency (Canosa and Bertucci, 2023). Density has similar effects. In *Amur sturgeon*, increasing stocking density reduced feeding rate and increased FCR, and the growth suppression was linked to lower food intake and poorer food conversion efficiency under crowding stress. In *Asian seabass* reared in RAS, higher stocking density significantly decreased both growth performance and feed utilization efficiency, while lower-density fish also maintained higher digestive enzyme activities and protein deposition (Ezhilmathi et al., 2022). By contrast, moderate hydrodynamic stimulation can support nutrient use: in Chinese sea bass, moderate flow increased digestive enzyme activity and improved growth, while in simplified indoor recirculating systems, continuous water flow appears to enhance exercise-related protein deposition in muscle. These results suggest that farming systems improve FCR and nutrient utilization when they minimize physiological stress while maintaining water movement, oxygenation, and feeding conditions within the species' optimum range.

4.3 System-related growth regulation mechanisms

The effects of farming systems on growth are mediated by physiological regulation rather than by environment alone. Fish growth is controlled primarily through the GH/IGF axis, and this axis is strongly influenced by external factors such as temperature, salinity, photoperiod, pollutants, and stocking density. More generally, fish performance reflects an interaction between genetic potential and immediate environmental conditions, and adverse conditions such as poor water quality, disturbance, or social stress reduce growth through endocrine pathways rather than through simple feed limitation alone. In Chinese sea bass specifically, temperature and salinity changes regulate growth through a stress-feeding-growth neuroendocrine cascade. Growth after 30 days was markedly better at 21 °C than at 14 °C or 28 °C, and transcriptomic analysis identified responsive modules linking stress signaling to feeding and growth control. This means that farming systems differ in growth outcome partly because they differ in how strongly they activate or suppress these endocrine networks.

Several mechanisms identified across the evidence base are directly relevant to system design. In L. *maculatus*, stress-induced heat shock proteins appear to activate the hypothalamic-pituitary-interrenal axis, then stimulate anorexigenic genes and growth-inhibiting somatostatin, providing a plausible pathway by which unfavorable thermal or salinity conditions suppress feeding and growth. Hydrodynamic conditions also regulate metabolism at the molecular level: higher flow enhanced growth but increased oxidative stress, and transcriptomic analysis identified *foxo3* and the FoxO signaling pathway as key hubs coordinating oxidative stress mitigation and energy mobilization. Density-related regulation follows a similar pattern. In juvenile Chinese sturgeon reared in RAS, high density elevated ACTH, cortisol, glucose, lactate, and HSP70 while down-regulating GH and IGF-I, whereas in *Asian seabass* increasing density down-regulated the GH/IGF axis and up-regulated myostatin. At the tissue-growth level, muscle development depends on GH, IGFs, TOR-related signaling, and myogenic regulators, so any farming system that chronically disrupts endocrine balance, oxygen supply, or activity pattern is likely to limit growth even when feed is abundant.

5 Survival Rate and Mortality Patterns under Different Systems

5.1 Disease incidence and mortality dynamics

Disease is a major source of mortality in sea bass culture, and outbreaks can cause rapid stock losses when pathogen exposure coincides with intensive farming conditions (Yue and Guo, 2025). In Chinese sea bass specifically, pond investigations in Zhuhai found clear contrasts between high- and low-mortality ponds, with the high-mortality pond showing significantly different bacterial community structure and function, indicating that mortality events are closely tied to the surrounding microbial environment (Deng et al., 2021). This pattern suggests that disease incidence in pond systems is not only a matter of host infection, but also of ecological imbalance in the culture water. As pond systems become more intensified, the probability that unfavorable microbial shifts will amplify mortality risk appears to increase.

Pathogen-specific studies show that mortality dynamics can be abrupt and severe in both pond and cage systems. In farmed L. *maculatus*, *Aeromonas veronii* caused acute death marked by hemorrhagic lesions, and experimental infection produced mortality within 24 h, reaching 100% at the highest challenge dose (Wang et al., 2022). In marine cage culture, a sudden disease outbreak with significant mortality was linked to coinfection by *Vibrio harveyi* and *Photobacterium damselae* subsp. *piscicida*, and dual infection produced faster and more pronounced mortality than single-pathogen challenge (Zhou et al., 2024). Together, these findings indicate that mortality under different farming systems depends not only on whether pathogens are present, but also on whether the system promotes pathogen proliferation, coinfection, and rapid transmission through dense fish populations.

5.2 Environmental stability and survival regulation

Environmental stability is a direct regulator of survival because fish mortality rises when water quality fluctuates beyond the range that the stock can physiologically tolerate. In earthen pond seabass culture, survival remained statistically similar across the tested densities when temperature, dissolved oxygen, pH, salinity, transparency, and ammonia stayed within suitable ranges, showing that stable water conditions can buffer survival even when density increases (Nhan et al., 2022). More broadly, seabass culture reviews identify site suitability, salinity maintenance, and water quality control as basic requirements for reducing mortality in both pond and cage farming. This means that system effects on survival are mediated less by the label of the system itself than by how consistently that system maintains acceptable culture conditions.

Recirculating and industrialized systems aim to improve survival precisely by stabilizing the rearing environment. Good water quality in RAS is described as crucial for successful growth and survival, and real-time monitoring is increasingly used to provide warnings of critical situations before they develop into mortality events (Lindholm-Lehto, 2023). Evidence from seabass culture also indicates that inconsistent water quality and traditional tank management can lead to contaminant accumulation, disease, stunted growth, and high mortality, whereas RAS-based white seabass culture achieved survival above 75% under maintained water quality conditions (Jais et al., 2024). These results support the view that environmental regulation is one of the main survival advantages of recirculating systems, although that advantage depends on reliable filtration, sensor performance, and timely management responses.

5.3 Stress-induced mortality mechanisms

Stress-induced mortality typically develops through chronic crowding, endocrine activation, oxidative damage, and immune suppression rather than through a single isolated event. High stocking density in cultured fish consistently elevates cortisol and other stress indicators, and in juvenile Chinese sturgeon reared in RAS it also suppressed growth and reduced immune and antioxidant capacity. Comparable evidence from grass carp shows that long-term overcrowding increases cortisol, decreases lysozyme, complement, and IgM, and drives an unbalanced inflammatory response, demonstrating a plausible mechanistic path from crowding stress to greater vulnerability and eventual mortality (Li et al., 2023). These mechanisms are highly relevant to Chinese sea bass because farming systems differ fundamentally in crowding intensity, water exchange, and the persistence of stress exposure.

Stress can also alter survival indirectly by weakening the fish before pathogen or environmental insults occur. In striped catfish, increasing stocking density elevated un-ionized ammonia and nitrite while lowering dissolved oxygen, and survival decreased significantly as density increased, linking environmental deterioration to physiological stress and mortality (Zaki et al., 2023). In marine fish more broadly, high stocking density produces chronic stress, raises plasma cortisol about fourfold, and depresses immune function, which helps explain why intensive systems can show mortality even when outright disease is not initially apparent. For L. *maculatus*, stress-induced mortality under different farming systems therefore appears to arise from the interaction of crowding, reduced water quality, impaired immunity, and increased susceptibility to opportunistic infection.

6 Water Quality and Environmental Regulation Effects

6.1 Dissolved oxygen, ammonia, and nitrogen accumulation

Dissolved oxygen and nitrogenous waste are among the main environmental constraints separating pond, cage, and recirculating systems. Across aquaculture systems, production is progressively limited by oxygen supply and the accumulation of growth-limiting wastes such as ammonia, while in RAS the removal of nitrogen pollutants remains difficult because wastewater typically has high dissolved oxygen but low organic carbon for denitrification (Ott et al., 2025). This matters directly for Chinese sea bass because high-density holding already shows the expected deterioration pattern: during simulated live transport, higher density reduced dissolved oxygen and increased total ammonia nitrogen, indicating how quickly confined systems can shift toward stressful water chemistry (Zhang et al., 2021). In pond systems, the pattern is somewhat different because natural biogeochemical processes buffer part of the ammonia load, but that buffering weakens as feed input and aeration intensity rise.

System design determines whether added nitrogen accumulates as toxic reduced forms or is pushed into less harmful oxidized forms. In intensively aerated earthen ponds, average total ammonia and un-ionized ammonia did not increase with higher stocking density, while nitrite and nitrate increased, indicating that nitrification became a more important ammonia-removal pathway under high loading. Similarly, ponds managed at a higher minimum dissolved oxygen concentration produced fish that were 35% larger, and the higher-oxygen treatment also had higher nitrite and nitrate, consistent with greater oxidation of ammonia through nitrification (Ott et al., 2025). In RAS, oxygen management can also directly suppress reduced nitrogen compounds: microbubble aeration stabilized dissolved oxygen at 4.28 mg/L and reduced both carbon dioxide and ammonia, while optimized MBBR operation reached 50% TAN removal once dissolved oxygen conditions supported biofilm performance.

6.2 Temperature fluctuation and seasonal variability

Temperature fluctuation affects farming systems not only through direct fish physiology but also by altering the stability of the rearing environment. Across aquaculture species, temperature is a major abiotic driver of growth and survival, and temperatures above species-specific thermal thresholds reduce performance, health, and productivity (Mugwanya et al., 2022). Extreme temperature events are also becoming more frequent and more intense, and they influence metabolism, immunity, and stress responses across cultured fish, which means that systems with poor thermal buffering are more exposed to seasonal production losses. For Chinese sea bass, this issue is especially relevant because open ponds and cages are more directly affected by ambient seasonal variation than industrialized land-based systems.

Evidence from Chinese sea bass and other farmed fish suggests that both average temperature and short-term fluctuation matter. During temporary holding and transport, L. *maculatus* was maintained at 20 °C-22 °C before cooling to 12 °C, illustrating that temperature is actively controlled to reduce stress in intensive handling conditions rather than left to fluctuate freely (Zhang et al., 2021). More broadly, daily fluctuation between 27 °C and 18 °C in Nile tilapia suppressed immune function, elevated heat-shock responses, and increased mortality after bacterial challenge to 35%-40%, showing how unstable temperature can worsen disease vulnerability even when mean conditions appear acceptable. Seasonal water instability can interact with nitrogen dynamics as well: in an aquaponics comparison, the control system experienced sharp ammonia accumulation followed by a nitrite spike to 13 mg/L, and all fish died, whereas the regulated system maintained more stable water quality and avoided those losses (Huang et al., 2025).

6.3 Biofiltration capacity and self-purification differences

Biofiltration capacity is one of the clearest differences among farming systems. In RAS, nitrogenous wastes cannot be controlled safely without in situ nitrification and denitrification through biofilters or bioreactors, and different systems support distinct nitrifying communities that determine how effectively nitrogen is converted and removed. By contrast, ponds depend more heavily on natural self-purification in the water column and sediment interface, which makes them biologically flexible but less predictable under high feeding and organic loading (Ott et al., 2025). This distinction is central to Chinese sea bass farming because more industrialized systems replace ecological buffering with engineered microbial treatment, while traditional ponds rely more on sediment processes, phytoplankton uptake, and water exchange.

Recent work shows that engineered biological treatment can substantially improve both water quality and production, but outcomes depend on the treatment pathway used. In recirculating ponds, adding a bacteria-microalgae association with biofilm carriers reduced TN by 29.15%, TAN by 51.28%, and nitrite-N by 33.48%, while fish production increased by 13.3% (Wang et al., 2022). Advanced oxidation in RAS similarly reduced NH_4^+ -N and NO_2^- -N, and O_3/UV treatment also increased fish length and weight, although it increased antibiotic resistance genes and therefore introduced a clear biosafety trade-off (Xue et al., 2023). Other side-loop treatments show comparable promise: woodchip denitrification with sand filtration achieved 96% denitrification efficiency and supported safe water reuse, while nitrate diffusion from RAS tailwater into pond sediments improved native sediment denitrification and lowered sediment ammonium accumulation (Lindholm-Lehto et al., 2021; Jia et al., 2022).

7 Feeding Management and Behavioral Adaptation

7.1 Feeding frequency and feeding strategy differences

Feeding frequency is a major determinant of growth efficiency in sea bass culture because it governs feed access, digestive loading, and the regularity of nutrient supply. In *Asian seabass* fry, feeding three times daily produced the best final body weight, specific growth rate, feed conversion, and survival, whereas feeding once daily gave the poorest overall performance (Hassan et al., 2021). A second fingerling study reached the same practical conclusion, showing that feeding frequency significantly affected feed intake, feed utilization efficiency, protein efficiency ratio, and relative growth rate, with the best results again at three meals per day. For Chinese sea bass production, this supports the use of moderate meal frequency as a core management tool, especially in systems where fish competition and feed loss are likely to increase under low-frequency feeding schedules.

Feeding strategy interacts with the farming environment rather than operating as a fixed rule across systems. In a freshwater aquaponic system for sea bass, four or eight meals daily produced higher final weight, weight gain, and specific growth rate than two meals, while survival was not affected by feeding frequency itself. By contrast, striped bass reared in recirculating systems showed no growth or efficiency penalty when feeding frequency was reduced, because fish compensated by eating more per meal and less over the full trial. These results indicate that optimal feeding schedules for L. *maculatus* are likely to depend on whether the system is a pond, cage, aquaponic, or RAS environment, since water exchange, feed recovery, and fish access to pellets differ substantially among those systems.

7.2 Behavioral adaptation under different farming environments

Behavioral adaptation to farming conditions is strongly shaped by density, oxygen availability, and the predictability of feeding. Under high stocking density, farmed fish often shift toward more cohesive and synchronized group behavior, and in gilthead sea bream this included reinforced schooling and a more clearly organized swimming rhythm centered on feeding time. High-density fish also showed reduced feed intake and growth, indicating that behavioral coordination under crowding is adaptive for coexistence but not necessarily favorable for production (Holhorea et al., 2023). For Chinese sea bass, similar adjustments are likely in cage and intensive pond systems, where crowding and competitive feeding can force fish to prioritize synchronized access to feed over low-cost routine behavior.

Feeding method also alters social behavior and risk responses. In juvenile seabream, hand-feeding improved body weight relative to self-demand feeding, while self-demand systems appeared to reinforce social hierarchy and competitiveness for resources within the group. Behavioral responses to rearing conditions are also density dependent but not always linear, because zebrafish held at the lowest density showed more aggression and higher cortisol than fish at intermediate or high density, even though high-density fish had lower and more variable growth rates (Sarma et al., 2023). This suggests that behavioral adaptation in aquaculture involves balancing social stress at both extremes: overly sparse groups can destabilize social interactions, whereas overly crowded groups can suppress feeding performance and increase competition, making intermediate density and predictable feeding especially important for sea bass welfare.

7.3 Nutritional physiology and energy allocation trade-offs

Nutritional physiology in farmed fish reflects a trade-off between growth, maintenance, and the metabolic capacity to cope with environmental challenge. Longitudinal data across teleosts show that faster ontogenetic growth is positively associated with standard metabolic scaling but negatively associated with aerobic scope, indicating that accelerated growth can reduce the metabolic margin available for functions beyond maintenance. A broader ecophysiological analysis in salmonids identified a similar dominant trade-off between high growth and consumption on one side and high aerobic scope and active metabolism on the other. In farming terms, systems that maximize growth through high ration and frequent feeding may therefore also narrow the physiological buffer available for activity, hypoxia tolerance, or other stress responses.

These trade-offs become more visible under intensive farming conditions that alter oxygen demand and energy partitioning. In high-density seabream, elevated swimming activity and respiration were accompanied by reduced energy partitioning for growth and impaired FCR, showing that more energy was diverted toward activity and coping functions rather than tissue deposition (Holhorea et al., 2023). Experimental and comparative work also shows that nutrient use depends on balancing intake with metabolic demand: protein synthesis requires both amino acids and energy, while absorbed protein and energy are under-utilized when their ratio is mismatched (Konnert et al., 2022). For L. *maculatus*, this means that feeding management should be evaluated together with farming system effects on density, oxygen, and activity, because the same diet can support either efficient growth or costly stress compensation depending on the rearing environment.

8 Case Study: Comparative Evaluation of Pond vs. Cage vs. RAS Systems in Commercial Chinese Sea Bass Farming

8.1 System design and operational characteristics

Commercial Chinese sea bass production is still centered on pond and marine net-cage culture, with pond farming especially established in the Bai Jiao area of Guangdong and cage farming concentrated in sheltered coastal waters such as Fujian (Huang et al., 2025). Pond systems are relatively simple and locally adapted, but they remain open to environmental fluctuation and disease-related microbial shifts, as shown by clear bacterial community differences between low- and high-mortality sea bass ponds (Deng et al., 2021). In contrast, cage systems use large open-water production units that increasingly approach industrial scale, and performance can change substantially with cage volume rather than density alone.

RAS differs from both pond and cage farming by replacing natural water exchange with engineered purification and near-continuous environmental control. Integrated land-based RAS can combine recirculating ponds with a primary biological pond, constructed wetlands, and ecological ditches, creating a managed treatment train rather than a single grow-out unit. Indoor RAS is also less exposed to rainfall, drought, salinity fluctuation, and other climatic disturbances than ponds or cages, although this operational stability comes with higher capital cost, higher energy demand, and greater design complexity (Ahmed and Turchini, 2021). For commercial Chinese sea bass farming, the core design trade-off is therefore between the low infrastructure burden of ponds, the spatial efficiency of cages, and the environmental controllability of RAS (Figure 2).

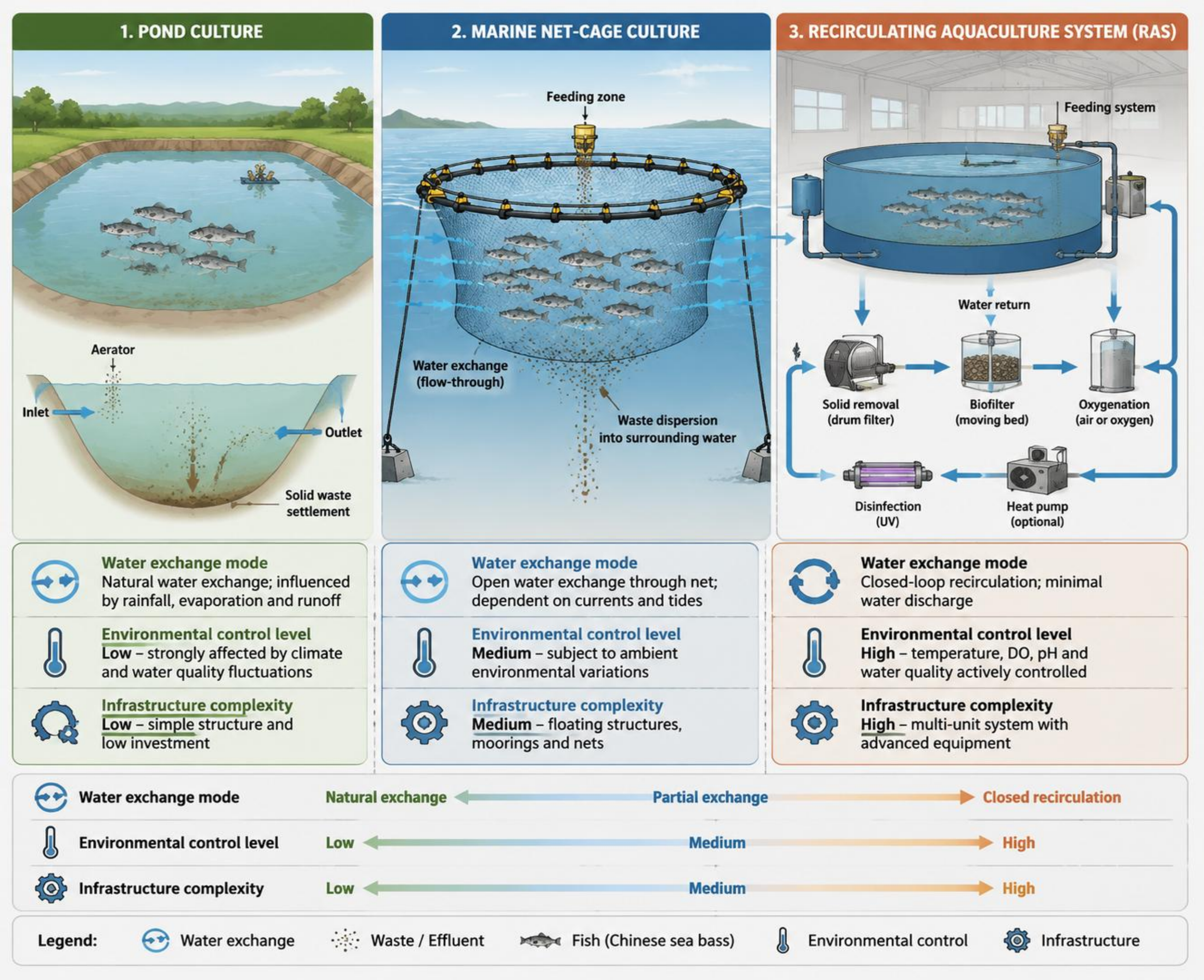

Figure 2 Comparative schematic of pond, cage, and recirculating aquaculture system (RAS) used for Chinese sea bass production, highlighting differences in water exchange mechanisms and environmental control levels

8.2 Integrated comparison of growth, survival, and FCR outcomes

Across systems, production outcomes track environmental control more closely than system label alone. In recirculating production, fish performance changed with water-quality gradients within the system, and final weight, survival rate, specific growth rate, and yield all responded to those differences. In cage production, larger rearing units produced better overall performance than the smallest cages, with higher growth rate, better FCR, and higher survival in European sea bass, which supports the view that well-scaled open-water systems can outperform undersized or stressed units. For Chinese sea bass, recent review evidence also notes that desalinated pond-reared fish can grow about one-third faster than fish reared in seawater, although this advantage is offset when high-density freshwater ponds degrade product quality (Huang et al., 2025).

A comparative case-study interpretation therefore suggests a three-way pattern. Pond systems can deliver strong growth under favorable local conditions and low capital cost, but their biological outcomes are more exposed to water-quality instability and disease-associated community shifts (Deng et al., 2021). Cage systems can support high production and good feed efficiency when cage size and site conditions are appropriate, but they remain vulnerable to environmental exposure and stress, including the typhoon risk explicitly noted for Chinese sea bass cage farming (Huang et al., 2025). RAS appears most consistent for stabilizing survival and feed use because it provides better year-round environmental conditions for water-quality-sensitive fish, and analogous bass evidence shows higher body weight in funnel-shaped recirculating systems than in traditional ponds (Xu et al., 2025).

8.3 Practical implications for system optimization and industry scaling

For system optimization, the strongest practical lesson is that each farming mode should be improved around its main constraint rather than replaced wholesale. Pond and cage systems remain commercially important because they are already embedded in China's sea bass industry, but their scaling is constrained by exposure to open-environment variability, storm risk, and site limitations (Huang et al., 2025). RAS offers a strategic pathway where land, water, pollution limits, or climate instability constrain expansion, because it is water-efficient, highly productive, and largely decoupled from external climatic shocks (Ahmed and Turchini, 2021). This makes RAS particularly attractive for high-value commercial Chinese sea bass operations targeting standardized production and secure supply.

Industry scaling, however, depends on solving operational bottlenecks rather than assuming that recirculation alone guarantees better outcomes. Interviews across the RAS sector identify poor system design and weak management capacity as major barriers, and they emphasize the need for commercial-scale equipment optimization and skilled personnel responsible for water quality and mechanical reliability. Broader sustainability reviews reach a similar conclusion: despite clear environmental advantages, RAS still contributes a small share of total production because high initial investment requires high stocking density and production to recover costs. In commercial Chinese sea bass farming, the most scalable pathway is therefore likely to be a hybrid industry structure in which ponds and cages remain dominant for lower-cost volume production, while RAS expands selectively in regions and market segments that reward tighter environmental control, product consistency, and climate resilience.

9 Integrated Strategies for Improving Farming System Efficiency

Precision aquaculture can improve the farming efficiency of Chinese sea bass by replacing intermittent manual checks with continuous measurement of critical water-quality variables such as temperature, pH, and dissolved oxygen. Real-time monitoring is especially relevant because instability in these parameters increases disease risk, mortality, and production losses, whereas IoT-based sensing allows faster detection of deteriorating conditions and more timely management responses. In *Asian seabass* farming specifically, low-cost IoT sensor platforms have already shown strong practical value, with calibrated systems achieving 76%-97% accuracy and supporting reliable real-time visualization for farm management. The next step is to connect monitoring with prediction and automated control so that environmental deviations can be corrected before they suppress growth or survival. Recent work shows that IoT systems coupled with machine learning can maintain stable water conditions, reduce mortality, and sustain survival above 90% during stressful periods, while fuzzy-logic control can autonomously regulate key variables such as dissolved oxygen and salinity to improve operational efficiency.

System hybridization offers a pathway to higher efficiency by redesigning Chinese sea bass farming systems so that wastes from fed fish become inputs for other cultured organisms. In integrated multi-trophic aquaculture (IMTA), finfish are cultured alongside extractive species such as seaweeds, mollusks, or deposit feeders, which recapture organic and inorganic nutrients, reduce waste discharge, and convert lost nutrients into additional biomass of market value. The main advantage of ecological intensification is that it can improve both environmental performance and farm diversification, but implementation depends on site design and economic feasibility. Open-water IMTA has been proposed as a way to combine biomitigation with added output from extractive crops, yet offshore settings impose technical and economic constraints, while spatially separated but ecologically linked regional IMTA may offer a more realistic model where direct co-culture is difficult in marine fish farming.

Long-term efficiency in Chinese sea bass farming depends not only on biological performance but also on economic optimization of inputs, infrastructure, and resource use. Across aquaculture systems, improved production efficiency has been associated with lower greenhouse-gas intensity, reduced land and freshwater use per unit output, and better feed management, indicating that environmental and economic sustainability often improve together rather than acting as opposing goals. Broader comparative evidence likewise shows that economic, social, and environmental outcomes are often mutually reinforced, although performance still varies substantially among production systems and leaves room for targeted innovation and investment. At the farm level, economic optimization requires matching system choice and intensity to cost structure. Reviews of cost-benefit analysis show that production-system assessment should account for environmental externalities as well as direct financial returns, while empirical evidence from intensive aquaculture indicates that higher-performing systems can lower unit costs by spreading fixed costs across greater output, even though technologies such as RAS remain vulnerable to feed and energy prices and therefore require careful control of electricity, water, and feed use.

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