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Chinese Soft-shelled Turtle, *Pelodiscus sinensis*, Monoculture and Co-culture with Rice Models-ecological and Economic Result

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Abstract

The Chinese soft-shelled turtle (*Pelodiscus sinensis*) is a key aquaculture species in China. This study provides a detailed description of the structural components and technical approaches of two representative cultivation models: intensive pond monoculture (Model A) and rice-*P. sinensis* co-culture (Model B). Their respective ecological and economic performances were systematically evaluated. Results showed that water quality parameters and plankton diversity were significantly poorer in Model A compared with Model B. The feed conversion rate (FCR) in Model A (3.07±0.29) was significantly higher than that in Model B (2.80±0.27), whereas the survival rate showed the opposite trend (Model A: 89.42%; Model B: 95%). Both models demonstrated economic feasibility; however, Model A involved substantially greater investment and return, and time to recover initial investment was 4.7 years. In comparison, the time for Model B aligned with the typical cultivation cycle of *P. sinensis*. Overall, Model A is better suited for aquaculture enterprises with matured technical capacity, large-scale operations, and sufficient financial resources. At the same time, Model B is more appropriate for small- to medium-sized farms with stable sales channels. The findings on aquaculture system design, water quality management, and economic performance provide valuable insights for optimizing *P. sinensis* production and advancing the sustainable development of this industry.

Introduction

The Chinese soft-shelled turtle (*Pelodiscus sinensis*) is a traditional and highly valued aquatic product in China (PRC), with a cultivation history dating back to 460 BC (Wang et al., 2024). Despite its long-standing significance, production yields have historically remained relatively low. Owing to its unique nutritional and medicinal properties, *P. sinensis* has consistently been regarded as a premium aquatic commodity (Hou et al., 2024). Bureau of Fisheries, Ministry of Agriculture and Rural Affairs of the PRC et al. (1996-2023) reported that in recent years, aquaculture production has increased steadily, as illustrated in Figure 1. In 2022, approximately 373,709 tons of *P. sinensis* were produced, 1.13 times higher than a decade earlier and 3.21 times greater than two decades ago, marking its gradual transition from an exclusive luxury food to a product for broader market consumption. The rapid expansion in production is primarily driven by its substantial economic returns. For instance, greenhouse cultivation covering 70 m² can generate an annual economic benefit of approximately ¥35,000 per year (Zhang et al., 2017), while integrated rice *P. sinensis* fish farming yields gross and net profits of about ¥106,606 and ¥105,753 per hectare, respectively (Liu et al., 2019).

The cultivation of *P. sinensis* in China is concentrated primarily in the middle and lower reaches of the Yangtze River and in southern regions, with two dominant production models: mono-culture and co-culture. Previous studies have reported an intensive mono-culture cultivation system using thermostatic greenhouses, which is characterized by short production cycles, high yields, and high profitability, mainly applied in seedling production (Zhang, et al., 2016). Intensive cultivation in cement ponds represents the main mono-culture approach, producing the majority of market-sized adults. Although the co-culture models have a long history, they have been widely promoted in recent decades, achieving significant improvements in both economic and ecological benefits compared to rice monoculture, and now account for the largest cultivation area. *P. sinensis* produced in rice co-culture models enjoys strong consumer acceptance. Studies have shown that *P. sinensis* raised in simulated natural environments show more balanced amino acid and fatty acid profiles, reflecting improved nutritional quality (Wang et al., 2019). Both mono-culture and co-culture models, especially rice-based co-culture, receive strong policy support from the Chinese government. In 2021, the Ministry of Agriculture and Rural Affairs (MARA) issued the "14th Five-Year National Fisheries Development Plan," calling for the expansion, intensification, and standardization of aquaculture to improve productivity per unit area. That same year, the "14th Five-Year National Agricultural Green Development Plan," jointly released by MARA and five other ministries, explicitly highlighted the ecological benefits of paddy fields and encouraged the integrated rice–aquaculture farming model.

The sustainability of aquaculture encompasses three interrelated dimensions: production technology, socio-economic impact, and environmental influence (Shi et al., 2013). Cultivation technologies are now well established, which could be seen in the increasing production. From an ecological standpoint, aquaculture operations are required to install wastewater treatment facilities and comply with government discharge standards. For integrated rice *P. sinensis* systems, national regulations mandate that rice paddies must occupy at least 90% of the total area, with *P. sinensis* stocked at low densities. This ensures stable rice yields while eliminating wastewater discharge. Moreover, co-culture systems substantially reduce the use of chemical fertilizers and pesticides, as well as methane (CH_4) emissions, when compared with rice monoculture (Yu et al., 2023). Water quality is a critical determinant of aquaculture success, directly affecting product quality, market value, and long-term sustainability. Physicochemical parameters and plankton diversity serve as key indicators for water quality assessment. For example, rice–fish co-culture systems have been shown to reduce nitrogen concentrations (total N, NH_3-N, NO_3-N, and NO_2-N) in water by 70–79% relative to fish monoculture. Furthermore, rice–animal co-culture systems enhance aquatic biodiversity, leading to more resilient and productive farming ecosystems (Bashir et al., 2020). Economic returns remain the primary driver for aquaculturists. Given that the market price of *P. sinensis* varies significantly depending on cultivation models and grow-out periods, determining how to maximize profitability and select the optimal production

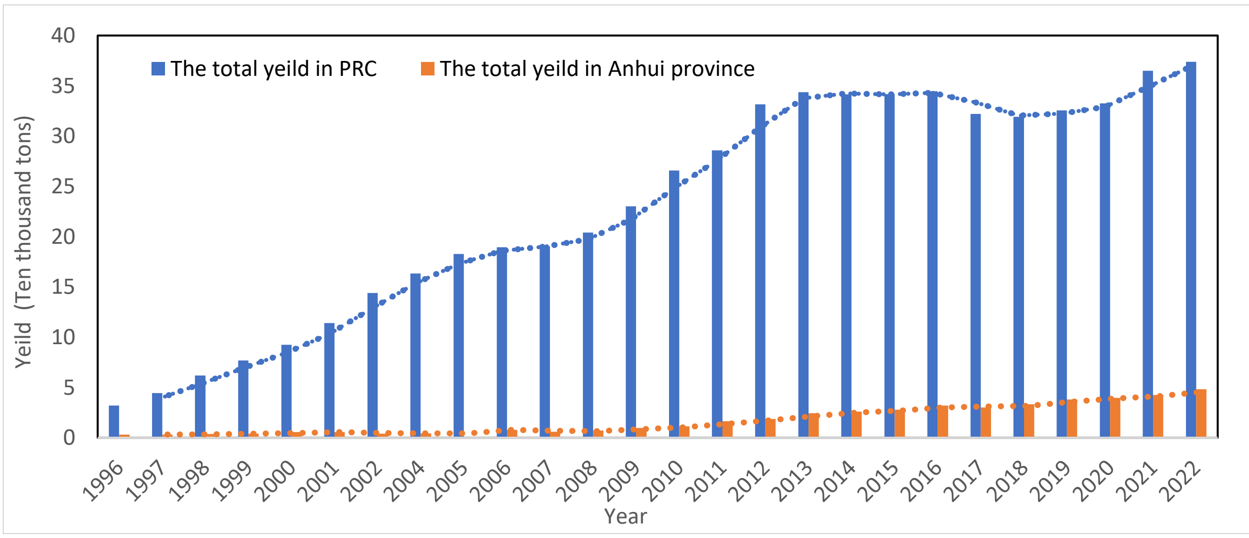

Figure 1. The yield of *P. sinensis* in China and Anhui Province from 1996 to 2022.

system is a critical consideration for both farmers and policymakers.

Accordingly, the present study aims to: (1) describe the infrastructure and main technical procedures of two representative *P. sinensis* cultivation models; (2) evaluate eco-efficiency through water quality and plankton diversity evaluations; (3) analyze the effects of cultivation model on growth performance; and (4) evaluate economic benefits by examining investment and returns. The findings are expected to guide decision-making in *P. sinensis* aquaculture and provide a reference for the future development of the industry.

Materials and Methods

The Study Area

Intensive Pond Mono-culture of P. sinensis (Model A)

Model A farms were located in Bengbu (117.43° E, 33.06° N), Xuancheng (118.55° E, 30.30° N), and Hefei (117.34° E, 31.58° N) cities in the middle and lower reaches of the Yangtze River. The pond areas were 66 ha, 87 ha, and 33 ha, respectively, with similar construction layouts. As illustrated in Figure 2, each pond was rectangular (900 m^2; 60 m×15 m) and bordered by a concrete berm with a slope ratio of 1:1. A 10-cm-wide inverted "┐"-shaped eave was installed along the top edge of the berm to prevent turtles from climbing out and escaping. The intake and drainage structures were positioned diagonally across the pond to ensure efficient water exchange. The pond bottom was covered with a 20–30 cm layer of sandy soil, and the water depth was maintained between 0.8 and 0.9 m. Feeding tables made of mesh were installed along both long sides of the pond, while an additional mesh platform with a backsplash was placed inside the pond to serve as a basking site for the turtles.

Rice–P. sinensis Co-Culture (Model B)

Model B farms were located in Bengbu (117.43° E, 33.06° N), Hefei (117.34° E, 31.58° N), and Anqing (117.02° E, 30.87° N) cities, all situated within the middle and lower Yangtze River basin. The total pond areas were 33 ha, 40 ha, and 20 ha, respectively, with rice paddies occupying 90% of each site. Surrounding the rice fields was a four-sided ring groove, one side of which featured a wider channel (Figure 2B). Excavated soil from the groove was used to reinforce the surrounding ridges, which were further stabilized with stalked grass. A wire fence encircled the entire paddy area, extending 30–40 cm underground and approximately 1.5 m above ground to prevent turtle escape and entry of predators. Similar to Model A, the intake and drainage system was arranged diagonally, with a water control pipe installed to regulate water levels and prevent excessive flooding during the rainy season.

Data Acquisition

From 2019 to 2022, data on the growth performance and economic benefits of the two models were continuously monitored over four consecutive years, with three farms sampled for each model. Economic benefit assessments included infrastructure construction costs and all relevant operational inputs during the farming process, such as feed, labor, land rent, water, and electricity. For each farm, three parallel sampling units were established.

From 2021 to 2022, water samples were collected every 1.5 months during the growth period of *P. sinensis* and rice. Within two days of collection, the concentrations of ammonia, nitrite, total nitrogen, and the potassium permanganate index (COD_{mn}) were determined. Plankton biodiversity was assessed only for water samples collected in 2022. For water sampling, farms located in Bengbu (117.43° E, 33.06° N) and Hefei (117.34° E, 31.58° N) were selected as representative sites for Models A and B, respectively, with three ponds or paddy fields at each farm serving as parallel sampling units.

Production Management

Water Quality Management

In Model A, a microbial preparation primarily composed of *Bacillus subtilis* was applied to the pond at a concentration of 20 g·m^{-3} twice per month, preferably during sunny mornings for optimal efficacy. During periods of high summer temperatures, a micro-flow water system was used to replenish evaporated water,

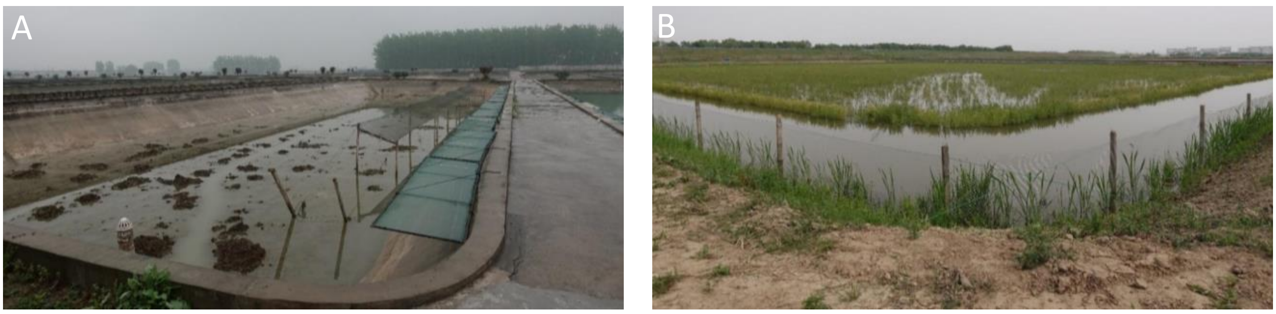

Figure 2. The photo of intensive pond monocultural base (A) and rice- *P. sinensis* co-culture base (B).

maintaining the water depth above 0.9 m. This practice also helped regulate water temperature, ensuring it did not exceed 32°C. In Model B, water exchange was generally unnecessary; however, a micro-flow water supply was employed during hot summer months to prevent excessive temperature increases.

Feeding

For Model A, powdered feed was processed into palatable soft granules, with vitamin C and effective microorganisms (EM bacteria) regularly incorporated during preparation. *P. sinensis* were fed at approximately 2–4% of body weight twice daily, at around 06:00 and 17:00 during the first month. Feeding amounts were adjusted daily following the principle that feed should be consumed entirely within 30 minutes, with subsequent adjustments made based on actual consumption.

For Model B, an expanded pellet diet was provided twice daily at 1–2% of body weight. The chemical composition of both the powdered feed (Model A) and expanded pellet diet (Model B) was identical on a dry matter basis: crude protein≥45%, crude lipid≥5%, crude fiber≤4%, crude ash≤17%, total phosphorus≤2%, calcium≤3%, moisture≤10%, and lysine≤10%.

Water Quality Monitoring

Water quality measurements were conducted on sunny days between June and August. Acidity (pH), dissolved oxygen (DO), and water temperature (°C) were measured immediately on-site using a portable water quality analyzer (YSI ProPlus). At the same time, 500 mL water samples were collected and transported to the laboratory for further analysis. Ammonia, nitrite, total nitrogen, and the potassium permanganate index (COD_{mn}) were determined using the Nessler's reagent method and the naphthylenediamine hydrochloride method (Dalian Environmental Testing Center, 2012; Beijing Environmental Monitoring Center, 1989).

Plankton Sampling and Detection

For phytoplankton counting and identification, water samples were collected using a 1 L Plexiglass water sampler at a depth of 0.5 m. The collected water was transferred into sampling bottles, and 1.5% Lugol's solution was added on-site for fixation. Samples were then transported to the laboratory and left to settle undisturbed for 48 h. The supernatant was concentrated using the siphon method, and the remaining concentrate was transferred into a 50 mL polyethylene sample bottle. The final volume was adjusted to 50 mL to ensure uniformity. Phytoplankton species were identified based on morphological characteristics (Han and Shu, 1995). Abundance was expressed as individuals per liter (ind. L^{-1}) and was determined by examining a 1 mL homogenized subsample placed on a Sedgewick–Rafter counting slide. Observations were made at 40× and 100× magnification using a microscope (Olympus BX53).

Biological Water Quality Indices

The biological evaluation based on phytoplankton parameters was carried out using phytoplankton of Margalef index (D) (Margalef, 1957), equitability index (J') (Pielou, 1966) and biodiversity of Shannon-Wiener diversity index (H') (Shannon, 1948) to illustrate the species diversity in the sampling sites in both seasons according to the following equations:

$$D = (S - 1) / \ln N \quad (3)$$

$$DH = -\sum_{i=1}^{s}(n_i/N)\ln(n_i/N) \quad (4)$$

$$J = H / \ln S \quad (5)$$

$$Y = (n_i / N) f_i \quad (6)$$

Where n_i: overall count of individuals of each species in a certain sample, N: the total phytoplankton abundance, S is the number of detected species in the sample, and *fi* represents the frequency of the species *i* individual present in the sampling sites. The dominant species or genus was defined as Y>0.02.

Growth Performance

The parameters of growth performance were measured by the following formula.

$$\text{Survival (\%)} = (N_t / N_0) \times 100\% \quad (1)$$

$$FCR = (D_f / (W_t - W_0)) \times 100\% \quad (2)$$

Where FCR represented feed conversion rate; N0 and Nt represented the initial and final numbers of *P. sinensis*; Df was the dry diet intake (g), Wt and W0 were the mean final and initial body weight (g), and were weighed at stocking and catching time.

Economic Analysis

Cost–Benefit Analysis is a widely used method for evaluating investment projects. In this study, it was applied to assess the economic performance of *P. sinensis* cultured under two models.

In this analysis, costs were categorized into depreciation costs and operating costs (Huang et al., 2022). Depreciation costs refer to the annual amortized value calculated using the straight-line depreciation method, based on infrastructure such as concrete ponds in Model A and field ditching in Model B (Chen et al., 2024). Operating costs encompass all expenses incurred during the farming process, including land rent, labor, water and electricity, seedlings, feed, animal health products, labor protection supplies, and other consumables. Cost and revenue components are detailed below:

(1) Depreciation Cost

For Model A, cultivation ponds had a service life of 20 years, with a construction cost of ¥800,000 per hectare. Using the straight-line depreciation method, the annual depreciation was calculated as ¥40,000 per hectare.

For Model B, infrastructure primarily included paddy field ditching and a drainage system, with a total construction cost of ¥35,000 per hectare and the same 20-year service life, resulting in an annual depreciation cost of ¥1,750 per hectare.

(2) Operating cost

Facility maintenance: Equipment had a service life of 5 years. In Model A, supporting facilities included basking platforms, feeding platforms, and escape-prevention structures. In Model B, the leading equipment included oxygenators and escape-prevention facilities.

Rent: Based on the market rate, land rent was ¥10,500 per hectare.

Labor: In Model A, one worker was paid ¥4,300 per month and managed 1 hectare. With a culture period of approximately 5 months, the annual labor cost was ¥21,500 per hectare. In Model B, one worker earned ¥3,500 per month and managed 5 hectares. With a 6-month culture cycle, the labor cost was ¥4,200 per hectare per year. Further manual work in Model B included soil loosening (¥1,200/ha), rice transplantation (¥3,300/ha), and rice harvesting (¥2,100/ha), bringing the total annual labor cost to ¥10,800 per hectare.

Water and electricity: In Model A, costs were mainly for pumping to maintain water levels and temperatures during the hot summer months. In Model B, expenses were primarily for water supply and aeration to support the growth of rice, *P. sinensis*, and fish.

Seedlings: In both models, greenhouse-raised *P. sinensis* juveniles were purchased at ¥30/kg. In Model A, the culture area accounted for 90% of the total pond surface (0.9 ha). Stocking density was 20,700 juveniles per hectare with an average weight of 618 g, resulting in a seedling cost of ¥383,778 per hectare. In Model B, 90% of the area was also used for co-culture, with 2,025 juveniles per hectare averaging 400 g, costing ¥24,300 per hectare. Additional seed inputs included rice (¥1,215/ha) and fish fry (¥2,565/ha), bringing the total seed cost for Model B to ¥28,080 per hectare per year.

Feed: Feed cost was ¥13,500 per ton.

Animal protection products: These included water conditioners and feed additives such as EM bacteria, vitamin C, chlorine dioxide, and quicklime.

Labor protection supplies and miscellaneous: Items included gloves, chest waders, buckets, feed preparation machines, tricycles, and other consumables.

(3) Revenues

P. sinensis: The market price for *P. sinensis* in Model A (cultured for 1 year) was ¥50/kg. In Model B, the price varied with culture duration: 1 year–¥50/kg, 2 years–¥63/kg, 3 years–¥85/kg, and 4 years–¥105/kg.

Rice: Yields averaged 9,000 kg per hectare, sold at ¥3/kg.

Fish: Production averaged 675 kg per hectare, sold at ¥10/kg.

Other aquatic products: Yields included 34 kg of finless eel per hectare (¥60/kg) and 34 kg of loach per hectare (¥20/kg).

Economic evaluation of *P. sinensis* cultured under two models was performed based on net present value (NPV), internal rate of return (IRR), payback period (PBP), benefit-cost ratio (BCR), and PR. The corresponding equations are presented below (Nguyen et al., 2024; Huang et al., 2022).

$$NPV = \sum_{t=0}^{n} CF_t/(1+r)^t \quad (7)$$

$$0 = \sum_{t=0}^{n} CF_t/(1+IRR)^t \quad (8)$$

$$PBP = I/CF_t \quad (9)$$

$$BCR_n = NR_n/TC_n \quad (10)$$

$$PR_n = NR_n/TR_n \quad (11)$$

Where NPV is the financial net present value of the individual's (yearly) cash flows. CF_t is the cash flow of the investment in time t (s); r is the discount rate (%); and t is the time from 0 to n (years). Here, t = 20, which is the lifespan of a digester; r denotes a discount rate and is assumed to be 5.0%. The advantage of NPV is that it is additive and that it reflects time as well as money. If the NPV is greater than 0, then a project is feasible.

The internal rate of return (IRR) is defined as the discount rate at which the after-tax NPV equals zero, indicating that the present value of the investment is equal to the present value of net operational revenues. A higher IRR reflects greater project profitability.

The payback period (PBP) refers to the time required to recover the total capital investment, typically expressed in years and measured from the commencement of production until the initial investment is fully recouped. In this study, the capital investment (I) was ￥800,000/ha for Model A and ￥35,000/ha for Model B.

The benefit–cost ratio for the nth year (BCR_n) was calculated as the ratio of net return (NR_n) to total cost (TC_n). The profit rate (PR_n) for the nth year was determined using the net return and total return values, following the method described by Huang et al. (2022).

Statistical Analysis

Graphs were generated using Origin 2025. Results are presented as mean±standard deviation (SD) from triplicate measurements. Data were analyzed using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test at a significance level of $P<0.05$, performed in SPSS version 22.

Result

Physical and Chemical Parameters of Water

The DO levels in the water of the monoculture pond (Model A) and the rice–fish co-culture system (Model B) were consistently above 5 mg/L, sufficient to meet the oxygen demands of phytoplankton and microorganisms. The pH values for both models ranged from 7.38 to 9.04, falling within the optimal range for *P. sinensis*. Between June and September, air temperatures varied from 21°C to 36°C, while water temperatures remained within 25.6–31.3°C and showed less fluctuation than air temperatures. This stability was attributed to the micro-flowing water regulation in Model A during the hot summer months and the shading effect of rice plants in Model B.

The concentrations of ammonia, nitrite, TN, and the permanganate index (COD_{Mn}) from June to September are shown in Figure 3. In Model A, all four parameters displayed a rising trend followed by a decline, peaking in July. This period coincided with the rapid growth of *P. sinensis*, during which intensified feeding increased the nutrient load in pond water. In Model B, ammonia and nitrite levels fluctuated slightly, COD_{Mn} followed a rise–fall pattern, and TN showed a gradual decrease over time.

As illustrated in Figure 3, ammonia (0.02 mg/L) and TN (3.46 mg/L) concentrations in Model A were significantly lower than in Model B (ammonia: 0.31 mg/L; TN: 8.04 mg/L) in June ($P<0.05$), whereas nitrite and COD_{Mn} levels were slightly higher in Model A, though the differences were not significant ($P>0.05$). By July and September, all parameters in Model A were significantly higher than in Model B. This pattern was mainly due to fertilizer application in rice fields during transplanting in June, which elevated ammonia and TN in Model B. From July to September, the concurrent peak growth periods of rice and *P. sinensis* led to substantial uptake of carbohydrates and nitrogenous compounds by rice, while uneaten feed and fecal matter accumulated in the pond environment.

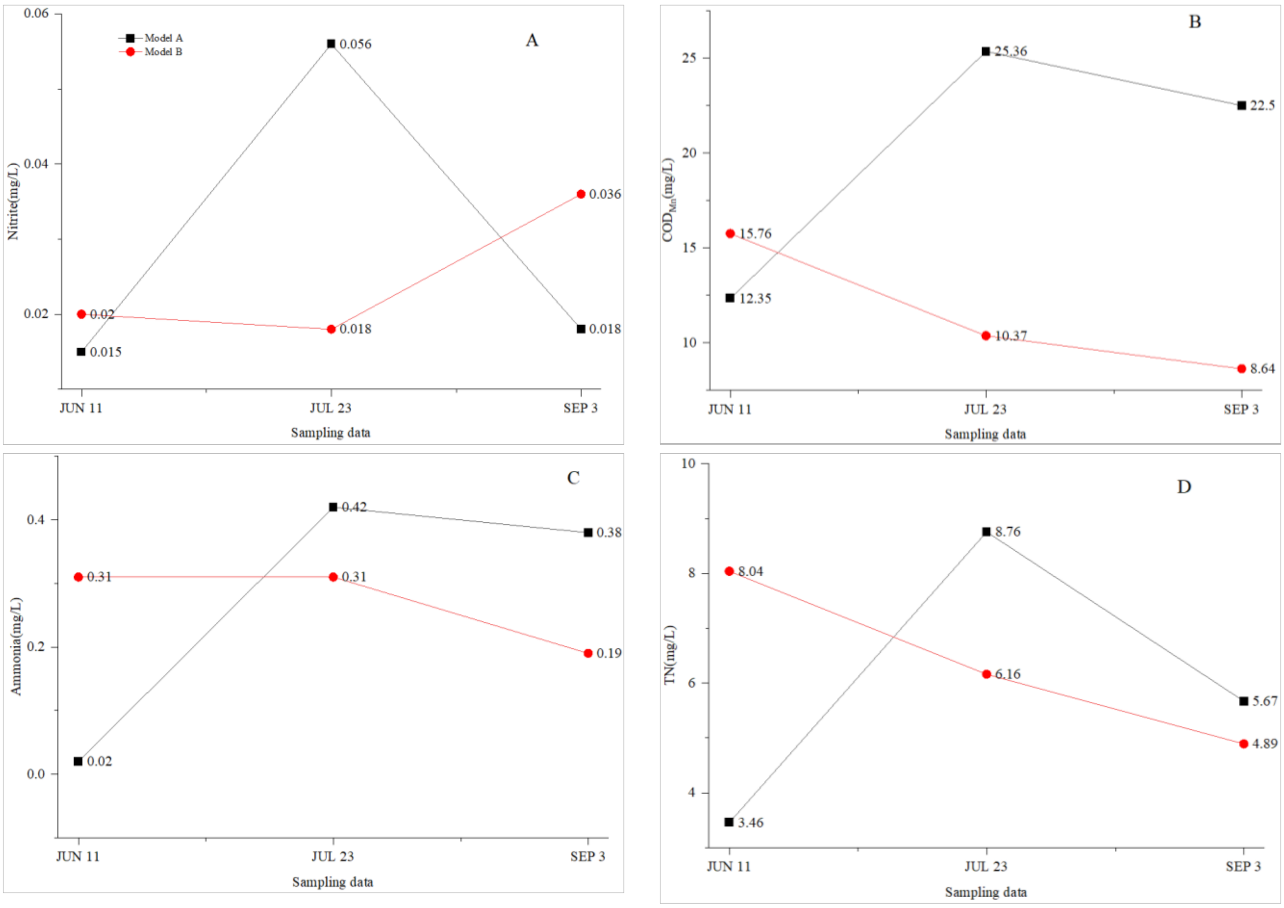

Figure 3. The concentrations of nitrite, ammonia, $COD_{Mn,}$ and TN in two models..

Biodiversity of the Phytoplankton

Establishing a healthy aquaculture environment requires maintaining an algal balance that benefits cultured organisms. The succession of dominant phytoplankton species plays a pivotal role in shaping the community structure, which in turn influences water quality and the sustainable development of aquaculture (Zhu, et al., 2023). Consequently, monitoring phytoplankton community composition and dominant species succession is essential for effective aquaculture management (Qiao et al., 2020).

Throughout the study period, the phytoplankton community in both models consisted of representatives from five phyla: Bacillariophyta, Chlorophyta, Cyanophyta, Euglenophyta, and Dinophyta, while Chrysophyta was also detected in Model B. In total, 62 species belonging to five phyla were recorded in Model A, and 65 species from six phyla in Model B. In both models, species richness initially declined and then increased, whereas phytoplankton density showed a gradual upward trend (Figure 4).

In both models, Chlorophyta was the dominant phylum; however, the dominant species varied by period (Figure 5). In July and September, the abundance in Model A reached 99%, with *Closterium gracile* being the dominant species (Y= 0.98). In June (Model A) and in June–July (Model B), the dominant species was *Oocystis solitaria* (Y= 0.17–0.72).

In terms of phytoplankton diversity, Margalef index (D), Shannon-Wiener diversity index (H') and equitability index (J') for the two models are presented in Figure 4. In Model A, seasonal succession was evident, with all three indices displaying a pattern of initial decline followed by an increase. In comparison, Model B showed a slight overall upward trend. In June, no significant differences were observed between the two models; however, in July and September, the indices for Model B were significantly higher than those for Model A.

Growth Performance of *P. sinensis*

Table 1 presents the growth performance of *P. sinensis* in Models A and B. In Model A, *P. sinensis* was reared in the outer pond for one year (with an actual growth period of approximately five months, from May to September) before being sold. In Model B, cultivation typically extended for over two years, with active growth occurring from May to September, followed by hibernation in the four-sided ring groove surrounding the rice field. Therefore, Table 1 reports growth

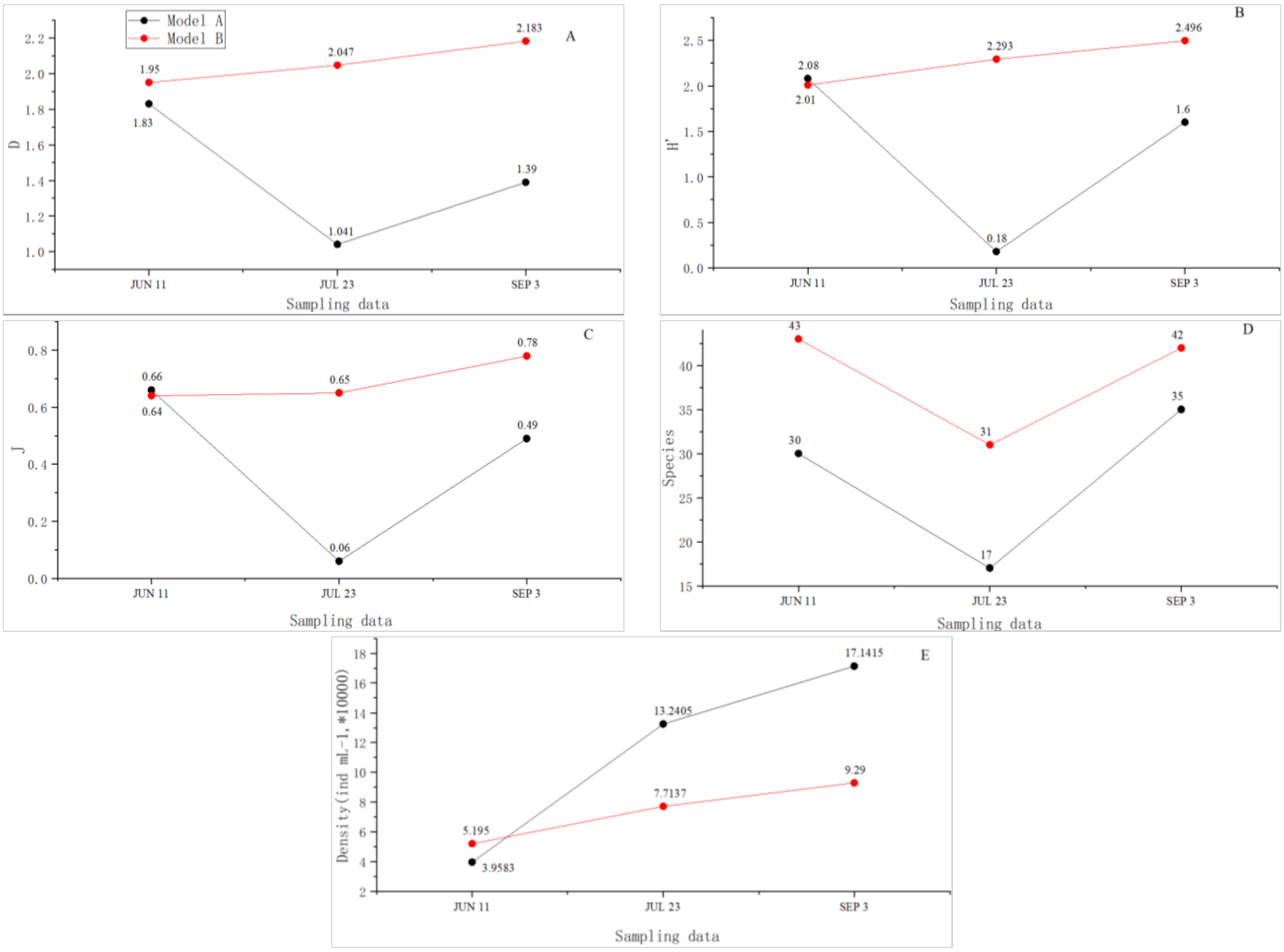

Figure 4. D: Margalef index (A), H': Shannon-Wiener index (B), J: Equitability index (C), species (D), and density (E) of Phytoplankton in two models.

performance for a single year in Model A and for four years in Model B.

The results indicate that the FCR was significantly higher in Model A than in Model B, while the survival rate was significantly lower. In Model A, the FCR was 3.07 and the survival rate reached 89.42%, considerably higher than values commonly observed in greenhouse nurseries (Zhang, et al., 2017). This was primarily attributed to the variable temperature conditions in outdoor ponds, which often exceeded a constant 30°C, enhancing protein application in feed (Lei, 2007). In comparison, FCR values in the paddy field were substantially lower than in outdoor ponds, primarily due to the availability of natural prey such as river snails, loaches, and other wild aquatic species that served as supplemental food for *P. sinensis*.

Economic Benefit

This economic evaluation aimed to identify the more profitable investment model.

The initial investment for Models A and B was ￥800,000/ha and ￥35,000/ha, respectively. In Model A, the major expenses included the construction of cement ponds, installation of water supply and drainage systems, cement roads, and other infrastructure (Figure 2A). In comparison, Model B's investment was primarily allocated to reconstructing paddy field ring ditches, upgrading water supply and drainage systems, and improving field roads (Figure 2B).

A detailed breakdown of production costs and revenues for both models is provided in Table 2. In Model A, the three most significant cost components were seed, feed, and depreciation, whereas in Model B, they were seed, feed, and land rent. Seed and feed costs accounted for a substantial proportion in both models. The seedlings used in both systems were greenhouse-raised, with prices depending on quality, sex, and size. From 2019 to 2022, the average cost of juvenile *P. sinensis* was ￥30/kg, sourced from the same aquaculture farm. Similar to other intensive monoculture or co-culture fish production systems, feed constituted a high proportion of expenses (Lu et al., 2022; Nhan et al., 2022; Xu et al., 2022). Although Model B benefited from supplemental natural feed sources such as river snails, loaches, and other wild species, the total feed cost remained high due to the elevated unit price.

In terms of revenue, *P. sinensis* was the sole income source in Model A, whereas in Model B, it accounted for 65.15% of total income. The cash flow, economic benefit, BCR, and NPV for both systems were positive, confirming their profitability. The unit economic benefit of Model A was 6.57 times greater

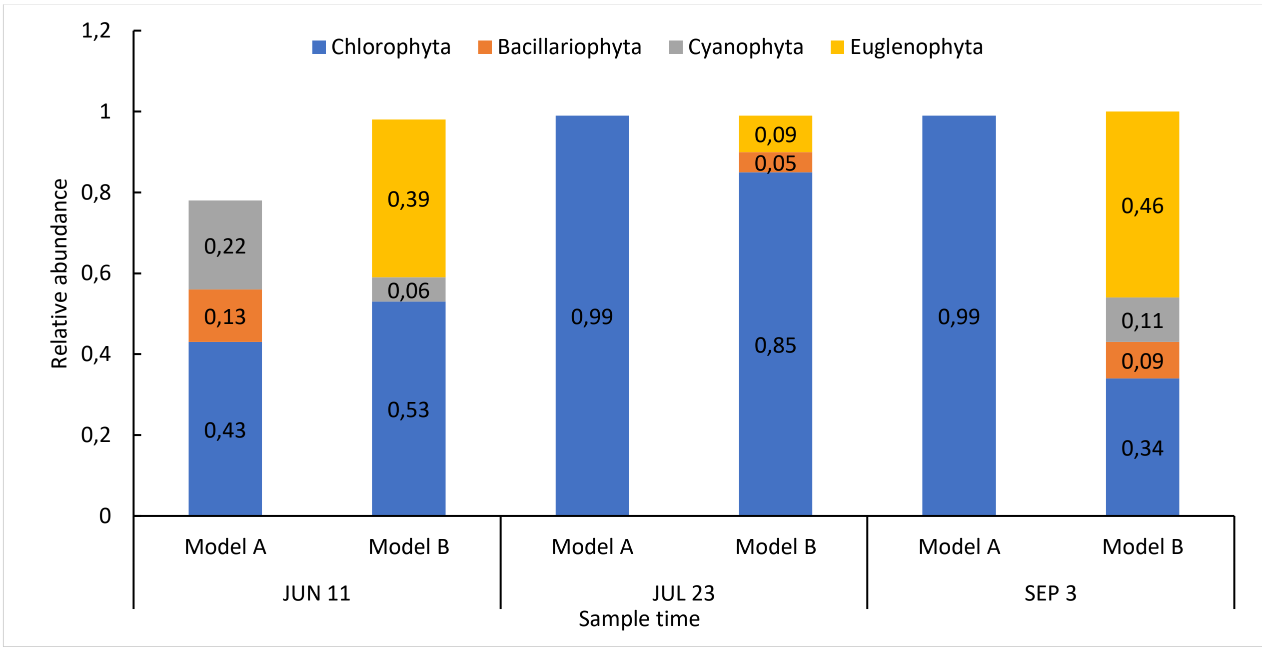

Figure 5. Relative abundance of Phytoplankton in two models.

Table 1. Growth performance of *P. sinensis* in models A and B

	Model A				Model B			
	W0 (g)	Wt (g)	FCR	Survival	W0 (g)	Wt (g)	FCR	Survival
1st year	618.85±48.15	875.15±131.41	3.07±0.29	89.42%±4.16	400.76±40.16	700±85.4	2.8±0.27	95%±0.5
2ed year	—	—	—	—	—	1060±163.2	2.7±0.31	96%±0.5
3rd year	—	—	—	—	—	1440±187.4	2.7±0.24	96%±0.5
4th year	—	—	—	—	—	1767.4±157.8	2.6±0.13	96%±0.5

than that of Model B, with a PBP of 4.47 years, indicating full recovery of investment after the fifth year of P. sinensis sales. Both models had IRR exceeding 5%, with Model B achieving a significantly high IRR of 53.61% and a shorter PBP of only 2 years, 3 years less than Model A, indicating strong profitability and high feasibility.

To maintain rice yields, the breeding ditch area should not exceed 10%, and the rice output should be at least 7,500 kg/ha (Bashir et al., 2020). Hu et al. reported a *P. sinensis* cultivation threshold of 3.621 ton/ha, beyond which rice yields decline (Hu et al., 2016). In the integrated Model B described here, a narrow-ditch + shallow-ditch + wide deep-pit configuration was adopted, allowing adequate aquatic habitat without exceeding the 10% ditch limit. The highest yield achieved after four years of cultivation was 3.0 ton/ha, which remained below the threshold, while rice yield reached 9,000 kg/ha above national requirements.

The nutrients, flavor, and lipid profile of *P. sinensis* are closely linked to age. In the Chinese market, longer cultivation periods command higher selling prices (Hou et al., 2024). Model B aimed to enhance product quality; thus, the cultivation period was a minimum of two years. Table 3 presents the economic analysis for *P. sinensis* cultured in Model B for 2–4 years. The market price rose progressively from ￥50/kg for one-year-old stock to ￥105/kg for four-year-old stock, with the average annual economic benefit from four-year cultivation being 2.5 times higher than that of one-year cultivation. As cultivation duration increased, average yearly economic benefit, BCR, and NPV all improved; however, the PBP lengthened. The highest profit and IRR were achieved when P. sinensis was cultured for three years. Economic returns were negative until the first sale of *P. sinensis*.

Table 2. Cost-benefit analysis of two models

		Model		Proportion	
		A	B	A	B
Cost (￥)	Rent	10500	10500	1.57%	12.58%
	Water and electricity	10500	3000	1.57%	3.59%
	Labor	21500	10800	3.20%	12.94%
	Depreciation	40000	1750	5.96%	2.10%
	Facility maintenance	2000	100	0.30%	0.96%
	Seed	383778	28080	57.21%	33.64%
	Feed	197156	22085	29.39%	26.46%
	Fertilizer	-	3450	-	4.13%
	Animal protection products	2700	-	0.40%	-
	Labor insurance supplies and others	2700	3000	0.40%	3.59%
	Total	670834	83465	100.00%	100.00%
Revenue (￥)	*P. sinensis*	809810	68163	-	65.15%
	Rice	-	27000	-	25.80%
	Fish	-	6750	-	6.45%
	Other aquatic products	-	2720	-	2.60%
	Total	809810	104633		100.00%
Benefit (￥)		138976	21168		—
benefit-cost ratio		0.37	0.25		—
Profit rate		0.17	0.20		
Cash flow (￥)		178976	24398		
NPV		1352320.53	246240.96		
IRR		21.64%	53.61%		
PBP (years)		4.47	2		

Note: The prices of juvenile and commercial *P. sinensis* were significantly affected by the market, and the average price provided in this project is from 2019 to 2022.

Table 3. The economic benefit analysis of *P. sinensis* breeding in model B for 2-4 years

Year	*P. sinensis* was sold after culturing for two years		*P. sinensis* was sold after culturing for three years			*P. sinensis* was sold after culturing for four years			
	1st year	2nd year	1st year	2nd year	3rd year	1st year	2nd year	3rd year	4th year
Cost	91985	55333	91985	55333	54666	91985	55333	54666	50576
Revenue	36470	161322	36470	36470	256155	36470	36470	36470	356151
Benefit	-55515	105989	-55515	-18863	201489	-55515	-18863	-18196	305575
Average annual economic benefit	25237		42370			53250			
Benefit/Cost	34.26%		62.93%			84.34%			
Profit rate	25.52%		38.62%			34.31%			
Cash flow	-53765	107739	-53765	-17113	203239	-53765	-17113	-16446	307325
NPV	¥253,592.94		¥444,682.66			¥532,051.09			
IRR	34%		39%			37%			
PBP (years)	2		3			4			

Discussion

Water Quality

Carbohydrates and nitrogenous compounds in the water primarily originated from the bait and feces of *P. sinensis*. The diet of *P. sinensis* contained relatively high crude protein (≥45%) and crude lipid (≥5%) levels. Previous studies have shown that although approximately 90% of dietary nitrogen (N) can be digested, only 20.4% is utilized by *P. sinensis*, with 6.96% excreted as feces, leaving substantial amounts of dietary N to enter the environment (Lei, 2007; Zhang et al., 2016). Thus, large quantities of carbohydrates and nitrogenous compounds were released into the water, increasing TN and COD_{mn} concentrations. This effect was particularly pronounced in Model A during July and September.

In Model A, *P. sinensis* density reached 20,700 ind/ha, with daily feed equivalent to 2–3% of body weight, compared to 2,025 ind/ha and 1–2% daily feed in Model B. This difference meant that substantially more carbohydrates and nitrogenous compounds were introduced in Model A. Moreover, in Model B, the presence of rice over 90% of the area, along with silver carp (*Hypophthalmichthys molitrix*), bighead carp (Ari*stichthys nobilis*), and other feral fish feeding on humus, detritus, and feces, contributed significantly to water purification. Rice, in particular, can directly absorb and assimilate dissolved nitrogen from both water and soil, playing a crucial role in indirectly regulating nutrient levels in aquaculture systems (Li et al., 2021).

Ammonia and nitrite are among the most toxic substances in aquaculture environments. Elevated ammonia levels can reduce disease resistance, impair physiological functions, cause oxidative damage, and even result in mortality. Nitrite toxicity occurs when it oxidizes hemoglobin into forms incapable of carrying oxygen, leading to growth inhibition, physiological disruption, oxidative stress, and increased disease susceptibility in aquatic organisms (Molayemraftar et al., 2022). Although *P. sinensis* demonstrates relatively high tolerance to ammonia and nitrite, excessive concentrations can still cause intoxication or death. Reports indicate that ammonia levels of 100 mg/L can induce poisoning and stress-related diseases, while levels of 1,000 mg/L can be fatal to juveniles (Liu & Li, 2013). Nitrite concentrations above 4 mg/L result in dark red blood upon dissection, a clear sign of nitrite poisoning (Bu, 1999).

In this study, the highest ammonia and nitrite levels were recorded in Model A during July, reaching 0.42 mg/L and 0.056 mg/L, respectively, well below the thresholds for inducing stress in *P. sinensis*. In Model B, concentrations were even lower, indicating no adverse effects on growth performance.

Phytoplankton diversity and abundance serve as important indicators of aquatic ecosystem quality, closely linked to ecosystem health, primary productivity, nutrient cycling, and food web dynamics, particularly in aquaculture ponds. In Model A, Chlorophyta was the dominant group, consistent with patterns observed in ponds cultivating *Eriocheir sinensis*, grass carp, and *Litopenaeus vannamei*, and likely related to higher nitrogen levels in the water (Xiao et al., 2023; Jia et al., 2022). In July and September, Chlorophyta accounted for nearly all phytoplankton (relative abundance≈ 0.99) (Lv, et al., 2024). During this period, elevated TN and COD_{mn} levels mainly derived from *P. sinensis* feed and feces contributed to eutrophication, which in turn promoted the overgrowth of certain phytoplankton groups, reducing overall diversity and dominance patterns. The nutrient enrichment also boosted phytoplankton biomass, with densities in Model A nearly double those observed in Model B (Figure 4E).

In model B, the dominant phytoplankton groups were Chlorophyta, Bacillariophyta, and Cyanobacteria, which aligns with community structures observed in rice–fish, and similar co-culture systems (Liu et al., 2024). The community structure exhibited greater similarity among sampling months characterized by greater H' (Wang, et al., 2025). The dominant algal species included *Chlorella vulgaris*, *Oocystis solitaria* (Chlorophyta), and *Euglena oxyuris* (Euglenophyta). As key primary producers in freshwater ecosystems, higher phytoplankton diversity supports greater primary productivity, enhances ecological resilience, and improves overall ecosystem stability.

Phytoplankton community structure and diversity indices are widely recognized as sensitive indicators of aquatic ecosystem responses to environmental stressors (Essa et al., 2024). In model A, elevated concentrations of carbohydrates and nitrogenous compounds led to extremely low H' values. An H' value below 1.0 is generally considered indicative of pollution in aquaculture ponds (Mukherjee et al., 2024). In July, model A recorded an H' of 0.18, along with other low biodiversity metrics (D= 1.041, J= 0.06), a limited number of species (17), and high phytoplankton density (13.2405×10^4 ind/mL). These findings indicate a degree of pollution and suggest that the ecosystem in model A was relatively fragile.

In comparison, model B showed a greater number of dominant algal species and significantly higher diversity indices compared to model A, indicating improved ecosystem stability and more favorable ecological conditions (Liu et al., 2024). Bunting et al. (2015) further noted that biodiversity in aquatic systems can be enhanced through rice–animal co-culture systems, which also promote resilient and productive agricultural systems (Bunting et al., 2014; Nhan, et al., 2007). Accordingly, the ecosystem in model B was more complex, stable, and better buffered against environmental fluctuations than that in model A. Through symbiotic ecological interactions, the paddy trench water self-regulates to sustain optimal conditions for aquatic organism growth without causing environmental pollution, demonstrating the ecological equilibrium principles of sustainable aquaculture-agriculture systems.

Growth Performance

In model B, the FCR was significantly lower than in model A, whereas the survival rate showed the opposite trend. This difference can be attributed to factors such as stocking density, availability of shelter, and diversity of food sources. High stocking density can deteriorate water quality and cause crowding stress, which suppresses growth. Moreover, it increases energy expenditure in fish, therefore elevating FCR (Lu et al., 2022). *P. sinensis* is a timid species prone to irritation; when frightened, it may attack conspecifics, leading to severe injuries and even mortality.

In model A, the stocking density was 20,700 ind/ha, concealment was limited to bottom silt, and forage was the sole food source. In comparison, in model B, rice plants covered 90% of the pond area, and the stocking density was reduced to 2,025 ind/ha, significantly lowering the likelihood of mutual attacks. Moreover, *P. sinensis* in model B had access to natural prey such as wild fish, shrimp, and river snails, which helped reduce FCR and increase survival rates. Similar findings have been reported in crustacean aquaculture, such as *Eriocheir sinensis*, where high densities promote cannibalism and mortality, while suitable shelters reduce aggression and injury (Zhang et al., 2024).

Production yield, determined by the growth and survival of cultured animals, forms the basis for estimating economic returns in aquaculture operations. Previous studies have shown that although high stocking densities lower growth and survival rates, they can increase production yield per unit area. For example, in mud crab (*Scylla paramamosain*), stocking density is positively correlated with production yield per unit area (Toi et al., 2023). Thus, production plays a decisive role in economic efficiency, and increasing stocking density remains a widely used strategy to boost output despite potential biological trade-offs.

Economic Assessment of Two Models

Pelodiscus sinensis has been regarded as a premium tonic in China since ancient times. In recent years, advancements in cultivation techniques have made it increasingly affordable; however, its price remains higher than that of large-scale aquaculture species, primarily due to greater investment and farming costs. Given that profitability strongly influences farmers' adoption of new agricultural practices, the economic performance of two major *P. sinensis* farming systems was evaluated.

Currently, intensive pond aquaculture dominates freshwater production, contributing approximately 73.39% of total output. Rice–fish co-culture, practiced in China for over 2,000 years, has expanded substantially in recent decades due to its dual benefits for food security and environmental sustainability. By 2021, rice–fish farming accounted for 11.77% of total freshwater aquaculture production, an increase of 8.86% (Yu et al., 2023; Bureau of Fisheries, Ministry of Agriculture and Rural Affairs of the PRC, et al., 2023).

High capital requirements in intensive aquaculture present a challenge for farmers and investors. In model A, investment was more than 22 times greater than in model B, yet only yielded six times the economic return (Table 2). Thus, model A demands large capital inputs and a longer payback period, making it more suitable for large-scale, high-density operations with strong technical expertise and financial capacity (Brande et al., 2023). In comparison, model B required significantly lower investment, with *P. sinensis* sold after only half a year of cultivation and a payback period of just two years. Extending the culture period to 2–4 years increased returns despite lengthening recovery time. This rice–*P. sinensis* co-culture approach is well-suited for small to medium farms, offering both economic and ecological benefits. Many farms under model B also benefit from organic certification for rice and aquatic products, shielding them from market volatility and enhancing profitability. Moreover, China's rice *P. sinensis* fish systems can generate 6–11 times the income of other rice multiple animal models, and they enjoy strong governmental policy and technical support (Li et al., 2023). Over the past decade, integrated farming has represented 9.48% of China's total rice cultivation area, with aquatic product output reaching 11.77% of total freshwater production.

In model A, *P. sinensis* is the sole source of income, making profitability highly sensitive to fluctuations in market price and production. Wholesale prices are volatile, with six major price swings recorded since the onset of commercial aquaculture. During downturns, many farms abandoned this model. Enterprises that remain typically have substantial capital, advanced breeding techniques, and standardized pond systems (Jiang et al., 2014). Production stability is critical; survival and growth rates peak between July and September, but high summer temperatures often degrade water quality, leading to disease outbreaks and mass mortality. Effective management in this period requires strict monitoring of temperature, water quality, and feeding behavior.

Furthermore, model B treats *P. sinensis* as a valuable secondary product while still contributing significantly to revenue. Prices under model B are less affected by market volatility, and production is more climate-resilient. Key production risks include (1) mortality from harvesting machinery when turtles fail to migrate to perimeter trenches during rice harvest and (2) escape losses from inadequate barriers. Although breeding times are longer and yields are lower than in model A, model B products target premium markets such as luxury restaurants, supermarkets, and direct-to-consumer channels. Success in model B depends on maintaining optimal water levels during rice harvest, reinforcing anti-escape measures, and developing stable direct marketing networks.

Conclusion

In conclusion, this study compared two representative cultivation systems for *P. sinensis*: intensive pond monoculture (model A) and rice *P. sinensis* co-culture (model B). Both models maintained water quality within the healthy range for *P. sinensis*, although model A experienced some water pollution during summer high-temperature periods. Growth performance was higher in model B than in model A. Economically, model A represents a high-investment, high-yield approach that is highly sensitive to market fluctuations, making it more suitable for investors with substantial capital and advanced farming expertise. In comparison, model B offers greater system stability, minimal environmental impact, and considerable economic returns, making it ideal for small- and medium-sized farms with lower capital and technical demands, provided they have reliable sales channels. These can be serve as a reference for enterprises' investment choices. When formulating policies, the government should emphasize enhancing water quality regulation in Model A and strengthening brand development for Model B. Providing appropriate subsidies would significantly improve the engagement and motivation of aquaculture farms, thereby advancing the technological development and practical application of both models.

Ethical Statement

The study was approved by the ethical committee of Anhui Academy of Agricultural Sciences (AAAS2023-5).

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Author Contribution

The first author is in charge of the experimental part and most writing. The second, third, forth, fifth, sixth and seventh authors are in charge of the modification and assist the first author in completing the experiments. The eighth, ninth, tenth and twelfth authors are responsible for the cultivation of P. sinensis and provide the production and economic data to the first author. The eleventh, thirteenth and fourteenth authors propose some changes some advices.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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References

Bashir, M.A., Liu, J., Geng, Y., Wang, H., Pan, J., Zhang, D., Rehim, A., Aon, M. & Liu, H. (2020). Co-culture of rice and aquatic animals: An integrated system to achieve production and environmental sustainability. Journal of Cleaner Production, 249, 119310. https://doi.org/10.1016/j.jclepro.2019.119310.

Brande, M.D.R., Santos, D.F.L., Fialho, N.S., Proença, D.C., Ojeda, P.G., Godói, F.C.M., Roubach, R. & Bueno, G.W. (2023). Economic and financial risks of commercial tilapia cage culture in a neotropical reservoir. Heliyon, 9, e16336. https://doi.org/10.1016/j.heliyon.2023.e16336.

Bu, W.S. (1999). The Toxicity of Nitrite to Chinese soft-shelled turtles and its control measures. Inland fisheries, 3, 29.

Bunting, S.W., Mishra, R., Smith, K.G. & Ray, D. (2014). Evaluating sustainable intensification and diversification options for agriculture-based livelihoods within an aquatic biodiversity conservation context in Buxa, West Bengal, India. International Journal of Agricultural Sustainability, 13, 275-293. https://doi.org/10.1080/14735903.2014.966530.

Bureau of Fisheries, Ministry of Agriculture and Rural Affairs of the PRC. (1996-2023). China fishery statistical yearbook, Agricultural Press, Beijing, China.

Chen, B. Y., Huang, P.L., Hou, Y.L., Lan, H.Y., Huang, C.T. & Nan, F.H. (2024). The economic feasibility of aquavoltaics in Taiwan - A case study of whiteleg shrimp (*Litopenaeus vannamei*) culture. Aquaculture, 581, 740454. https://doi.org/10.1016/j.aquaculture.2023.740454.

Essa, D.I., Elshobary, M.E., Attiah, A.M., Salem, Z.E., Keshta, A.E. & Edokpayi, J.N. (2024). Assessing phytoplankton populations and their relation to water parameters as early alerts and biological indicators of the aquatic pollution. Ecological Indicators, 159, 111721. https://doi.org/10.1016/j.ecolind.2024.111721.

Han, M. and Shu, Y. (1995). Atlas of Chinese freshwater organisms, Ocean Press, Beijing, China.

Hou, M., Sun, W., Ma, Y., Ye, H., Zhai, X., Xue, Y., Tang, R., Teng, S., Wu, R. & Luo, H. (2024). Comparative analysis for nutrients, flavor compounds, and lipidome revealed the edible value of pond-cultured male *Pelodiscus sinensis* with different ages. Food Chemistry, 454, 139795. https://doi.org/10.1016/j.foodchem.2024.139795.

Hou, M., Sun, W., Xiao, C., Yang, D., Li Y., Zhai, X., Xue, Y., Wu, R. & Ye, H., and Luo, H. (2024). Integrated metabolome and transcriptome revealed the metabolite characteristics and potential gene regulation mechanism in muscle of different ages male Chinese soft-shelled turtles (*Pelodiscus sinensis*). Aquaculture, 586, 740784. https://doi.org/10.1016/j.aquaculture.2024.740784

Hu, L., Zhang, J., Ren, W., Guo, L., Cheng, Y., Li, J., Li, K., Zhu, Z., Zhang, J., Luo, S., Cheng, L., Tang, J. & Chen, X. (2016). Can the co-cultivation of rice and fish help sustain rice production? Scientific Reports, 6, 28728. https://doi.org/10.1038/srep28728

Huang, C.T., Afero, F., Hung, C.W., Chen, B.Y., Nan, F.H., Chiang, W.S., Tang, H.J. & Kang, C.K. (2022). Economic feasibility assessment of cage aquaculture in offshore wind power generation areas in Changhua County, Taiwan. Aquaculture, 548, 737611. https://doi.org/10.1016/j.aquaculture.2021.737611

Jia, Y., Ma, X., Zhang, W., Dai, D. & Liu, Y. (2022). Characteristics of phytoplankton community in the water of ecological culture ponds for juvenile mitten crabs. Wetland Science, 20(1), 24-33. https://doi.org/10.13248/j.cnki.wetlandsci.2022.01.003

Jiang, Y.L., Li, X., Liu, D., Cheng, Y., Zhang, J., Hou, G. (2014), New Technologies for Healthy Breeding of Chinese soft shelled turtle, *Pelodiscus sinensis*. Jindun Press.

Lei, S. (2007). Effect of water temperature on nitrogen budget in juvenile soft-shelled turtle, *Trionxy sinensis*. Journal of Huazhong Agricultural University, 26(1), 85-89. https://doi.org/10.13300/j.cnki.hnlkxb.2007.01.021

Li, T., Zhang, B., Zhu, C., Su, J., Li, J., Chen, S. & Qin, J. (2021). Effects of an ex situ shrimp-rice aquaponic system on the water quality of aquaculture ponds in the Pearl River estuary, China. Aquaculture, 545, 737179. https://doi.org/10.1016/j.aquaculture.2021.737179.

Li, Y., Wu, T., Wang, S., Ku, X., Zhong, Z., Liu, H. & Li, J. (2023). Developing integrated rice-animal farming based on climate and farmers choices. Agricultural Systems, 204, 103554. https://doi.org/10.1016/j.agsy.2022.103554.

Liu, G., Huang, H. & Zhou, J. (2019). Energy analysis and economic assessment of a rice-turtle-fish co-culture system. Agroecology and Sustainable Food Systems, 43, 299-309. https://doi.org/10.1080/21683565.2018.1510870

Liu, L.X.& Li, H.Q. (2013), The harmful effects of ammonia in greenhouse soft-shelled turtle farming. Scientific Fish Farming, 3, 62.

Liu, Q., Zhang, L., Yang, Y., Zou, J., Yang, Y., Ge, J., Yan, H., He, K., Yang, C., Tahir, R., Zhao, L. & Yang, S. (2024). Ecological performance of an integrated ex-situ rice-fish co-culture system. Aquaculture, 582, 740511. https://doi.org/10.1016/j.aquaculture.2023.740511.

Lu, J., Li, S., He, X., Tang, R. & Li, D. (2022). An in-pond tank culture system for high-intensive fish production: Effect of stocking density on growth of grass carp (*Ctenopharyngodon idella* Valenciennes, 1844) and blunt snout bream (*Megalobrama amblycephala* Yih, 1955). Aquaculture, 549, 737808. https://doi.org/10.1016/j.aquaculture.2021.737808.

Lv, Z.Z., Ma, L., Zhang, H.R., Zhao, Y.Y., Zhang, Q. (2024). Environmental and hydrological synergies shaping phytoplankton diversity in the Hetao irrigation district. Environmental Research, 263, 120142. https://doi.org/10.1016/j.envres.2024.120142

Molayemraftar, T., Peyghan, R., Jalali, M. R. & Shahriari, A. (2022). Single and combined effects of ammonia and nitrite on common carp, Cyprinus carpio: Toxicity, hematological parameters, antioxidant defenses, acetylcholinesterase, and acid phosphatase activities. Aquaculture, 548, 737676. https://doi.org/10.1016/j.aquaculture.2021.737676

Mukherjee, M., Jarzembowski, P., Polechoński, R., & Prećków, J. (2024). Integrated plankton and trace metal analysis as indicators of organic pollution threats from carp-cultured ponds to adjacent ecosystems: Implications for sustainability. Ecological Indicators, 166, 112242. https://doi.org/10.1016/j.ecolind.2024.112242

Nguyen, T.H., Doan, Q.V., Khan, A., Derdouri, A., Anand, P. & Niyogi D. (2024). The potential of agricultural and livestock wastes as a source of biogas in Vietnam: Energetic, economic and environmental evaluation. Renewable and Sustainable Energy Reviews, 199, 114440. https://doi.org/10.1016/j.rser.2024.114440.

Nhan, D.K., Phong, L.T., Verdegem, M.J.C., Duong, L.T., Bosma, R.H. & Little, D.C. (2007). Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: Determinants and the role of the pond. Agricultural Systems, 94, 445-458. https://doi.org/10.1016/j.agsy.2006.11.017.

Nhan, D.T., Tu, N.P.C., & Tu, N.V. (2022). Comparison of growth performance, survival rate and economic efficiency of Asian seabass (*Lates calcarifer*) intensively cultured in earthen ponds with high densities. Aquaculture, 554, 738151.https://doi.org/10.1016/j.aquaculture.2022.73-8151

Qiao, L., Chang, Z., Li, J. & Chen, Z. (2020). Phytoplankton community succession in relation to water quality changes in the indoor industrial aquaculture system for *Litopenaeus vannamei*. Aquaculture, 527, 735441. https://doi.org/10.1016/j.aquaculture.2020.735441.

Shi, H., Zheng, W., Zhang, X., Zhu, M. & Ding, D. (2013). Ecological-economic assessment of monoculture and integrated multi-trophic aquaculture in Sanggou Bay of China. Aquaculture, 410-411, 172-178. http://dx.doi.org/10.1016/j.aquaculture.2013.06.033.

Toi, H.T., Anh, N.T.N., Ngan, P.T.T., Nam, T.N.H. & Hai, T.N. (2023). Effects of stocking densities and seaweed types as shelters on the survival, growth, and productivity of juvenile mud crabs (*Scylla paramamosain*). Egyptian Journal of Aquatic Research, 49, 401-407. https://doi.org/10.1016/j.ejar.2023.01.005.

Wang, F., Lai, N., Cheng, H., Wu, H., Liang, F., Ye, T., Lin, L., Jiang, S., & Luo, J. (2019). Comparative analysis of the nutritional quality and volatile flavor constituents in the muscle of Chinese soft-shelled turtle from three different environments, Food and Fermentation Industries, 45(22), 253-261. https://doi.org/10.13995/j.cnki.11-1802/ts.021276

Wang, F., Zuo, L., Zhou, X., Chen, Z., Xu, X.N., Ji, S.F., Hou, G.J., Zhu, C.J., Zhang, Y., Su, Y.F., Jin, G., Wang, J.J., Gao, Y. Song, G.T. & Jiang, Y.L., (2024). Effects of selective breeding on the nutritional composition of Chinese soft-shelled turtles, *Trion*yx *sinensis*. Pakistan Journal of Zoology, 56 (2), 937-946. https://dx.doi.org/10.17582/journal.pjz/20220920090925

Wang, J., Lai M., Tong, M., Yuan Y., Zhang W. & Liu Q. (2025). Multi-omics insights into seasonal dynamics and interaction networks underpinning planktonic community stability in a subtropical mussel aquaculture system. Water Research, 285, 124142. https://doi.org/10.1016/j.watres.2025.124142

Xiao, S., Liu, X., Lu, S., Zhao, Y., Gu, Z. & Zhou, R. (2023). Water quality and bio-composition in a monoculture and polyculture grass carp pond. Journal of Hydroecology, 44, 79-87. https://doi.org/10.15928/j.1674-3075.202201100013

Xu, Q., Dai, L., Gao, P. & Dou, Z. (2022). The environmental, nutritional, and economic benefits of rice-aquaculture animal coculture in China. Energy, 249, 123723. https://doi.org/10.1016/j.energy.2022.123723.

Yu, H., Zhang, X., Shen, W., Yao, H., Meng, X., Zeng, J., Zhang, G. & Zamanien, K. (2023). A meta-analysis of ecological functions and economic benefits of co-culture models in paddy fields. Agriculture, Ecosystems and Environment, 341, 108195. https://doi.org/10.1016/j.agee.2022.108195.

Yu, X., Hao, X., Dang, Z., & Yang, L. (2023). Report on the development of integrated rice-fisheries in China. China Fisheries, 8, 19-26.

Zhang, G., Jiang, X., Zhou, W., Chen, W., Levy, T. & Wu, X. (2024). Stocking density affects culture performance and economic profit of adult all-female Chinese mitten crabs (*Eriocheir sinensis*) reared in earthen ponds. Aquaculture, 581, 740352. https://doi.org/10.1016/j.aquaculture.2023.740352.

Zhang, J., Hu, L., Ren, W., Guo, L., Tang, J., Shu, M. & Chen, X. (2016). Rice-soft shell turtle coculture effects on yield and its environment. Agriculture, Ecosystems and Environment, 224, 116-122. http://dx.doi.org/10.1016/j.agee.2016.03.045.

Zhang, J., Wang, F., Jiang, Y.L., Hou, G.J., Cheng, Y.S., Chen, H.L. & Li, X., (2017). Modern greenhouse culture of juvenile soft-shelled turtle, *Pelodiscus sinensis*. Aquaculture International, 25, 1607-1624. https://doi.org/10.1007/s10499-017-0137-y

Zhu, Y., Wang, Z. Song, L., Gu, J., Ye, Z., Jin, R. & Wu J. (2023). Spatiotemporal variation of phytoplankton communities and water quality among seaweed, shellfish and cage fish culture systems. Science of the Total Environment, 896, 165305. http://dx.doi.org/10.1016/j.scitotenv.-2023.165305