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Regulatory Effects of Integrated Rice-Farming Systems on Soil Nutrient Dynamics

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Abstract Integrated rice farming combines rice planting with aquaculture or livestock farming to form a benign cycle of farmland ecosystems. This study systematically analyzes the regulatory effects of typical models such as rice-duck, rice-fish, and rice-crab on paddy soil organic matter, nitrogen, phosphorus, and potassium nutrients, and trace elements, explores key mechanisms such as animal manure return to the field, water disturbance, and microbial activity, and verifies the actual effects of integrated farming in improving acidic soil and enhancing fertility stability through practical cases such as Deqing Xingqing Family Farm. At the same time, its green agricultural value is evaluated from the perspectives of reducing weight and pollution, efficient nutrient utilization, and ecosystem services. Studies have shown that integrated rice farming plays a positive role in promoting the dynamic optimization of soil nutrients and improving soil health, providing strong support for the sustainable development of agriculture. Finally, this study proposes suggestions such as strengthening mechanism research and policy support, and promoting regional adaptation models, in order to promote the scientific application and large-scale promotion of integrated rice farming models.
Keywords Integrated rice farming; Soil nutrients; Rice-duck farming; Rice-fish symbiosis; Organic matter; Nutrient cycle

1 Introduction

Integrated rice farming refers to the introduction of aquatic animals (such as fish, shrimp, crab) or poultry (such as duck) for synchronous farming on the basis of traditional rice field planting, so as to achieve a three-dimensional agricultural model of "one water for two uses, one field for multiple harvests". This model originated from the ancient Chinese practice of rice-fish symbiosis, which can be traced back to the tradition of rice-fish farming more than 2 000 years ago. After the founding of New China, rice-fish farming was restored and developed, and in 2005 it was listed as the first batch of global important agricultural cultural heritage by the Food and Agriculture Organization of the United Nations (Zhejiang Qingtian rice-fish symbiosis system). Since the 21st century, driven by the concepts of ecological agriculture and circular agriculture, the traditional "rice-fish farming" has gradually expanded into a richer "integrated rice farming" model, including rice-fish, rice-shrimp, rice-crab, rice-duck and other symbiotic combinations. In the past decade, the scale of integrated rice farming in my country has expanded rapidly, and the model has been continuously innovated and upgraded. In 2018, the area of integrated rice farming in China exceeded 2.26 million hectares, accounting for about 7% of the total rice planting area. The government attaches great importance to this green efficiency-enhancing technology and has introduced a number of supporting policies to promote its industrial development. Integrated rice farming has become one of the important production methods of rice farming systems in my country (Dou et al., 2024).

Paddy field soil is the material basis of rice production, and its fertility level directly affects rice yield and quality (Sun et al., 2025). However, long-term monoculture of rice often relies on high-intensity fertilizer input to maintain yield, resulting in a decrease in soil organic matter, an imbalance of nitrogen and phosphorus nutrients, and an increase in environmental problems. Poor soil nutrient management can cause soil degradation and a decrease in productivity, as well as agricultural non-point source pollution such as nitrogen leaching and phosphorus enrichment. Improving the sustainability of soil nutrient supply, nutrient cycle efficiency, and reducing loss are key issues that must be addressed to achieve green yield increases in rice farms (Miao et al., 2025). The integrated rice farming model introduces animals to achieve multi-level recycling of nutrients within the rice field ecosystem, and is considered an effective way to improve the efficiency of soil nutrient management. Animal activities and metabolism add organic nutrients to the soil, promote soil nutrient turnover, and improve soil physical and chemical properties, which is expected to enhance soil fertility and buffering capacity.

A large number of field studies have shown that integrated farming systems such as rice-fish and rice-duck have complex effects on soil nutrient cycles and the environment while increasing yields. This study will systematically sort out the characteristics of soil nutrient content and dynamic changes under the integrated farming model of rice fields, summarize the regulatory role of animal farming on the soil nutrient cycle mechanism, evaluate its sustainable benefits and practical significance, discuss the impact of integrated farming on soil organic matter and major nutrient content, and its regulatory role on nutrient cycles through mechanisms such as manure return to the field, water disturbance, and microbial activation, and analyze it in combination with practical cases, pointing out the current bottlenecks and future development suggestions. This study hopes to provide a scientific basis for a deep understanding of how integrated farming in rice fields regulates soil nutrient dynamics and provide a reference for green agricultural practices.

2 Typical Models of Integrated Rice Farming

2.1 Rice-duck, rice-fish, and rice-crab symbiotic systems

Rice-duck farming refers to releasing a moderate amount of domestic ducks during the growing season of rice fields, allowing them to move freely to eat weeds and pests, and excrete feces to fertilize the fields, so as to achieve a mutually beneficial symbiosis between rice and domestic ducks. Ducks "weed and control insects, trample and loosen the soil, and return manure to the fields" in rice fields, which is one of the most widely used ecological farming models in my country. Studies have shown that rice-duck symbiosis can effectively control pests such as barnyard grass and rice leafhoppers, reduce the application of pesticides, and have a positive impact on soil nutrients (Lan et al., 2021). Rice-fish symbiosis has a long history. Fish ditches or fish ponds are dug in rice fields to raise fish (such as carp, crucian carp, etc.). Fish feed on field bait, and their excrement provides nutrients for rice. Rice and fish promote each other, which has the effect of "rice, millet and fish fertilizer". Modern rice-fish farming introduces specialized species such as loach and tilapia, which significantly increases protein output per unit area. Fish farming in rice fields has become a large-scale industry in southern China, which has dual benefits in increasing farmers' income and grain production. Rice-crab farming is the cultivation of crustaceans such as river crabs in rice fields. This model is common in the middle and lower reaches of the Yangtze River. Crabs are raised by digging ditches in rice fields. Crabs prey on fish, insects and snails in the fields, loosen the soil, and their excrement can fertilize the soil. Studies have shown that the soil organic matter and total nitrogen in rice-crab fields are significantly higher than those in monoculture rice fields (Xu et al., 2025). Different integrated farming models are based on the shallow water ecology of rice fields, organically combining rice planting with aquaculture, but the types of animals introduced are different, and the functional emphasis is slightly different.

2.2 Ecological characteristics of integrated cultivation

The integrated farming model of rice fields forms a rice-animal symbiotic micro-ecological system with ecological characteristics of integrated farming and recycling. First, the food chain is expanded: rice provides habitats and some biomass (such as Cordyceps) for animals, and animals eat weeds, pests and feed in the field, producing feces that are decomposed and used by rice, forming a material cycle. For example, in the rice-duck farming system, ducks feed on weeds and snails in the field, reducing the consumption of soil nutrients by weeds. At the same time, duck manure contains about 1.0% to 1.5% nitrogen, which directly supplements soil nutrients (Lan et al., 2021). Secondly, diversity is improved: rice fields are transformed from a single rice crop system to a multi-species coexistence system such as rice-fish/duck, and the biodiversity of microorganisms, benthic animals and other organisms in the soil and water bodies increases, which helps maintain ecological balance (Liao et al., 2019). Thirdly, energy utilization efficiency is improved: integrated rice farming converts part of the unused energy (such as aquatic biological resources) in the original rice field monoculture system into aquatic or livestock output, and the multi-level utilization of energy significantly improves the energy conversion efficiency of the rice field ecosystem. Studies have shown that rice-fish symbiosis can effectively recycle nutrients and energy wasted in rice field monoculture for fish production, thereby increasing the overall output rate of the ecosystem. The integrated farming system has a strong ecological regulation function. For example, the activities of ducks and fish can destroy the breeding environment of pests and diseases, inhibit the occurrence of rice blast and insect pests, and reduce the input of pesticides; the stirring of animals can promote soil aeration and nutrient mineralization, and maintain the dynamic balance of soil fertility. These ecological characteristics enable the integrated farming model of rice fields to achieve agricultural production while taking into account environmental friendliness and ecological service functions, and is known as the "micro-ecological cycle in rice fields."

2.3 Fertilization differences across models

Due to the different types and densities of animals introduced, the fertilization and field management strategies of integrated farming in rice fields are somewhat different. Generally speaking, integrated farming can partially replace the application of chemical fertilizers, but different modes require reasonable adjustment of fertilizer input to avoid excess or insufficient nutrients. In rice-duck farming, since ducks mainly feed on field feed and rarely receive supplementary feeding, the amount of their feces returned to the field is limited, and generally a certain amount of base fertilizer and topdressing fertilizer still need to be applied according to soil testing formula. However, practice shows that compared with conventional rice farming, the amount of nitrogen applied to rice-duck fields can be reduced by 20% to 30%, and a comparable yield can be obtained without the application of herbicides and pesticides. Rice-fish and rice-crab models often require feeding, and the animal's food conversion rate is limited, so leftover bait and feces become an important source of nutrients in the field. This type of model can appropriately reduce the amount of chemical fertilizer application and emphasize the application of organic fertilizer or bio-organic fertilizer to cooperate with aquaculture. For example, it is recommended to reduce chemical nitrogen fertilizer by more than 50% in rice-shrimp farming fields and replace it with organic fertilizer to prevent the superposition of feed nitrogen and fertilizer nitrogen from causing nutrient excess. Xu et al. (2025) found in the Erhai Lake Basin that partially replacing chemical fertilizer with organic fertilizer can significantly reduce nitrogen and phosphorus concentrations in field water while maintaining yield in rice-duck farming fields, reducing environmental risks. Different animal species and breeding densities also affect soil nutrient management strategies. For example, Zhang et al. (2021) compared the effects of different duck breeds in the rice-duck symbiotic system and found that local duck breeds with strong adaptability had more obvious improvements in soil physical and chemical properties, and higher rice yields and economic benefits. Too high density may lead to excessive nutrient accumulation and oxygen debt, aggravating soil reduction, and need to be carefully controlled. Ni et al. (2022)'s survey showed that in Hubei Province, when the area of the breeding ditch dug for shrimp farming in rice fields accounted for more than 20%, the rice yield decreased significantly, indicating that excessive breeding intensity may weaken the planting benefits. Therefore, for different integrated breeding modes, it is necessary to optimize the fertilization system, such as adjusting the ratio of base and topdressing, increasing the application of organic fertilizers and slow-release fertilizers, etc., to adapt to the nutrient supply and demand characteristics of the breeding system and achieve a dynamic balance between nutrient input and output.

3 Effects on Soil Nutrient Content

3.1 Organic matter accumulation and humus enrichment

Integrated farming in rice fields is generally observed to increase soil organic matter content and improve soil humus levels. The main reason is that animal feces, bait residues and aquatic organism remains are continuously returned to the soil, supplementing exogenous organic matter. Compared with conventional rice fields, the soil organic carbon content of integrated farming rice fields is usually significantly higher. For example, Li et al. (2025) found in a field experiment in Zhejiang that compared with single-season rice, rice-fish farming can increase the organic carbon of the surface soil by 4.8%~13.6% (2-year and 5-year farming); when the farming lasts for more than 15 years, the increase in soil organic carbon is as high as 23%~32%. Another study in Hunan also showed that long-term rice-fish symbiosis can increase the organic matter content of rice field soil by 18%~42% compared with single farming. Rice-duck farming also significantly accumulates organic matter. Lan et al. (2021) reported that the soil organic carbon in rice-duck symbiotic fields increased by about 10% compared with conventional rice fields, indicating that the addition of duck manure and aquatic biomass effectively supplemented the soil organic matter. Under the conditions of integrated farming, the composition of soil humus also tends to be optimized. A study found through infrared spectroscopy that the proportion of humus components such as humic acid and fulvic acid in rice-shrimp symbiotic soil increased, indicating that the quality of soil organic matter has improved (Xu et al., 2025). Humus is the cornerstone of soil fertility, and its increase helps to improve the soil's water and fertilizer retention capacity and buffering performance. It is worth noting that the large accumulation of organic matter mostly occurs in the 10 cm~20 cm soil layer on the surface of the rice field, which is related to the fact that animal activities and residues are mainly distributed in the surface layer. Therefore, how to evenly mix the accumulated organic matter in the surface layer into the deep layer through appropriate tillage measures is also one of the issues that need to be paid attention to in the management of integrated farming soil.

3.2 Dynamics of macronutrients: nitrogen, phosphorus, potassium

The impact of integrated rice farming on the content of nitrogen (N), phosphorus (P) and potassium (K) in the soil is relatively complex. The overall trend is that the total nutrients in the soil increase, and the level of available nutrients changes dynamically during the growth period and is higher than that of the single-crop control. In terms of nitrogen, due to the nitrogen content of animal excrement, the total nitrogen content of the soil in integrated farming fields is often higher than that in conventional rice fields.

According to the experiment of Li et al. (2020), the system of mixed planting of multiple varieties of rice combined with rice-duck farming increased the total nitrogen content of the soil by 4.3%~17.9% in the mid-season compared with single planting, and the soil alkaline nitrogen increased by 4%~18%. Yan et al. (2023) compared the rice-duck-crayfish ternary ecological farming with the single and double rice systems, and found that the total nitrogen in the 0 cm~10 cm soil layer of the farming system was 8.5%~28.4% higher than the control, and the available nitrogen increased by 6.9%~22.7%. These data show that integrated farming can increase soil nitrogen reserves while maintaining a high level of available nitrogen. This is related to the provision of organic nitrogen by animal manure and the continuous release of nitrogen by microbial decomposition and mineralization. However, at different stages of the growing season, the dynamics of soil inorganic nitrogen will be jointly affected by plant absorption and loss processes.

Some studies have observed that the ammonium nitrogen content in rice-duck fields is significantly higher than that in the control, while the difference in nitrate nitrogen is not obvious, indicating that the activity of ducks increases the circulation of ammonia but has little effect on nitrification. In terms of phosphorus, integrated farming introduces phosphorus into the soil through feed and biological cycles. Both total phosphorus and available phosphorus in rice-fish co-cultivation fields have increased. Gao et al. (2025) pointed out that the rice-duck model significantly enhanced the size of the soil available phosphorus pool and improved the effectiveness and utilization of phosphorus. This is related to the fact that duck manure contains more phytic phosphorus, which is converted into a form that can be absorbed by crops after microbial action. In the rice-fish-duck ternary co-cultivation system, the available phosphorus in the soil increased by 9%~16% compared with monoculture, indicating that the synergistic effect of multiple animals has an enrichment effect on soil phosphorus.

Potassium mainly comes from soil background and organic matter mineralization. Studies have reported that the available potassium content in the soil of rice-duck farming can be increased by 8% to 39% compared with the control. The reason is that on the one hand, animal feces and residues are rich in potassium, and on the other hand, the stirring of aquatic animals promotes the release of soil mineral potassium. Meng et al. (2021) compared the single-crop, rice-fish and rice-shrimp modes in rice fields. The results showed that the available potassium in the soil of all integrated farming treatments was higher than that of the single-crop control. It should be noted that under different farming densities and management conditions, soil nutrients may also be locally excessive. For example, in rice-fish fields with large feeding amounts, the accumulation of soil phosphorus may cause surplus, and excess nutrients should be consumed through crop rotation or planting green manure. Therefore, under the conditions of integrated farming, soil N, P, and K show the characteristics of "overall increase and dynamic balance", and it is necessary to maintain a benign cycle of nutrients between soil-rice-animals through optimized management.

3.3 Enhancement of micronutrients and soil biotic activity

In addition to the main macroelements, integrated farming in rice fields can also affect the supply of trace elements in the soil and the biological activity of the soil. Rice growth requires trace nutrients such as zinc, boron, and molybdenum. Integrated farming may improve the effectiveness of trace elements by increasing organic matter and changing the physical and chemical environment of the soil. Studies have shown that rice-fish farming can increase the effective zinc content in the soil, which is attributed to the fact that fish stirring increases the release of zinc in the soil, and the chelation of organic matter keeps the zinc available. In the rice-duck model, since duck manure contains a certain amount of trace elements (such as copper and zinc), continuous return to the field can also slightly increase the accumulation of these elements in the soil. More importantly, integrated farming improves nutrient cycling by promoting soil biological activity.

Soil biological activity can be measured by indicators such as microbial quantity, diversity, and soil enzyme activity. A large number of studies have confirmed that integrated rice farming can significantly increase the microbial biomass and enzyme activity in rice fields. Yan et al. (2023) found that the soil urease activity in this model increased by 17% to 72% compared with monoculture, and the acid phosphatase activity increased by 23% to 66%. These enzymes are involved in the transformation of soil nitrogen and phosphorus, respectively, and their enhanced activity means an improvement in the nutrient mineralization supply capacity. Similarly, Sun et al. (2025) reported that the total soil microbial index (PLFA content) increased by about 18% when the rice-fish farming system was operated for 5 years compared with conventional rice fields, and increased by nearly 49% when it was operated for 30 years. The number of various groups such as bacteria, fungi, and actinomycetes in the soil increased significantly. The growth and diversification of microbial communities make the soil nutrient cycle more active and efficient.

In addition, rice-duck farming can also enrich soil macrobial communities, such as the number of earthworms. Li et al. (2025) observed that the number of earthworms per square meter in rice-fish farming fields was significantly higher than that in control fields, which helped to improve soil structure and nutrient status. In general, integrated farming in rice fields stimulates the biological activity of the soil through organic matter input and ecological disturbance, forming a pattern of "animal-microorganism-soil" linkage and synergy. This enhancement of biological activity not only promotes the release and circulation of trace elements (for example, microorganisms secrete organic acids to dissolve insoluble mineral nutrients), but also improves the efficiency of soil utilization of external inputs, thereby consolidating the foundation of soil fertility.

4 Mechanisms of Soil Nutrient Regulation

4.1 Nutrient recycling via animal excreta

In the integrated rice field farming system, animal manure is one of the key links in the soil nutrient cycle. Farmed animals obtain nutrients from the rice field ecosystem and convert a considerable proportion of their intake into manure and discharge it back into the field, realizing the nutrient feedback of "raising to promote rice". This is particularly evident in the nitrogen cycle. Taking rice-duck farming as an example, each duck excretes dozens of grams of nitrogen-containing manure every day, which is equivalent to continuous "topdressing" for the soil. Studies have shown that the increase in total nitrogen and available nitrogen in rice-duck fields comes from the contribution of duck manure. Since duck manure is organic nitrogen, its decomposition and release are relatively slow, and it can continuously supply nitrogen during the rice growth period, reducing the loss caused by excessive one-time application of chemical fertilizer nitrogen.

The experiment of Xiao et al. (2024) further revealed that the rice-red claw crayfish farming system did not significantly increase ammonia volatilization losses under high nitrogen input conditions, and there was a downward trend. The reason is that organic nitrogen such as shrimp manure is adsorbed by soil and fixed by microorganisms, avoiding excessive nitrogen volatilization. At the same time, the activity of crayfish improved soil aeration conditions, increased nitrogen absorption by rice roots, and the total nitrogen accumulation of the whole plant increased by 10.2% compared with the control.

This shows that returning animal manure to the field not only directly increases the soil nitrogen pool, but also promotes the effective use of nitrogen by rice by changing the physical and chemical environment of the soil. The global meta-analysis results of Chen et al. (2024) also support this view: the nitrogen fertilizer partial productivity (i.e., the yield per unit fertilizer) of the integrated farming system is significantly higher than that of the monoculture rice field, indicating that the same input of nitrogen is more fully converted into output under the integrated farming conditions. In the rice-fish symbiotic system, in addition to part of the nitrogen in the feed being used for fish growth, most of the rest enters the soil-water environment through fish metabolism. How to rationally utilize feed nitrogen and reduce losses has become one of the research focuses.

The current experience is to achieve efficient recycling of feed nitrogen and reduce environmental pressure by optimizing the feeding amount and matching aquatic plants (such as planting floating aquatic vegetables to absorb surplus nitrogen). Overall, returning animal manure to the field changes the rice field from an open nutrient system to a partially closed cycle, and the nitrogen reuse rate is significantly improved. It is estimated that a well-functioning rice-fish symbiosis system can basically recycle the nitrogen converted from crop straw, feed, plankton, etc. into rice and fish output, and the nitrogen utilization efficiency can be increased by more than 10%. This is an important mechanism for rice field integrated farming to achieve high efficiency of weight loss. However, it is also necessary to prevent problems such as excessive soil nutrients and methane fermentation caused by excessive accumulation of manure. Therefore, in actual production, the nitrogen fertilizer application structure should be appropriately adjusted according to the number of animals and the amount of manure to ensure the dynamic balance of nutrient input and output.

4.2 Nutrient fluxes driven by water and bioturbation

The disturbance caused by the activities of animals in rice field water and soil under the integrated farming model is one of the important mechanisms affecting the dynamics of soil nutrients. The trampling and paddling of ducks in the field, and the foraging and burrowing of fish and shrimp in the mud all affect the material exchange at the soil-water interface. First, animal disturbance can enhance the release of nutrients in the soil. The stirring of ducks causes the nutrients deposited on the mud surface to suspend in the water, which is absorbed and utilized by the rice roots or evenly distributed through the water layer. Benthic animals such as shrimps and crabs dig holes in the mud and release nutrients such as phosphorus and silicon in the soil into the overlying water. It has been observed that the concentration of dissolved phosphorus in the root zone of rice under crab farming conditions is higher than that in the control field, which is speculated to be related to the destruction of soil phosphorus fixation by crab digging holes (Xu et al., 2025). Secondly, animal activities can improve soil ventilation and redox conditions. Long-term flooding of rice fields can easily form an anaerobic environment with strong reduction, while the swimming of ducks in the fields and the water circulation of fish and shrimp increase the chance of oxygen diffusion into the soil. The thickening of the oxidation layer is conducive to the nitrification of ammonium nitrogen and the oxidation of ferrous iron, reducing the accumulation of toxic reducing substances, thereby protecting the root system and facilitating nutrient absorption.

In addition, water disturbance can also crush large soil particles, making soil particles more finely dispersed, thereby increasing the contact surface between soil and water and accelerating the diffusion and release of nutrients. This is similar to the "micro-tillage effect" of soil, which helps to balance the nutrient distribution in various parts of the field. Thirdly, the presence of aquatic animals changes the nutrient dynamics of rice field water. Fish and snails feed on plankton, which controls the number of algae and prevents too many nutrients from being fixed by algae, thus leaving more water nutrients for rice to use. This has a stabilizing effect on seasonal changes in nitrogen and phosphorus concentrations. It is worth noting that while animal disturbance enhances nutrient release, it may also accelerate the loss of certain nutrients, such as ammonia volatilization and runoff loss. Therefore, it needs to be regulated through field management. For example, the depth of the water layer and the exchange rate of water flow should be reasonably controlled to both utilize animal disturbance to release nutrients and prevent nutrients from being lost with the water flow.

Experiments have shown that in the rice-shrimp co-cultivation system, ditching shrimp in the water layer of rice fields can help reduce the ammonia volatilization flux of rice fields, and even under higher nitrogen application conditions, ammonia losses have not increased. This may be because the ditch area absorbs some ammonia, and the activity of shrimp makes the nitrogen cycle in the water body more complicated, thereby reducing the peak ammonia loss. Other studies have shown that rice-fish co-cultivation can reduce the accumulation of nitrate nitrogen in field surface water and reduce the risk of leaching to groundwater through the ecological effects of water bodies (Lan et al., 2021). The disturbance mechanism of animals on water and soil makes rice field integrated farming a dynamically stirred nutrient reactor: on the one hand, it accelerates the flow of nutrients between soil and plants, and on the other hand, it also requires us to manage carefully to prevent excessive nutrient loss.

4.3 Changes in microbial communities and enzymatic activities

The regulation of soil nutrient cycling by rice field integrated farming is largely achieved by affecting soil microbial communities and their functions. Soil microorganisms are the drivers of nutrient decomposition and transformation, and their community structure and activity determine key processes such as the decomposition rate of organic matter, nitrogen mineralization, and phosphorus dissociation. Under integrated farming conditions, the soil microbial environment undergoes many changes, thereby regulating nutrient cycling. First, the number and biomass of microorganisms have increased significantly. As mentioned above, the rice-fish-rice-duck system has observed an increase in soil microbial biomass carbon and nitrogen (SMBC/SMBN), and an increase in the total phosphatidic acid (PLFA) content of the microbial community.

Li et al. (2025) conducted a long-term experiment in two places and found that after 30 years of rice-fish farming, the total amount of soil microorganisms was about 1.5 times that of the single-crop control, and the number of various microorganisms such as fungi, bacteria, and actinomycetes increased across the board. The increase in the number of microorganisms means that more "workers" are involved in the degradation of organic matter and nutrient transformation, making the soil nutrient supply more active and stable. Second, the structure of the microbial community has been adjusted. Integrated farming often promotes the improvement of bacterial diversity and changes the relative abundance of dominant groups. For example, Liao et al. (2019) found that the Shannon diversity index of soil bacteria and fungal communities under rice-duck farming conditions was higher than that of conventional rice fields.

At the same time, rice-fish farming is conducive to a moderate increase in the fungus/bacteria ratio. The increase in the proportion of fungi in long-term farming soils is conducive to the formation of more stable humus (fungi have a strong ability to decompose lignin, which is conducive to the decomposition of difficult-to-degrade organic matter). In the bacterial community, some functional bacteria related to nitrogen cycle are significantly enriched. For example, Liu et al. (2024) reported that rice-fish farming promoted the reproduction of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) in the soil, thereby improving the effectiveness of soil nitrogen supply. AOA and AOB are key bacterial groups in the nitrification process. Their increase means that ammonium nitrogen is converted into nitrate nitrogen more quickly, and the efficiency of plant absorption or further conversion is improved. This is one of the microscopic mechanisms for the accelerated nitrogen conversion in integrated farming. Third, soil enzyme activity is significantly enhanced. Soil enzymes are products and mediators of microbial metabolism and are directly involved in the decomposition of organic nutrients. In the integrated farming system, due to the rich matrix and active microorganisms, the activity of various nutrient conversion enzymes is generally improved. Yan et al. (2023) observed that the activities of urease, sucrase, phosphatase and other enzymes in the rice-duck-shrimp farming soil were more than 20% higher than those in monoculture. The long-term positioning experiment of Sun et al. (2025) also found that the activities of soil β-glucosidase, cellulolytic enzyme, chitinase and urease in 5-year rice-fish co-cultivation were significantly improved compared with monoculture, and the activities of these enzymes in 30-year co-cultivation were more than 50% higher than the control. The increase in enzyme activity directly leads to an increase in the mineralization rate and turnover rate of soil nutrients, which is manifested in the faster release of nutrients that can be absorbed by plants.

For example, the increase in urease activity means that the conversion of organic nitrogen to ammonium nitrogen is faster, and the increase in phosphatase promotes the inorganicization of organic phosphorus. When comparing different models, Meng et al. (2021) pointed out that the comprehensive soil fertility index of all rice field models involving animals is higher than that of the control without animals, among which the enzyme activity contributes outstandingly. It should be noted that the enhancement of microbial activity will also accelerate the rate of decomposition and loss of soil organic matter.

Therefore, although integrated farming increases organic matter and nutrients, excessive consumption of nutrients by microorganisms should also be avoided. Fortunately, the ecological balance formed by integrated farming and breeding is generally self-regulating. For example, when organic matter increases, the amount of microorganisms increases and reaches a new balance point, which does not cause nutrient "burning". Integrated rice field farming and breeding significantly stimulates the potential of soil microorganisms by "promoting microorganisms with movement", making the soil nutrient cycle process faster and more efficient. This is also one of the internal motivations for maintaining or even improving soil fertility and crop yields while reducing external inputs.

5 Case Studies

5.1 Xingqing Farm's rice-duck-saffron rotation model

Xingqing Family Farm, located in Deqing, Huzhou, Zhejiang, pioneered a new integrated farming model of "rice-saffron rotation + rice-duck co-cultivation" based on rice-duck co-cultivation (Figure 1; Figure 2). The farm releases about 2 000 ducks in the fields every year during the rice growing season, implements rice-duck co-cultivation, uses ducks to control Cordyceps, and returns manure to the fields; after the rice is harvested, the fields are used to plant precious medicinal materials saffron in the winter, achieving two harvests a year.

Figure 1 Panorama of planting base of Deqing Xingqing family farm Co., Ltd. (Photographed by Yuchao Shen)

This rotation co-cultivation model has significant ecological and economic benefits: it is reported that the comprehensive income per mu (≈0.067 hectares) can reach more than 20 000 yuan. Rice-duck co-cultivation improves the quality and unit price of rice, and saffron planting brings high added value, making the unit benefit of farmland far exceed that of single planting. From the perspective of soil nutrient management, this model improves soil organic matter and nitrogen and phosphorus levels through duck manure, providing fertile soil for saffron growth, while the decomposition of saffron residues replenishes soil organic matter, achieving a virtuous cycle. The practice of Xingqing Farm has proved that the integrated breeding model can be adapted to local conditions and rotated with efficient cash crops, which not only maintains the health of the rice field ecosystem, but also creates considerable benefits. It has been rated as a typical case of innovative breeding model by the Ministry of Agriculture and Rural Affairs for promotion and reporting (Xu et al., 2017; Gao et al., 2025). This case reflects the huge potential of "rice field+aquatic products+cash crops" compound management, and provides a demonstration for family farms to increase land output and achieve green income.

Figure 2 Rice-duck farming system (Photographed by Yuchao Shen)

5.2 Improvement of acidic soils under rice–fish co-culture

The soil in some southern rice-growing areas is acidic and heavy, which often leads to reduced rice production. The rice-fish co-cultivation model shows a unique role in improving acidic soil. In the red soil rice fields (pH≈5.5) of the Hunan experimental site, loaches and crucian carp were introduced to carry out rice-fish symbiosis. After three years of continuous cultivation, the soil pH value rose to about 6.2, effectively buffering the acidity. According to analysis, the reasons for the reduction in soil acidity are: first, fish excrement contains alkaline ions such as calcium and magnesium, which neutralize part of the acidity; second, the water-reducing and oxygen-reducing environment of the rice-fish field inhibits acid-producing processes such as sulfate reduction; third, the increase in organic matter and humification increase the soil buffering capacity, reducing pH fluctuations (Zhou et al., 2024). Guo et al. (2020) also pointed out that the soil nutrients in the rice-fish system are sufficient and can increase pH, which is conducive to the improvement of acidified soil. In addition to pH, rice-fish symbiosis also improves other physical and chemical properties of acidic soil. A comparative experiment in Fujian showed that after fish farming in rice fields, the exchangeable aluminum in the soil was significantly reduced, while the content of effective phosphorus and potassium increased, the soil particle structure improved, and the tillage layer changed from compacted to loose.

This shows that rice-fish farming can alleviate adverse factors such as aluminum toxicity and nutrient fixation in acidic soils through bioturbation and nutrient cycling. A typical case comes from the acidic field improvement project in Guangxi: the local introduction of rice-fish farming combined with lime improvement increased the soil pH from 4.8 to 5.6 within two years, and the rice yield per unit area increased by 15%, proving the effectiveness of the rice-fish model in improving acidic low-yield fields. Of course, it should be noted that the effect of rice-fish farming on soil pH is gradual and limited, and lime and other conditioners are still needed to fundamentally improve strong acidic soils. However, the rice-fish model can at least partially alleviate the harm of soil acidification and provide a more friendly soil environment for crops.

5.3 Stability of soil fertility across integrated systems

Although various types of rice field integrated farming systems have their own characteristics, they can all improve soil fertility and enhance its stability to varying degrees. Meng et al. (2021) quantitatively evaluated the effects of several ecological farming models in rice fields in South China on soil comprehensive fertility, including rice-fish, rice-frog, rice-duck and rice-shrimp models. The results showed that compared with single planting, the soil organic matter, total nitrogen, available nutrients and microbial indicators of these integrated planting and breeding treatments were improved to varying degrees, and the calculated soil comprehensive fertility index increased by 5% to 15%. Among them, the composite model of raising fish and ducks at the same time had the largest increase, indicating that multi-species co-cultivation has a superimposed gain effect under certain conditions. Other long-term monitoring studies also showed that integrated planting and breeding can maintain the long-term stability of soil fertility.

A 10-year rice-duck co-breeding experiment conducted in Jiangxi found that the soil organic matter and nutrient content increased rapidly in the first 3-4 years, then stabilized, and remained at a plateau about 15% higher than single planting after 10 years (Teng et al., 2016). This shows that there may be a process in which the nutrient "reservoir" in the integrated planting and breeding system is gradually filled and reaches a dynamic balance. Once entering the equilibrium period, soil fertility can be maintained at a high level for a long time without fertilizer waste or environmental risks caused by continued accumulation. In contrast, due to continuous high-intensity fertilization, the soil organic matter of traditional single-season rice first increases, then often decreases and tends to decline, and the fertility stability is poor. Different animal combinations have different focuses on the impact of various soil fertility indicators. For example, the rice-duck model significantly improves the nitrogen supply of the soil, while the rice-shrimp model improves the effectiveness of phosphorus and potassium more prominently; the rice-frog model (farming frogs) can significantly increase the diversity of soil microorganisms and enzyme activity, thereby improving soil biological fertility.

These differences suggest that we can choose a suitable integrated breeding model according to production needs to focus on improving certain aspects of soil fertility indicators. In general, a variety of integrated breeding models can promote the formation of higher and more stable fertility levels in the soil, and the fertility improvement effect tends to stabilize after several years of continuous operation, showing good sustainability. This is of great significance for ensuring stable grain production and long-term soil productivity. Therefore, in practice, diversified rice field integrated breeding models can be promoted according to local conditions, and the problem of nutrient accumulation that may occur in a single model can be avoided through crop rotation or model conversion, so as to achieve a long-term balance of soil nutrient dynamics.

6 Sustainability and Eco-Benefit Assessment

6.1 Reduction in fertilizer input and pollution risk

The integrated rice farming model is regarded as an important way to achieve environmentally friendly agriculture. One of its major advantages is that it can significantly reduce external inputs such as fertilizers and pesticides while ensuring production. According to statistics from the national fishery technology promotion department, the average use of fertilizers and pesticides in rice-fish integrated farming fields is reduced by more than 30% compared with traditional rice fields. Taking Hubei rice-shrimp farming as an example, this model has been widely promoted in the past 10 years. The use of fertilizers in rice fields in the main crayfish production areas has decreased by about 20% compared with ten years ago, while the total rice production has increased instead of decreased. This is because shrimp feed and feces in the rice-shrimp system make up for part of the fertilizer function, while the incidence of pests and diseases has decreased, significantly reducing the application of pesticides. The direct environmental benefit brought about by the reduction of chemical inputs is the reduction of agricultural non-point source pollution load.

Excess nitrogen and phosphorus in rice fields often enter the water body through leakage and runoff, causing eutrophication, and integrated farming inhibits this process. Yan et al. (2023) quantified the impact of rice-duck-shrimp farming on nutrient loss, and the results showed that compared with conventional rice fields, the total nitrogen and phosphorus runoff losses were reduced by 24.3% and 10.3%, respectively. This is mainly due to the improvement of nutrient recycling efficiency within the system and the improvement of the field environment. For example, in rice-duck farming fields, the soil is more permeable due to the ducks digging up the mud, and the rice root system is well developed, so more fertilizer nitrogen is retained in the soil-crop system rather than lost. For another example, because herbicides and insecticides are not applied to rice-fish fields, the pesticide residues in the field water are close to zero and will not enter the surrounding water environment through drainage. Integrated farming can also reduce greenhouse gas emissions from rice fields, which is also a manifestation of environmental benefits.

Miao et al. (2025) reported that rice-duck farming significantly inhibited methane (CH_4) emissions from rice fields, and the overall warming potential of the system decreased, which helped to mitigate the impact of agriculture on climate change. Although greenhouse gases do not directly belong to non-point source pollution, they are also worthy of recognition as part of the green benefits (Figure 3) (Xu et al., 2017). It should be pointed out that integrated farming is not without environmental risks. For example, if the rice-fish field with too much feeding is not well managed, the field surface water may also become eutrophic. Therefore, it is necessary to limit its environmental load within the tolerable range of the ecosystem through scientific stocking density and feed control. In general, a large number of studies and practices have proved that the rational implementation of integrated rice farming can achieve weight reduction and pesticide reduction while maintaining stable production and high efficiency, and is one of the effective ways to develop green agriculture and control agricultural non-point source pollution.

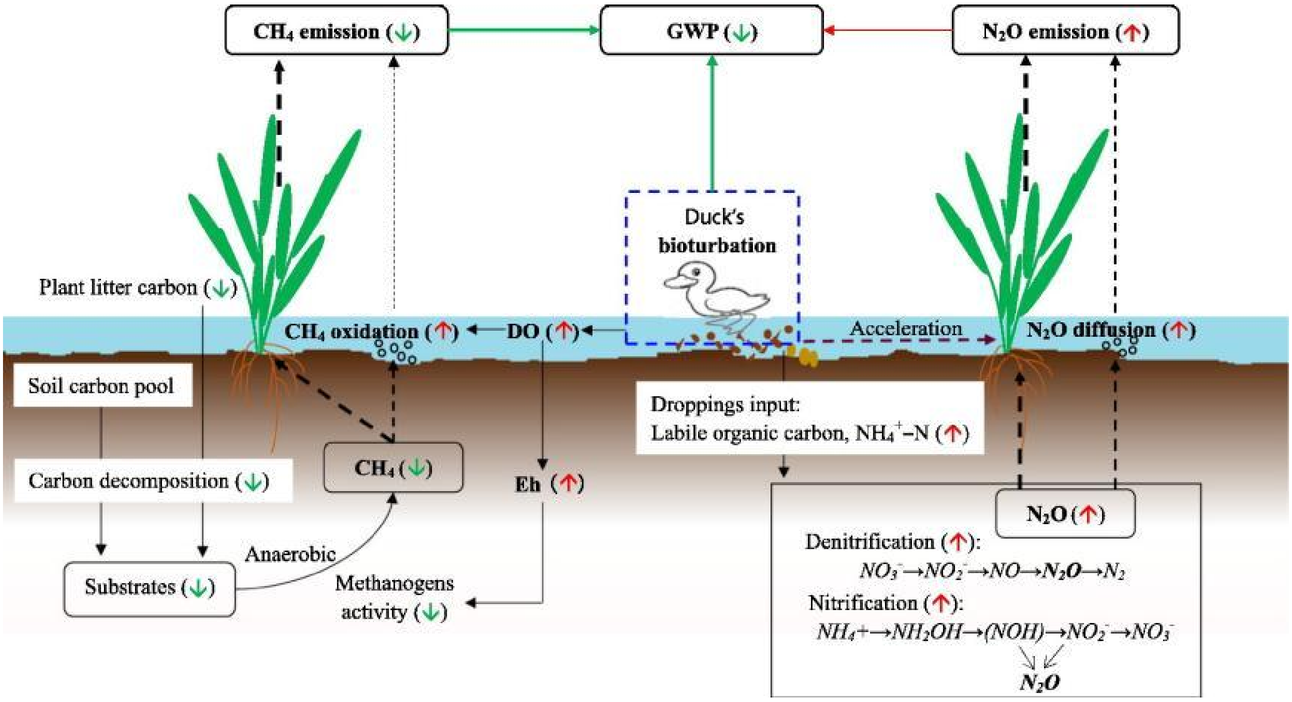

Figure 3 Effect pathways of rice-duck farming system on greenhouse gas emissions from rice fields and its regulatory mechanism (Adapted from Xu et al., 2017)

6.2 Improved soil nutrient retention and efficiency

The sustainability of integrated rice farming is also reflected in the protection and efficient utilization of soil nutrient resources. Long-term single crop production often leads to "overdraft" of soil nutrients, while integrated farming is conducive to restoring soil nutrient reserves and improving system nutrient utilization efficiency. As mentioned above, integrated farming can steadily increase and maintain the nutrient reserves of rice field soil organic matter, total nitrogen, total phosphorus and other nutrients at a high level. This means that as time goes by, the soil nutrient pool is enriched, which can provide more abundant nutrient supply for continuous farming, thereby improving the sustainability of production. For example, in the aforementioned 10-year rice-duck experiment in Jiangxi, the total nitrogen and organic matter content of paddy soil increased slightly year by year, and in the tenth year it increased by about 15% compared with the initial value, while the control monoculture field decreased by about 5%. The enhancement of soil nutrient reserves provides a nutrient buffer for the sustained and stable yield of rice.

When encountering years with reduced external inputs or unfavorable climate, the integrated farming field can still maintain a good yield due to its high soil fertility and has a stronger ability to resist stress and maintain stable yield. On the other hand, integrated farming improves the utilization efficiency of nutrient inputs. The meta-analysis of Chen et al. (2024) showed that compared with monoculture, the nitrogen fertilizer partial productivity of rice-fish/duck co-cultivation systems increased by an average of 10% to 20%, which means that more rice is produced per unit of nitrogen application. Nutrients circulate at multiple levels within the system, reducing losses and waste. In addition, the plant-animal dual-channel absorption of nutrients allows some nutrients that were originally not absorbed and utilized by rice to be transformed into forms after being utilized by animals and then absorbed by rice.

For example, some organic phosphorus and algae nutrients are excreted in inorganic form after being ingested by fish, but are absorbed by rice, which indirectly improves the efficiency of nutrient utilization. For another example, in rice-duck farming, ducks eat weeds, which reduces the competition between weeds and rice for fertilizer, and improves the efficiency of fertilizer nutrients used to increase rice production. It can be said that integrated farming converts more soil nutrients into useful agricultural products rather than ineffective losses or harmful accumulation. In the long run, this efficient and cyclical soil nutrient management model helps to maintain the balance of soil nutrient income and expenditure and avoid "overdraft" of soil fertility. Admittedly, the degree to which integrated farming improves nutrient efficiency varies in different regions and models, and specific evaluation and optimization are required.

For example, in black soil areas with high fertility, the advantages of integrated farming may be mainly reflected in reducing environmental loads, while in poor soil areas, its effect of improving nutrient utilization is very significant. Therefore, the integrated farming plan should be designed according to local soil nutrient conditions to maximize its function of enhancing soil nutrient reserves and utilization efficiency.

6.3 Soil health as a foundation for green agriculture

Healthy soil is the foundation of green sustainable agriculture, and integrated rice farming has laid a good foundation for the development of green agriculture by improving soil health properties. First, integrated farming restores and improves the biodiversity and ecological functions of the soil. Soil health not only refers to rich nutrients, but also requires an active biosphere and a good structure. Integrated rice farming has greatly increased the richness of soil microbial populations and soil animal communities. For example, in the rice-duck model, field organisms such as spiders and frogs have increased significantly, and the soil food web structure has become more complex, which has improved the stability of the soil system from an ecological perspective.

This biodiversity gives the soil a stronger self-regulation ability and is more resilient in the face of diseases or environmental stress. Secondly, the comprehensive improvement of soil physical and chemical properties has brought rice fields closer to the standard of "healthy soil". Healthy soil usually means sufficient organic matter, good aggregate structure, moderate acidity and alkalinity, and no accumulation of harmful substances. Integrated farming practices have shown that after several years of fish-duck farming in rice fields, the aggregate structure of the soil tillage layer has been significantly improved, the porosity has increased, the organic matter has increased, and the heavy metal and pesticide residues have been significantly reduced (Huang, 2024).

Studies have shown that the total salt content of soil in long-term rice-fish farming fields has decreased by more than 20%, the pH has tended to be neutral, and the organic matter has increased by 2-3 percentage points. These changes are consistent with the direction of healthy soil (Wang et al., 2022). Thirdly, integrated farming helps to reduce the carbon and nitrogen footprint of agricultural production and improve ecological services. Paddy field soil is one of the sources of greenhouse gas emissions, and rice-duck farming has been shown to significantly reduce CH_4 emissions, while having only a slight impact on greenhouse gas emissions such as N_2O, and the overall greenhouse effect potential has decreased. This shows that the integrated farming model is conducive to the construction of "carbon neutral" soil and is also meaningful to the country's "dual carbon" strategy. Integrated farming soil provides more ecosystem services, such as cleaner farmland runoff and richer biological habitats, which have a positive impact on the surrounding environment.

Integrated farming in rice fields improves soil fertility and environment, allowing paddy field soil to move from "production soil" to "healthy soil", providing a solid foundation for the green agricultural system. This foundation is reflected in the fact that healthier soil can support efficient agriculture with less chemical inputs, and achieve the unity of safe and high-quality agricultural products and ecological and environmental friendliness. Therefore, in the process of promoting green agriculture, integrated rice field farming should be regarded as one of the important measures to improve the health of farmland soil, and its comprehensive benefits in improving soil fertility and ecological restoration should be fully utilized.

7 Concluding Remarks

A large number of studies and practical experience have shown that the integrated rice field farming model has a significant positive regulatory effect on soil nutrient dynamics. Integrated farming stimulates the nutrient cycle between soil, plants and animals by introducing biological elements such as ducks, fish and shrimp. Compared with single planting, integrated farming significantly increases the content of soil organic matter and major nutrients, improves soil structure and microbial ecology, and makes paddy soil more fertile and vibrant. At the same time, integrated farming reduces excessive dependence on chemical fertilizers, reduces the risk of nutrient loss and environmental pollution, and achieves an efficient balance between nutrient input and output. The rice-fish integrated farming model meets the development requirements of ecological circular agriculture. It not only reduces resource input, improves rice yield and quality, but also increases by-product output and farmers' income, contributing to rural revitalization and green and sustainable development of agriculture.

It can be said that integrated rice field farming achieves a win-win adjustment of soil fertility and environmental friendliness at the soil level by creating a small ecological circulation system for farmland. This model provides a feasible path for modern rice field agriculture to transform from "high input-high output but high pollution" to "low input-stable output and low pollution". In summary, integrated rice field farming is an important form of realizing "storing grain in the land and storing grain in technology", and its dynamic regulation of soil nutrients is of great significance to ensuring food security and sustainable agricultural development.

Although integrated rice field farming has significant advantages, it still faces some management and technical challenges in large-scale promotion and long-term operation. First, the bottleneck of large-scale mechanization. Since integrated farming requires digging ditches and building ridges in the field (such as rice-shrimp ditches) and setting up fences, the irregularity of the field and the complexity of paddy field operations are increased, resulting in increased difficulty in mechanized farming and harvesting.

For example, the operation of combine harvesters in rice fields with ditches is limited, and farmed animals may also be disturbed by machinery and injured. This limits the promotion and application of the model in large fields. How to optimize field engineering design and achieve effective connection between integrated farming and mechanization is one of the problems that need to be overcome. Secondly, the bottleneck of disease prevention and control and breeding management. Integrated farming introduces new biological populations, and also brings problems of animal diseases and water quality management. For example, fish farming in rice fields needs to prevent and control fish diseases and hypoxia caused by excessive water quality; duck farming in rice fields needs to consider duck plague vaccines and damage to young ears caused by ducks.

At present, many farmers lack experience and technical support in this area, resulting in the death of fish and shrimp and the destruction of duck seedlings when management is poor. Therefore, it is necessary to establish a supporting animal disease prevention and control system and water body monitoring and control technology. Third, regional adaptability bottleneck. The climate and soil conditions in different regions vary greatly, and a certain integrated breeding model may not be suitable for all regions. For example, the rice-crab model is suitable in the middle and lower reaches of the Yangtze River, but it is difficult to implement in high-altitude or northern regions due to growth period and temperature restrictions; the rice-duck model works well in the double-season rice areas in the south, but how to efficiently use ducks in single-season rice areas is also a problem. Therefore, it is necessary to carry out regional experiments to summarize the best models and combinations in various places and realize the "local optimization" of the model. Fourth, the long-term benefits and risk assessment are insufficient.

Although some integrated breeding models have outstanding short-term benefits, there is still a lack of sufficient monitoring of long-term impacts. For example, will high-intensity rice-shrimp farming for many consecutive years accumulate soil salt or heavy metals? Will the long-term change in the structure of the rice field ecosystem lead to new imbalances? These need further research and evaluation. Finally, the bottleneck of promotion organization and brand building. Integrated farming requires high knowledge and skills of farmers, and the initial investment is also large. It is difficult for a family to fight alone, and it needs to be led by cooperatives or leading enterprises. However, many regions currently lack such a degree of organization and brand influence, and the low price of agricultural products also affects farmers' enthusiasm. In response to these bottlenecks, it is urgent to solve them in a two-pronged approach in terms of policies and technology.

In order to give full play to the advantages of integrated farming and breeding in rice fields and promote the large-scale application of efficient ecological farming and breeding models, we put forward the following policies and development suggestions: First, increase policy support and improve subsidies and technical services. The government should include integrated farming and breeding in rice fields in the special project of green agricultural development, provide certain facilities construction and subsidies for the purchase of improved varieties, and reduce the cost of farmers' transformation; at the same time, establish a professional technical promotion team, carry out farming and breeding technology training and disease prevention and control guidance for farmers, and cultivate new professional farmers. Second, strengthen scientific research and solve key technical bottlenecks. Scientific research units should carry out collaborative research on issues such as mechanized integration of planting and breeding, ecological regulation technology, and animal disease prevention and control, such as developing a combine harvester or small unmanned agricultural machinery suitable for ditch rice fields. At the same time, in-depth research should be conducted on the soil and ecological change mechanisms under long-term integrated planting and breeding to provide a basis for the formulation of scientific management measures. Third, encourage organizational innovation and scale operation. Support the establishment of an industrial consortium of leading enterprises + cooperatives + farmers, and promote the model of "company supply of seedlings and materials for disease prevention + farmers' breeding + guaranteed price purchase". Through the leadership of leading enterprises, unify technical standards and brand marketing, and enhance the added value and market competitiveness of integrated rice field breeding products. For example, create green organic rice and special aquatic product brands, improve quality and price, and maximize the benefits of planting and breeding. Fourth, demonstrate and promote according to local conditions. For different ecological regions, summarize suitable main promotion models and build demonstration bases to play a radiating and driving role.

For example, in the acidic soil area of South China, focus on promoting the rice-fish and rice-frog models to improve soil, in the middle and lower reaches of the Yangtze River, promote the rice-shrimp and rice-crab models to promote stable grain and increase income, and in hilly and mountainous areas, develop the rice-duck model according to local conditions. Through demonstration and typical guidance, farmers' cognition and confidence can be enhanced. Looking to the future, with the advancement of science and technology and policy support, the integrated rice field breeding model is expected to enter a high-speed development stage of "improving quality and expanding coverage". This will not only further release the production potential of my country's rice fields, achieve stable grain and protein, and diversified and efficient agricultural supply, but also make greater contributions to the prevention and control of agricultural non-point source pollution, soil quality improvement and rural ecological civilization construction. It can be foreseen that under the general trend of green and sustainable development, integrated rice field breeding, as an innovative agricultural model that integrates my country's traditional wisdom with modern technology, will surely shine in a broader world.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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