Pol. J. Environ. Stud. Vol. 34, No. 2 (2025), 1415-1423
DOI: *10.15244/pjoes/187139* ONLINE PUBLICATION DATE: 2024-05-31

Original Research

Impact of Different Modes of Comprehensive Rice Field Planting and Aquaculture Systems in Paddy Fields on Rice Yield, Quality, and Economic Benefits

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Received: 3 February 2024
Accepted: 13 April 2024

Abstract

In order to elucidate the characteristics and variations in rice yield, quality, and economic benefits under different modes of comprehensive rice field planting and aquaculture systems. This study investigated three modes: rice-shrimp (RL), rice-fish (RF), and rice-duck (RC). These were compared with the rice monoculture mode (CK). Results indicate that, compared to CK, three modes significantly increased rice yield. A higher accumulation of dry matter during the main growth stages, a larger LAI, and elevated photosynthetic potential, population growth rate, and net assimilation rate during crucial growth phases. The three modes significantly increased the rice milling yield compared to CK. They increased the content of amylose by 0.90% to 1.29% and improved the protein content by 0.03% to 0.78%. RC demonstrated a more pronounced effect on enhancing the taste quality of rice. Economically, the three modes exhibited a notable increase in economic benefits, ranging from 153.06% to 431.40% compared to CK. This improvement in economic returns was primarily attributed to increased income from aquatic product farming and premium pricing for high-quality rice. In conclusion, the comprehensive rice field planting and aquaculture system represents a stable, quality-enhancing, and efficient rice production method.

Keywords: comprehensive rice field planting and aquaculture system, rice yield, characteristics of photosynthetic matter production, quality, economic benefit

Introduction

Comprehensive rice field planting and aquaculture systems stand as the quintessential model of ecological recycling agriculture in China, with a rich historical legacy [1, 2]. In recent years, propelled by the influence of national policy directives, market dynamics, and the rapid development of integrated farming technologies, comprehensive rice field planting and aquaculture systems have experienced swift dissemination and application. This approach not only effectively mitigates the existing conflicts between agricultural and aquaculture lands but also provides pragmatic solutions

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to various challenges in the current intensive production of rice fields. Issues such as excessive or indiscriminate use of nitrogen fertilizers, low utilization rates of nutrients such as nitrogen, and significant nutrient losses leading to increased surface pollution have been effectively addressed by comprehensive rice field planting and aquaculture [3-5]. This model concurrently tackles challenges such as escalating production costs and diminished overall income. It is a versatile approach that not only yields staple rice for sustenance but also produces safe aquatic (poultry) animal products to meet diverse consumer demands. Simultaneously, it engenders significant ecological, economic, and social benefits [6-8].

Due to differences in resource endowments, market consumption demands, and historical and cultural factors, various types of comprehensive rice field planting and aquaculture models, such as rice-shrimp, rice-fish, rice-loach, rice-snail, and rice-duck, have emerged based on local conditions in different rice-growing regions. The total area of such integrated farming has surpassed 2.33 million hectares nationwide, accounting for over 7% of the total rice cultivation area [9]. Previous research has extensively explored the comprehensive benefits of different comprehensive rice field planting and aquaculture models. Studies by Yang et al. [10] have found that the adoption of comprehensive rice field planting and aquaculture improves soil structure, increases soil nutrients, and effectively promotes the growth and development of rice. Research conducted by Yu et al. [11] reveals that the comprehensive rice and duck cultivation system model enhances rice yield, improves plant population quality, and optimizes indicators such as leaf area index, panicle formation rate, and root system vitality compared to control fields. The adoption of the comprehensive rice and snail cultivation system model in the later stages of rice growth was associated with increased nutrient concentrations in water, elevated organic matter and total nitrogen content in the soil, enhanced total biomass accumulation, and significantly higher yield levels compared to control fields. However, Kou et al. [12] found that the use of models involving rice-shrimp and rice-fish to some extent impacted rice tillering, resulting in varying degrees of yield reduction.

Regarding rice quality, research by Wang et al. [13] suggests that the comprehensive rice and duck cultivation system model improves the appearance, nutritional content, and taste quality of rice, with a noticeable reduction in chalkiness. Chen and his team propose that the comprehensive rice and loach system model significantly reduces rice chalkiness, enhances rice appearance, and increases alkali digestion value and protein content [14]. In terms of economic benefits, some studies indicate that comprehensive rice field planting and aquaculture involve increased labor and capital inputs compared to sole rice cultivation. However, corresponding increases in field outputs result in improved overall economic returns, stimulating the production enthusiasm of rice farmers [15].

Consistent findings in previous research suggest that comprehensive rice field planting and aquaculture play a role in beautifying the rice field environment, improving rice quality, and increasing overall income. However, there is a limited amount of systematic comparative research on the characteristics and differences in rice yield and quality, as well as economic benefits, particularly the formation of photosynthetic substances in rice plants, across different types of comprehensive rice field planting and aquaculture models. Therefore, this study aims to conduct experimental research on major types and locally distinctive comprehensive rice field planting and aquaculture models at the same location. As a comparison with sole rice production, the study systematically investigates the characteristics and differences in yield, photosynthetic substance production, quality, and economic benefits of different types of comprehensive rice field planting and aquaculture models. Among these, the comprehensive rice and shrimp cultivation system model has the largest application area nationwide, accounting for 49.67%, showing strong development momentum, and the crayfish market is booming. The comprehensive rice and fish cultivation system model is a typical traditional model with relatively mature development, characterized by simple field engineering and easy promotion. The comprehensive rice and crab cultivation system model has strong market potential and can meet diverse consumer demands. This experiment aims to provide data support for the integrated innovation of rice quality improvement, high-yield, and efficient cultivation techniques for different types of comprehensive rice field planting and aquaculture models.

Methods and Materials

Test Site and Material

The experimental variety of rice used in this study was Yanfeng 47, and the trials were conducted in 2022 at the experimental base of the Liaoning Academy of Agricultural Sciences in Liaoning Province, China. The region is characterized as a northern single-season rice area, featuring a warm temperate continental semi-humid monsoon climate with an average annual temperature of 8.3ºC, average annual precipitation of 623.6 mm, and average annual sunshine duration of 2787 h. Irrigation was carried out using water from the Liao River, meeting the criteria for irrigation in green food production and freshwater aquaculture. The soil in the experimental area is saline-alkali paddy soil. The organic matter content in the plow layer (0~20 cm) is 25.4 g·kg^{-1}, total nitrogen is 1.38 g·kg^{-1}, total phosphorus is 0.53 g·kg^{-1}, total potassium is 1.75 g·kg^{-1}, absorbable phosphorus content of 26.10·mg kg^{-1} and absorbable potassium content of 128.00 mg·kg^{-1}.

Experimental Design

Three comprehensive rice field planting and aquaculture models – rice-shrimp (RS), rice-fish (RF), and rice-crab (RC – were employed in this experiment, with conventional rice monoculture as a control (CK). For the fields utilizing the comprehensive rice field planting and aquaculture models, a "return" shaped trench, 2.5 m wide and 2 m deep, was dug around the experimental plots. Following the rice harvest, the rice field residues were mechanically crushed and incorporated into the soil by deep plowing. On February 20th, the experimental fields and shrimp ditches were irrigated, maintaining a water depth of 30-40 cm. The entire field was then treated with a mixture of quicklime and tea seed cake to control diseases and wild fish. All rice planting in the different models employed plastic disk seeders for dry nursery seedlings, with sowing on May 20th and mechanical transplanting on June 7th. The machine-transplanted rows were spaced at 30 cm × 10 cm, with an initial seedling rate of 133.4×10^4 plants per hectare. Five sampling points were designated for each treatment, covering an area of 30 m^2 each. At each point, four seedlings were established on each hill after transplanting. The total nitrogen application for the integrated rice field planting and aquaculture models was 226.5 $kg\cdot hm^{-2}$. The base fertilizer included 2250 $kg\cdot hm^{-2}$ of commercial organic fertilizer (with 1% nitrogen) and 300 kg hm^{-2} of compound fertilizer (with 28% nitrogen), totaling 106.5 $kg\cdot hm^{-2}$ of pure nitrogen. Additional nitrogen fertilizer was applied twice during tillering, at an interval of 7 days, with each application consisting of 56.25 $kg\cdot hm^{-2}$ of urea, totaling 51.75 $kg\cdot hm^{-2}$ of pure nitrogen. Panicle fertilizer included 225 $kg\cdot hm^{-2}$ of compound fertilizer (with 15% nitrogen) and 75 $kg\cdot hm^{-2}$ of urea, totaling 68.25 $kg\cdot hm^{-2}$ of pure nitrogen. In the control plots, the total nitrogen application was 311.25 $kg\cdot hm^{-2}$. The base fertilizer included 375 $kg\cdot hm^{-2}$ of compound fertilizer (with 28% nitrogen) and 105 kg hm^{-2} of pure nitrogen. Nitrogen fertilizer was applied twice during tillering, at an interval of 7 days, with each application consisting of 150 kg hm^{-2} and 112.5 $kg\cdot hm^{-2}$ of urea, totaling 120.75 $kg\cdot hm^{-2}$ of pure nitrogen. Panicle fertilizer included 225 $kg\cdot hm^{-2}$ of compound fertilizer (with 15% nitrogen) and 112.5 $kg\cdot hm^{-2}$ of urea, totaling 86.3 $kg\cdot hm^{-2}$ of pure nitrogen. Seedlings (fingerlings) were introduced after rice regreening, with 450 kg of langoustine per hectare for the RS model, 90,000 Taiwan red tilapia per hectare for the RF model, and 9000 crabs per hectare for the RC model. All paddy fields were uniformly sprayed by drone with equal amounts of pesticides commonly used by local farmers.

Measurement Items and Methods

Yield and Its Components

At the maturity stage, a comprehensive survey of 100 hills per plot was conducted to calculate the effective panicle number per hectare. For each plot, an average of 10 hills was selected to investigate the number of grains per panicle and the fertility rate. Additionally, samples of filled grains (rice kernels) were collected from each treatment for a thousand-grain weight assessment. Each weighing was repeated three times, with an error margin within 0.05 g. During the maturity stage, a designated area of 10 m^2, excluding border rows, was identified in each plot. Harvesting was performed to measure the actual yield, which was then converted to the moisture content of 14.5% to obtain the adjusted yield. The entire process was repeated across all replicates to ensure data accuracy and reliability.

Dry Matter Weight

At different growth stages – 25 days after transplanting, the jointing stage, heading stage, and maturity stage – five representative hills were selected from each plot based on the average tiller number. The Leaf Area Index (LAI) was determined using the proportional method. For each selected plant, samples were collected and subjected to blanching at 105°C for 30 min, followed by drying at 80°C to a constant weight. The dry matter accumulation was then measured, providing insights into the physiological characteristics of the plants at various critical developmental stages. This process was conducted with meticulous attention to accuracy, ensuring robust and reliable data for analysis.

Rice Quality

Following rice harvesting, the paddy samples from each plot were dehulled and naturally dried until the moisture content reached below 14%. Subsequently, a NP-4350 air-screen cleaner was employed for winnowing, adhering to the standards outlined in the national regulation GB/T17891-2017 for high-quality rice. Parameters such as brown rice rate, milled rice rate, head rice rate, chalky rice rate, and chalkiness were determined. The protein content of the rice was quantified using the semi-micro Kjeldahl method, while the straight-chain starch content was measured using the iodine blue colorimetric method. The taste profile and related attributes were evaluated using a rice taste analyzer (STA1A, produced by Satake Corporation, Japan), which automatically assessed indicators such as rice hardness, appearance, and balance and provided an overall taste score. This comprehensive analysis aimed to provide a detailed characterization of the rice quality and taste attributes for each treatment group.

Data Statistics and Analysis

$$\text{Population spikelets per Hectare } (\times 10^4 \text{ hm}^{-2}) = \text{Number of panicles} \times \text{number of grains per panicle}$$

$$\text{Decrease rate of leaf area index (LAI day}^{-1}\text{) during Grain} - \text{Filling period} = |LAI_2 - LAI_1|/(t_2 - t_1)^{-1}$$

Here, LAI_1 and LAI_2 represent the Leaf Area Index measured during the heading and maturity stages, and t_1 and t_2 denote the corresponding time points.

$$\text{Photosynthetic Potential } (\text{m}^2 \cdot \text{day} \cdot \text{hm}^{-2}) = 0.5 \times (L_1 + L_2) \times (t_2 - t_1)$$

In this equation, L_1 and L_2 represent the Leaf Area measured at two different time points, and t_1 and t_2 are the corresponding time values.

$$\text{Population Growth Rate } [\text{g}(\text{m}^2 \cdot \text{day})^{-1}] = (W_2 - W_1)/(t_2 - t_1)$$

Here, W_1 and W_2 indicate the dry matter weight measured at two different time points, and t_1 and t_2 represent the corresponding time values.

$$\text{Net Assimilation Rate } [\text{g}(\text{m}^2 \cdot \text{day})^{-1}] = [(\ln LA_{I2} - \ln LAI_1)/(LAI_2 - LAI_1)] \times W_2 - W_1)/(t_2 - t_1)$$

In this formula, W_1 and W_2 are the dry matter weights measured at two different time points, t_1 and t_2 represent the corresponding time values, and LAI_1 and LAI_2 are the Leaf Area Index values measured at the same time points.

Using DPS software [16], the trial's raw data were submitted to a one-way ANOVA after being tallied using Excel 2019.

Results

Yield and Its Components

As depicted in Table 1, compared to the control group (CK), the number of spikes in the RL, RF, and RC treatments increased by 2.6%, 4.0%, and 9.8%, respectively. Notably, the difference between the RC treatment and the CK treatment was particularly significant. Regarding the number of grains per spikelet, the RL, RF, and RC treatments showed slight increases compared to the CK treatment, with increments of 1.2%, 0.7%, and 3.5%, respectively. Although the magnitude of the increase was modest, the difference between the RC treatment and the CK treatment remained notably significant. In terms of increasing the total number of spikelets, the effect of RC treatment was most remarkable, exhibiting a 19.1% difference compared to CK treatment. Additionally, RL and RF treatments increased by 8.5% and 11.2%, respectively. The differences in the percentage of filled grains among treatments were relatively small, but the effect of RC treatment was particularly significant, showing a 2.4% increase compared to CK treatment. Although the differences in 10^3-grain weight among treatments were small, the effect of RC treatment was particularly significant, with a 2.6% increase compared to CK treatment. Actual yield serves as a direct indicator of rice production. Compared to CK, the actual yield increased by 2.6%, 4.0%, and 9.8% in the RL, RF, and RC treatments, respectively. This increase is associated with multiple factors contributing to yield, including the number of spikelets, total spikelets, and percentage of filled grains. Notably, the RC treatment exhibited the largest increase in actual yield, emphasizing the significant effectiveness of the comprehensive rice and crab cultivation system model in enhancing rice production.

Leaf Area Index and Leaf Area Decay Rate

According to the data presented in Table 2, it is evident that the comprehensive rice field planting and aquaculture system have a certain impact on the Leaf Area Index (LAI) and the rate of leaf area decline in rice. In comparison to the CK, the LAI in RL, RF, and RC modes increased during the tillering and heading stages, with a more pronounced increase observed in the RF and RC modes during the maturation stage. Additionally, the RC mode exhibited a significant reduction in the rate of leaf area decline compared to the control. After 25 days of planting, the LAI in the RL mode increased by 2.95% compared to the CK mode, the RF mode increased by 3.81%, and the RC mode increased by 6.43%. During the jointing stage, the RL mode showed a 3.57% increase

Table 1. Rice yield and yield components under different modes of comprehensive planting-breeding in paddy fields.

Type	Number of spikes ($\times 10^4$ m^{-2})	Number of grains per spikelet	Total number of spikelets ($\times 10^4$ hm^{-2})	Filled grain percentage (%)	10^3-grain weight (g)	Actual yield (t·hm^{-2})
CK	350.04c	106.20b	3830.21c	91.26a	25.42b	9.05c
RL	353.60c	108.32b	3894.49b	92.12a	26.61a	9.16bc
RF	356.60bc	108.13b	3903.06b	92.48a	26.10a	9.25b
RC	378.57a	117.02a	4430.02a	92.60a	26.61a	9.83a

Note: Values followed by different lowercase letters are significantly different at the 5% probability level.

Table 2. Leaf area index and decreasing rates of leaf area of rice at main growth stages.

Type	25 days after planting	Jointing	Heading	Maturity	Decreasing rate of leaf area (LAI·day^{-1})
CK	1.72b	3.25c	6.68c	2.69b	0.0662c
RL	1.76b	3.29bc	6.91b	2.73b	0.0675b
RF	1.78b	3.36b	7.07ab	2.80ab	0.0692b
RC	1.89a	3.51a	7.22a	2.92a	0.0717a

Note: Values followed by different lowercase letters are significantly different at the 5% probability level. BBCH codes for rice growth stage: '25 days after planting'-1.12; 'Jointing'-3.30; 'Heading'-5.51; 'Maturity'-8.89.

in LAI, the RF mode showed a 6.25% increase, and the RC mode showed a 9.84% increase compared to the CK mode. In the heading stage, the RL mode exhibited a 3.67% increase, the RF mode showed a 7.41% increase, and the RC mode showed a 10.96% increase in LAI compared to the CK mode. In the maturation stage, the RL mode increased by 2.63%, the RF mode increased by 6.25%, and the RC mode increased by 9.84% in LAI compared to the CK mode. Regarding the rate of leaf area decline, the RL mode decreased by 1.98%, the RF mode decreased by 2.27%, and the RC mode decreased by 3.18% compared to the CK mode.

Dry Matter Accumulation

As demonstrated in Table 3, the comprehensive rice field planting and aquaculture systems exhibit a discernible influence on the dry matter accumulation and harvest index of rice. Prior to maturation, the dry matter content in the RL, RF, and RC modes consistently equals or surpasses that of the CK. Similarly, in terms of harvest index, all three comprehensive rice field planting and aquaculture systems consistently outperform or match the control. After 25 days of cultivation, the dry matter content in the RL mode increased by 1.73% compared to the CK mode, the RF mode increased by 1.79%, and the RC mode increased significantly by 5.19%. During the tillering stage, the RL mode showed a slight decrease of 0.36%, the RF mode increased by 3.23%, and the RC mode exhibited a substantial increase of 7.69% in dry matter content compared to the CK mode. In the heading stage, the RL mode exhibited a modest increase of 0.36%, the RF mode increased by 3.81%, and the RC mode demonstrated a substantial increase of 8.94% in dry matter content compared to the CK mode. Finally, at the maturation stage, the RL mode increased by 2.85%, the RF mode increased by 4.79%, and the RC mode demonstrated a remarkable increase of 11.24% in dry matter content compared to the CK mode. In terms of the harvest index, the RL mode increased by 1.41%, the RF mode increased by 1.79%, and the RC mode exhibited a significant increase of 2.24% compared to the CK mode.

Dry Matter Accumulation and Its Proportion at Each Major Fertility Stage

As illustrated in Table 4, it can be observed that the comprehensive rice field planting and aquaculture systems have a certain impact on the dry matter accumulation of rice at different growth stages. Across all stages, the RC mode consistently exhibits higher dry matter content than other treatments, while from the heading to maturation stage, the RF mode also surpasses other treatments in dry matter accumulation. From sowing to jointing, the dry matter content in the RL mode increased by 0.84% compared to the CK (control) mode, the RF mode increased by 1.38%, and the RC mode exhibited a significant increase of 4.49% in dry matter content. From jointing to heading, the dry matter content in the RL mode increased by 0.19%, the RF mode increased by 2.59%, and the RC mode exhibited a significant increase of 3.89% in comparison to the CK mode. From heading to maturity, the dry matter content in the RL mode increased by 3.22%, the RF mode increased by 5.71%, and the RC mode exhibited a substantial increase of 6.76% compared to the CK mode. Notably, the RC mode consistently outperformed

Table 3. Dry matter accumulation and harvest index of rice at the main growth stages.

Type	25 days after planting	Jointing	Heading	Maturity	Harvest index (%)
CK	1.79b	4.15c	10.90c	17.52d	48.69b
RL	1.84b	4.12c	10.92c	18.27c	50.14a
RF	1.85b	4.23b	11.56b	18.85b	50.46a
RC	2.00a	4.58a	12.32a	20.19a	50.88a

Note: Values followed by different lowercase letters are significantly different at the 5% probability level. BBCH codes for rice growth stages: '25 days after planting'-1.12; 'Jointing'-3.30; 'Heading'-5.51; 'Maturity'-8.89.

Table 4. Dry matter accumulation and rate at the different main growth stages of rice.

Type	Sowing-Jointing		Jointing-Heading		Heading-Maturity	
	Dry matter accumulation ($t\cdot hm^{-2}$)	Ratio (%)	Dry matter accumulation ($t\cdot hm^{-2}$)	Ratio (%)	Dry matter accumulation ($t\cdot hm^{-2}$)	Ratio (%)
CK	4.03b	22.99	6.96c	38.39	6.62d	37.79
RL	4.11b	22.69	6.98c	38.84	6.95c	38.48
RF	4.15b	22.88	7.33b	38.86	7.29b	38.67
RC	4.58a	22.74	7.74a	38.42	7.82a	38.83

Note: Values followed by different lowercase letters are significantly different at the 5% probability level. BBCH codes for rice growth stages: ‘Sowing-Jointing’-10~30; ‘Jointing-Heading’-31~50; ‘Heading-Maturity’-51~89.

other modes in dry matter accumulation across all stages, indicating its positive impact on enhancing the overall growth performance of rice.

Photosynthetic Potential, Population Growth Rate, and Net Assimilation Rate

As depicted in Table 5, an overall analysis reveals that, in comparison to the CK treatment, RC demonstrates superior performance in terms of rice photosynthetic potential, crop growth rate, and net assimilation rate, while RF follows, and RL exhibits the least favorable outcomes. Regarding photosynthetic potential, RC mode consistently recorded the highest values at three periods (sowing-jointing, jointing-heading, and heading-maturity), showing respective increases of 8.96%, 10.58%, and 16.39% compared to the CK. RF mode also displayed relatively high values in photosynthetic potential, while RL mode exhibited slightly lower values compared to the control. In terms of crop growth rate, RC mode demonstrated the highest rates during the three periods (sowing-jointing, jointing-heading, and heading-maturity), with increases of 3.39%, 17.56%, and 20.99% compared to the CK. RF mode showed a slightly lower crop growth rate during sowing-jointing but surpassed the CK during jointing-heading and heading-maturity. RL mode consistently displayed lower crop growth rates across all three stages compared to the CK. For net assimilation rate, RC mode consistently exhibited the highest rates during the three periods (sowing-jointing, jointing-heading, and heading-maturity), with respective increases of 8.88%, 4.58%, and 7.88% compared to the CK. RF mode’s net assimilation rate was comparable to the CK during sowing-jointing but slightly higher during jointing-heading and heading-maturity. The RL mode consistently showed lower net assimilation rates across all three stages compared to the CK.

Processing and Appearance Quality

Based on the data presented in Table 6, it is evident that different comprehensive rice planting and aquaculture system modes in rice paddies have varying effects on the milling and visual quality of rice. In terms of milling quality, the RC mode exhibited the highest milled rice rate, reaching 76.78%. Compared to CK, with rates of 74.04%, there was an improvement of 2.74% in the milled rice rate. The RF mode also showed higher rates compared to the CK, with milled rice rates of 75.09%. Conversely, the RL mode demonstrated slightly lower milled rice rates compared to the CK. Regarding visual quality, the RC mode exhibited the highest chalky rice rate and chalkiness degree, recording 13.62% and 4.63%, respectively. In comparison to the CK with rates of 12.26% and 4.17%, there was an increase of 1.36% and 0.46% in chalky rice rate and chalkiness degree. The RF mode also showed higher rates compared to the CK, with chalky rice and chalkiness rates of 12.54% and 4.28%, respectively. On the other hand, the RL mode demonstrated slightly lower chalky rice and chalkiness rates than the CK.

Table 5. Photosynthetic potential, crop growth rate, and net assimilation rate of rice.

Type	Photosynthetic potential ($\times10^4$ $m^2\cdot day\cdot hm^{-2}$)			Crop growth rate ($g\cdot m^{-2}\cdot day^{-1}$)			Net assimilation rate ($g\cdot m^{-2}\cdot day^{-1}$)		
	Sowing-Jointing	Jointing-Heading	Heading-Maturity	Sowing-Jointing	Jointing-Heading	Heading-Maturity	Sowing-Jointing	Jointing-Heading	Heading-Maturity
CK	113.75b	134.33b	276.42c	5.76b	25.44c	11.03c	2.15b	5.42b	2.56c
RL	114.10b	135.95b	286.20b	5.93b	25.85b	11.53b	2.09b	5.38c	2.58bc
RF	115.15ab	137.70b	290.10b	5.94b	25.48c	11.34c	2.16b	5.41b	2.61b
RC	122.85a	149.80a	303.30a	6.54a	28.67a	13.12a	2.34a	5.59a	2.76a

Note: Values followed by different lowercase letters are significantly different at the 5% probability level. BBCH codes for rice growth stages: ‘Sowing-Jointing’-10~30; ‘Jointing-Heading’-31~50; ‘Heading-Maturity’-51~89.

Table 6. Milling and appearance quality of rice.

Type	Milled rice rate (%)	Chalkiness percentage (%)	Chalkiness degree (%)
CK	74.04b	12.26c	4.17c
RL	73.65b	12.50b	4.23bc
RF	75.09ab	12.54b	4.28b
RC	76.78a	13.62a	4.63a

Nutritional Quality and Flavor Values

The data presented in Table 7 reveals notable differences in the content of amylose, protein, and sensory attributes among rice paddies subjected to different comprehensive rice planting and aquaculture systems. In terms of amylose content, the RC mode exhibited the highest content at 10.51%, surpassing the CK mode by 1.16%. The RF mode followed closely with a content of 10.64%, a 1.29% increase compared to the CK mode. The RL mode had the lowest amylose content at 10.25%, representing a 0.9% increase over the CK mode. Regarding protein content, the RC mode demonstrated the highest content at 7.95%, exceeding the CK mode by 0.78%. The RF mode followed with a content of 7.36%, a 0.29% increase compared to the CK mode. The RL mode had the lowest protein content at 7.20%, showing a slight increase of 0.03% over the CK mode. In terms of sensory attributes, the RC mode achieved the highest sensory score at 80.80, surpassing the CK mode by 8.46 points. The RF mode followed with a score of 79.83, a 7.50-point increase compared to the CK mode. The RL mode scored the lowest at 75.71, representing a 3.37-point increase over the CK mode.

Economic Benefit

Based on Table 8, it is evident that all three comprehensive rice planting and aquaculture system modes contribute to increased rice production values. RL, RF, and RC modes exhibit respective improvements of 1.21%, 2.21%, and 8.62% compared to CK. When considering the aquatic product values, RC demonstrates the highest production value, followed by RL, while RF has the lowest production value. Analyzing the overall production costs provides insights into the profitability of each mode. Among them, RC mode yields the highest profit, followed by RL, and RF mode ranks third. In comparison to CK, these three modes enhance the final profit by 431.40%, 372.81%, and 153.06%, respectively. This economic analysis underscores the economic viability of integrated rice farming, with the RC mode emerging as the most financially rewarding among the studied modes. The substantial increase in profits indicates the potential for integrated farming to provide economic benefits beyond traditional rice cultivation methods.

Discussions and Conclusions

Previous research has extensively investigated the effects of various integrated farming modes, such as rice-duck farming, which demonstrated increased rice yield due to the beneficial effects of ducks stimulating robust rice growth [17, 18]. However, it also highlighted the complexity of achieving optimal yields in different contexts. Our research focused on three comprehensive rice planting and aquaculture systems: crab, fish, and shrimp, examining their influence on rice yield. Our results demonstrate that the three modes positively

Table 7. Amylose content, protein content, and taste value of rice.

Type	Amylose content (%)	Protein content (%)	Taste value	Appearance	Hardness	Viscosity	Balance degree
CK	9.35c	7.17c	72.34c	7.8b	5.7b	7.2b	7.8b
RL	10.25b	7.20c	75.71b	7.8b	5.8ab	7.7b	7.5bc
RF	10.64a	7.36b	79.83a	8.1b	5.9ab	7.8b	7.2c
RC	10.51a	7.95a	80.80a	8.5a	6.2a	8.7a	8.6a

Table 8. Economic benefits of different modes of comprehensive planting-breeding in paddy. fields (Yuan·hm^{-2}).

Type	Production value		Investment								Profit
	Paddy	Aquatic products	Seed	Fry	Fertilizer	pesticide	Forage	Machinery	Labor	Other	
CK	23457	-	540	-	1950	2205	-	2100	2100	675	13887
RL	23742	79800	540	25950	1950	2205	750	2400	3000	1088	65659
RF	23976	36750	540	13500	1950	2205	900	2400	3000	1088	35143
RC	25479	87000	540	26300	1950	2205	1200	2400	3000	1088	73796

impact rice yield, with increased panicle and grain numbers, heightened leaf area index, and enhanced photosynthetic efficiency. Additionally, the study reveals that rice quality is influenced by cultivation practices, with three modes showing improvements in certain quality traits, such as whole and head rice rates. These findings are consistent with earlier research on rice-duck integrated farming, emphasizing the potential of integrated farming in optimizing rice quality.

Economically, integrated farming is shown to increase rice production value, with the rice-shrimp mode exhibiting the highest economic benefits despite higher initial investments. This aligns with previous studies indicating that integrated farming can be a viable alternative to traditional rice monoculture, offering increased economic returns [19]. Furthermore, our research highlights the need for continued innovation in cultivation techniques to optimize integrated farming practices. While these modes enhance certain rice quality traits, such as improved appearance and cooking quality, there is room for further improvement. Mechanization and streamlined production techniques are identified as essential components for maximizing efficiency and reducing labor costs.

In conclusion, integrated farming, particularly the crab-rice mode, emerges as a promising approach for enhancing rice yield and quality, presenting economic advantages. However, the success of integrated farming depends on factors such as technological proficiency, cost-effectiveness, and market conditions. It is crucial to tailor integrated farming practices to local resources and market demands for sustainable and profitable outcomes. The study emphasizes the importance of ongoing research and technological innovation to advance integrated farming methods and address challenges in the evolving landscape of rice cultivation.

Acknowledgments

This work was supported by the Liaoning Provincial Science and Technology Program “Creation and Application of Ecological Pollution Control System for Optimizing Biodiversity Structure in Rice Field Ecosystems”(2022JH2/101300161).

Conflict of Interest

The authors declare no conflict of interest.

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