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Enhancement Effects of Rice-Duck Co-Culture Systems on the Ecosystem Services of Paddy Fields

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Abstract Rice-duck symbiosis is an ecological agricultural technology that combines traditional and modern farming by raising ducks in rice fields. In recent years, this model has attracted much attention due to its outstanding advantages in controlling pests, diseases and weeds, optimizing soil nutrient cycles, and improving farmland ecological service functions. This study systematically sorted out the historical evolution and modern value of rice-duck symbiosis, and analyzed the mechanism of improving rice field ecological service functions, including ducks eating rice field pests and weeds to reduce pesticide application, duck manure as organic fertilizer to optimize soil nutrients, and indirect improvement of rice yield and quality. At the same time, through practical cases such as Xingqing Family Farm in Deqing County, the effectiveness of rice-duck symbiosis in reducing fertilizer and pesticide input, reducing environmental pollution and increasing the added value of agricultural products was evaluated. On this basis, the current promotion of rice-duck symbiosis faced problems such as high labor input, insufficient mechanization, and limited market recognition, and countermeasures and suggestions such as strengthening technology research and development and policy support, improving the standard system and brand building were proposed. The rice-duck symbiosis system helps to achieve synergistic effects between food production and ecological protection. This study hopes to promote the green and sustainable development of agriculture and the continuous improvement of the service functions of rice field ecosystems.

Keywords Rice-duck symbiosis; Rice field ecological services; Pest and weed control; Soil nutrient cycle; Sustainable agriculture

1 Introduction

The rice-duck symbiotic farming model originated from traditional Chinese agriculture and is an important part of my country's agricultural civilization with a history of thousands of years. As early as the Ming and Qing Dynasties, there were records of using "rice field duck farming" in South China to increase grain and livestock output. Rice field duck farming combines rice planting with free-range duck farming to form a mutually beneficial symbiotic relationship between crop production and livestock farming, and has been proven to have significant comprehensive benefits (Liang et al., 2022). The development of modern agricultural technology has given new connotations to rice-duck symbiosis. Since the 1980s, Japan and other countries have also begun to promote rice field integrated farming technology to restore traditional ecological farming models, reduce chemical inputs, and protect the agricultural ecological environment. In 2005, the rice-fish-duck symbiotic system in Congjiang Dong Township, Guizhou was selected as a Global Important Agricultural Heritage System (GIAHS), highlighting the unique value of this model and its contribution to biodiversity (Zhang et al., 2023). In terms of modern value, rice-duck symbiosis has received much attention in the transformation of ecological agriculture. Studies have shown that compared with monoculture, the rice-duck symbiosis system can form a virtuous cycle of food and ecological chains, produce safe and high-quality rice and duck meat, and achieve quality and efficiency improvement of the rice and duck industries (Luo et al., 2010). For example, the practice of ecological farms in Hunan Province shows that the adoption of integrated rice field farming can achieve a "win-win situation of grain and money", which not only ensures grain production but also increases farming income. The rice-duck symbiosis system combines traditional wisdom with modern technology, improves the service function of the rice field ecosystem while ensuring food security, and is of great significance to the current sustainable development of agriculture.

The service function of the rice field ecosystem refers to the regulation, support and cultural service functions provided by the rice field ecosystem to the environment and human well-being in addition to providing food output, including biodiversity maintenance, pest and disease control, soil fertility improvement, water purification and landscape cultural value. With the emphasis on sustainable agricultural development and environmental protection, how to improve the ecological service function of farmland while ensuring food production has become a research hotspot (Lin, 2025). Traditional high-input chemical agriculture often brings ecological and environmental problems while increasing production, such as pesticide and fertilizer pollution, eutrophication of water bodies, and biodiversity decline. Ecological farming models such as rice-duck symbiosis are considered to be an effective way to practice green agricultural development. They reduce dependence on chemical inputs by simulating natural ecological processes and are believed to promote the improvement of farmland ecological service functions (Chen et al., 2023). Recent studies have shown that integrated farming models can help achieve the dual goals of increasing agricultural production and efficiency and being environmentally friendly. For example, a comprehensive analysis of global rice farming models showed that such "rice-poultry/fish" farming systems can improve the nutrient utilization efficiency of rice fields and increase food output, which is conducive to achieving multiple goals of the United Nations Sustainable Development Goals, such as zero hunger, clean water sources, and climate action. In my country, driven by policies related to ecological agriculture and circular agriculture, research and demonstration of integrated rice farming technology has developed rapidly. As a typical model, rice-duck symbiosis has become a frontier topic in cross-disciplinary research in the fields of agriculture and ecological environment. This study is carried out in this context, focusing on how the rice-duck symbiosis system can enhance the ecological service function of rice fields and its mechanism.

This study will explore the effect of the rice-duck symbiosis system on the ecological service function of rice fields, clarify its mechanism of action and practical benefits, analyze the basic composition and operation mode of the rice-duck symbiosis system, including the mutualistic mechanism between ducks and rice, the field management method of rice-duck co-cultivation, and the application status of this model in different regions, discuss the mechanism of rice-duck system on the ecological service function of rice fields, analyze the action principle from the aspects of biological control (pest and weed control), soil structure and nutrient cycle optimization, rice quality and indirect improvement of nutrition, evaluate the ecological benefits of reducing external inputs and environmental pollution, such as reducing the frequency of fertilizer and pesticide application, reducing the damage of pesticide residues to the water and soil environment, and achieving sustainable production through ecological weed control and organic fertilizer substitution, and select practical cases for analysis. This study also summarizes the significance of rice-duck co-cultivation for the transformation of ecological agriculture, proposes a feasible path to enhance the ecological service function of rice fields, and hopes to provide direction for the large-scale and intelligent development of rice-duck co-cultivation in the future.

2 Basic Composition and Operational Model of Rice-Duck Systems

2.1 Mutual benefits between ducks and rice

In the rice-duck symbiosis system, rice and domestic ducks benefit each other in the same ecological environment, forming a complex ecological chain. First, rice provides a habitat and foraging place for ducks. The shade of rice plants can reduce the field temperature and provide a comfortable activity environment for ducks. At the same time, organisms (such as insects, snails and aquatic weed larvae) that reproduce in rice plants and rice field water bodies become natural feed for ducks. In turn, the activities and feeding behaviors of ducks in rice fields play multiple positive roles in rice growth. First, ducks feed on pests and weeds in rice fields, reducing the threat of diseases, insects and weeds to rice, which is equivalent to acting as "biological insecticides" and "biological weed killers". According to research, the coverage and density of weeds in rice-duck symbiosis fields have been significantly reduced, and the incidence of major pests such as rice planthoppers and borers has also been significantly reduced. Second, ducks trample and play in the fields, which has a similar effect to loosening the soil by tilling, disturbing the soil surface to increase oxygen supply, improve soil ventilation and dissolved oxygen levels in the water.

It is reported that duck activities can increase the dissolved oxygen concentration in the surface water of rice fields by about 38%, thereby promoting the development of rice roots and nutrient absorption. The moderate stirring of ducks can also inhibit the anaerobic fermentation of methane-producing bacteria in the surface layer of rice fields, reducing the emission of greenhouse gases such as methane. Third, duck manure is a good organic fertilizer. After decomposition, duck manure and residual feed release nutrients such as nitrogen, phosphorus, and potassium, which are absorbed and utilized by rice plants, realizing the cycle of nutrients between animals and plants. Studies have shown that the total nitrogen content in the 0 cm-10 cm soil layer of rice-duck co-cultivation fields is 8.5%-28.4% higher than that of monoculture rice fields, and the soil organic matter and enzyme activity are also significantly improved (Xu et al., 2017; Wang et al., 2019). Through the above mechanisms, the rice-duck symbiotic system has established a complex food web and nutrient cycle network, with higher energy and material utilization efficiency than the single planting system, and the stability and resistance of the ecosystem have also been enhanced.

2.2 Farming practices and management in integrated systems

The field management under the rice-duck symbiotic model needs to be scientifically arranged according to the growth stage of rice and the biological characteristics of ducks. Generally speaking, about 7-10 days after the transplanting of early or mid-season rice, when the seedlings are basically rooted and alive and the plant height reaches 15 cm~20 cm, the appropriate-age ducklings are selected and put into the rice field for stocking. The stocking density depends on the conditions of the rice field. It is usually appropriate to stock 15-30 ducklings per mu (666.7 square meters of paddy field). Too high a duck density may cause trampling damage to the seedlings, while too low a density will make it difficult to fully play the role of controlling weeds and insects. During the symbiotic growth period, farmers need to carry out necessary feeding and management of the ducks. For example, anti-escape nets are set up around the edge of the field, and simple duck sheds are set up in the field for ducks to roost and shelter from rain at night. A small amount of grain feed can be supplemented in the evening to ensure the nutrition of ducks. In the early stage of rice growth, shallow water irrigation is maintained frequently to meet the needs of rice tillering and facilitate duck activities; in the later stage, when the fields are left for baking, the ducks can be transferred to ditches and ponds for short-term foster care or their activity time in the fields can be reduced.

The key node is that during the heading period of rice, ducks need to be completely withdrawn from the rice fields to prevent them from eating rice ears or stepping on plants. Generally, ducks are caught about 10 days before rice heading, or they are raised and fattened separately outside the rice fields. Rice is harvested normally after maturity, and duck-rice fields in different seasons can also be connected to the cultivation of other crops and poultry. For example, in some places, green manure or other economic crops are planted in winter after rice and ducks to achieve an efficient rotation of "one rice and one poultry". The entire rice-duck co-cultivation process emphasizes the coordination of the growth rhythm of rice and ducks: ducks help rice in the early stage and ducks give way to rice in the later stage, which not only ensures stable rice production but also cultivates high-quality ducks. In field management, attention should also be paid to disease prevention and control, such as regular water changes and timely disinfection, to ensure the healthy growth of ducks and rice. The operation process of rice-duck co-cultivation is to organically embed duck farming into the rice-growing cycle on the basis of following the laws of rice cultivation, and achieve synchronous increase in production and efficiency through fine management (Vipriyanti et al., 2021).

2.3 Overview of regional applications of co-culture systems

The rice-duck co-cultivation model has been put into practice in many rice-growing areas in my country, and various forms have been developed according to local conditions. In the middle and lower reaches of the Yangtze River, such as Huai'an District, Huai'an City, Jiangsu Province, the ecological cultivation and breeding of rice and ducks has been promoted since the 2010s, and many family farms have adopted this model to achieve significant economic and ecological benefits. Research statistics show that although the rice yield under the rice-duck model is slightly lower than that of the conventional machine-planting model, the comprehensive benefits are much higher than conventional planting because the rice produced is green, organic and high-quality rice with a higher market price (Gao et al., 2023). In southern rice-growing provinces such as Hunan and Jiangxi, integrated rice farming is seen as an important measure for the structural reform of the agricultural supply side. Some areas in Hunan have combined and promoted the "rice + duck" model with the "rice + fish" and "rice + frog" models to form a regional characteristic ecological agricultural industry. The traditional rice-fish-duck symbiotic system of the Dong ethnic group in Congjiang, Guizhou has been protected and developed, becoming an important carrier of eco-tourism and cultural heritage, attracting a large number of tourists to visit and experience it every year.

In the cold and cool rice-growing areas of Northeast China, there have been experiments in recent years to introduce rice-duck co-breeding into organic rice production, but due to climate and growth period restrictions, the model needs to be adjusted, such as selecting cold-resistant duck varieties. In Asian countries such as Japan and South Korea, modern rice-duck farming technology has also been applied as a means of reducing chemical inputs and producing organic rice. When applying rice-duck co-breeding, various places will improve it in combination with their own natural conditions and breeding traditions. For example, in the Erhai Basin in Yunnan, a scientific research team explored the use of organic fertilizers to replace some chemical fertilizers, and used rice-duck co-breeding to control non-point source pollution, achieving good results. The rice-duck symbiotic system has shown broad prospects in my country's rice-growing areas, but the degree of promotion varies from region to region, requiring targeted demonstration and technical optimization to achieve a balance between ecological and economic benefits.

3 Mechanisms Enhancing Ecosystem Services

3.1 Natural pest and weed control

Biological control of pests and diseases is one of the most prominent ecological service functions of rice-duck co-cultivation model. After the introduction of ducks into rice fields, ducks eat a considerable part of the pests and weeds in the fields, reducing the base number of pests and diseases from the source. For pests, experiments have shown that the incidence of major rice pests such as rice stem borer, rice planthopper, and rice leaf roller in rice-duck fields has been significantly reduced. For example, the field comparison experiment of Lan et al. (2021) showed that compared with the control field without ducks, the amount of insect traps in the rice-duck co-cultivation field was greatly reduced, and the incidence of diseases such as rice sheath blight and rice blast also decreased (because ducks eat pests and reduce the transmission medium). Ducks keep foraging in the fields during the day, preying on insect larvae, eggs and mollusks in the rice fields, effectively curbing the growth of pest populations. This biological insect control effect can replace or reduce multiple pesticide applications. Studies have shown that under the co-cultivation model, the application of pesticides can be reduced by 1-2 times per season without causing a rebound in insect population density, which reflects the green control advantage of "using ducks to control insects". For weeds, ducks like to eat tender weed seedlings and seeds. In the first few weeks after the seedlings are transplanted and survive, it is the period of rice tillering and weed germination. When ducks search for food in the field, they will peck at most broad-leaved weeds and grass weed seedlings such as barnyard grass and duckweed. Studies have determined that the weed biomass in rice-duck co-cultivation fields is more than 70% lower than that in conventional rice fields, and the weed control effect is comparable to that of chemical herbicides. The disturbance caused by duck activities makes it difficult for weeds to take root. After several years of continuous duck release, the weed seed bank in the rice field soil is greatly reduced.

The study of Nayak et al. (2020) also proved that in the integrated rice farming system where ducks or fish are introduced in India and other places, the field weed coverage and density are significantly lower than those in single-plant rice fields. Rice-duck co-cultivation achieves natural control of major pests in rice fields through the feeding and activities of ducks. This ecological regulation function reduces the frequency of pesticide use, not only reduces production costs, but also protects natural enemy insects and biodiversity around rice fields, and maintains the stability of farmland ecosystems. It should be noted that in practice, the release time and density of ducks should be reasonably regulated according to the situation of field pests and weeds to ensure the balance between biological pest control and rice seedling growth.

3.2 Soil health improvement and nutrient recycling

Rice-duck co-cultivation has a significant optimization effect on the soil environment and nutrient cycle of rice fields, which is also one of the key mechanisms for improving its ecological service function. On the one hand, the activities of ducks improve the physical and chemical properties of rice field soil. Ducks swimming and stirring in the field are equivalent to a continuous shallow tillage, making the soil surface more loose and breathable. This is conducive to the rooting and breathing of rice roots, and also increases the activity of soil microorganisms. Lan et al. (2021) found that compared with rice fields without ducks, the soil bulk density of the 0 cm-10 cm soil layer in rice-duck symbiotic fields was reduced, the porosity was increased, and the soil ventilation was improved. At the same time, ducks trample on the field to suspend some of the mud, which helps release the nutrients fixed in the soil for absorption by rice roots. On the other hand, duck feces and leftover feed provide a continuous supply of organic nutrients to the rice fields. Duck feces are rich in elements such as nitrogen and phosphorus. After decomposing in the water environment of the rice field, they directly become a source of nutrition for rice, improving soil fertility. Yan et al. (2023) conducted an experiment in the Chaohu Basin of Anhui Province and showed that in the rice-duck-crayfish tri-aquatic co-cultivation system, soil fertility indicators such as total nitrogen and available phosphorus were significantly higher than those in the monoculture rice field, and the activities of soil urease and phosphatase increased by more than 20%. This shows that rice-duck co-cultivation strengthens the recycling and regeneration capacity of soil nutrients.

The presence of ducks can also affect the water and fertilizer environment dynamics of rice field soil. Xu et al. (2024) pointed out that after organic fertilizers were used to partially replace chemical fertilizers in the Erhai Basin and combined with rice-duck co-cultivation, the nitrogen and phosphorus concentrations in the surface water of the rice fields were significantly reduced. Duck feces are more easily fixed in the soil or absorbed by rice after being diluted by water and mixed with mud and water, reducing nutrient loss and non-point source pollution. At the same time, the stirring of ducks increases the dissolved oxygen in the field water and inhibits the activity of anaerobic microorganisms, thereby reducing the production and emission of methane in rice fields to a certain extent. Wang (2018)'s research shows that the rice field farming model can reduce the greenhouse gas emission intensity per unit area by changing the redox environment. In general, rice-duck co-cultivation improves soil structure and fertility through "duck-assisted farming" and "duck fertilization": it not only builds a benign soil-plant-animal nutrient cycle, but also reduces fertilizer dependence and nutrient loss, and improves the soil quality and functional services of the rice field ecosystem.

3.3 Indirect effects on rice grain quality and nutritional value

In addition to the impact on the environment and yield, the rice-duck co-cultivation model also indirectly improves the quality and nutritional value of rice through various channels. First, the use of rice-duck symbiotic farming can usually produce rice that meets pollution-free or organic standards. Since no or less chemical pesticides and fertilizers are applied during the co-cultivation process, the harmful substance residues in rice are greatly reduced, and food safety is higher. At the same time, sufficient organic nutrient supply and a healthy ecological environment contribute to the improvement of rice quality (Wang et al., 2024). Che et al. (2021) compared the quality indicators of rice under different integrated farming modes in rice fields. The results showed that the rice polishing rate and transparency of rice produced by rice-duck co-breeding were similar to those of conventional farming, while the chalkiness was significantly reduced by 8%–11%, the amylose content increased by about 10%, and the protein content decreased by 6%–10%. Reduced chalkiness and increased amylose usually mean that the rice has a crystal-clear appearance and better taste, which is consistent with consumers' demand for high-quality rice. A moderate reduction in protein content may also make the rice softer and more delicious. Although the rice yield under the integrated farming mode in the above study decreased slightly, the yield decrease in the rice-duck mode was the smallest, only about 96% of the control. The improvement in rice quality allows rice-duck rice to be sold at a higher price in the market, thus compensating for or even exceeding the loss of income caused by the slight reduction in yield. Taking Xingqing Family Farm in Deqing County as an example, the "duck rice" produced by rice-duck co-breeding won the Zhejiang Good Rice Gold Award for its fragrant and sticky taste and safe quality, and the market price is about 15% higher than ordinary rice. Secondly, rice-duck farming also provides consumers with an additional source of high-quality animal protein.

The rice-duck produced by the farming model usually feeds on natural bait in the field. The meat is firm and delicious. Consumers believe that it is more flavorful than caged ducks, and the market price is about 30% higher than ordinary duck meat. Rice-duck farming achieves the production of "double excellence and double high" rice and duck meat, which helps to improve people's dietary nutrition structure and organically combines staple rice with poultry protein. From the perspective of nutritional ingredients, studies have found that the content of certain trace elements such as selenium and zinc in rice-duck rice is slightly higher than that in conventional rice, which may be related to organic fertilizers and biological symbiotic environments. The absence of pesticides also allows rice to retain its own natural aromatic substances, improving the taste quality. Rice-duck farming indirectly improves the quality and nutritional value of rice by creating a pollution-free growth environment and rich nutrient supply. At the same time, the rice-duck meat produced also provides the market with green and healthy animal food. This is of great significance for meeting consumers' demand for high-quality agricultural products and increasing the added value of agricultural products.

4 Ecological Benefits from Reduced Inputs and Pollution

4.1 Decreased use of chemical fertilizers and pesticides

One of the ecological benefits of the rice-duck co-cultivation system is that it significantly reduces the frequency of chemical fertilizer and pesticide application. In traditional rice cultivation, multiple applications of nitrogen fertilizers and spraying of pesticides are often required to prevent and control pests and diseases in order to ensure yield. In the rice-duck symbiotic model, since duck manure can partially replace chemical fertilizers and duck control of insects and weeds can reduce the use of pesticides, the dependence of rice fields on external chemical inputs is greatly reduced. Studies have shown that after adopting rice-duck co-cultivation, the number of rice fertilization and pesticide spraying per season can be reduced by 20%~50%. The experimental evidence of Du et al. (2023) is particularly typical: by introducing ducks to achieve rice-duck regeneration rice in two seasons, while maintaining rice yield, the use of pesticides was reduced by 88%, the use of chemical fertilizers was reduced by 15%, and there was no uncontrolled pests or soil nutrient deficiency. The rice-duck farming ecological model can effectively reduce the total amount of nitrogen fertilizer and pesticide input per mu of rice field, which helps to reduce the pressure of agricultural non-point source pollution. The direct benefit of the reduction of chemical input is the reduction of farmers' production costs. According to the practice of Xingqing Family Farm in Deqing, the cost of rice planting per mu has been reduced by about 17.6% due to the non-application of pesticides (Figure 1). At the same time, the less application of chemical fertilizers also saves certain expenses. Reducing input while ensuring food output is an important manifestation of green agricultural efficiency (Guo and Fu, 2024).

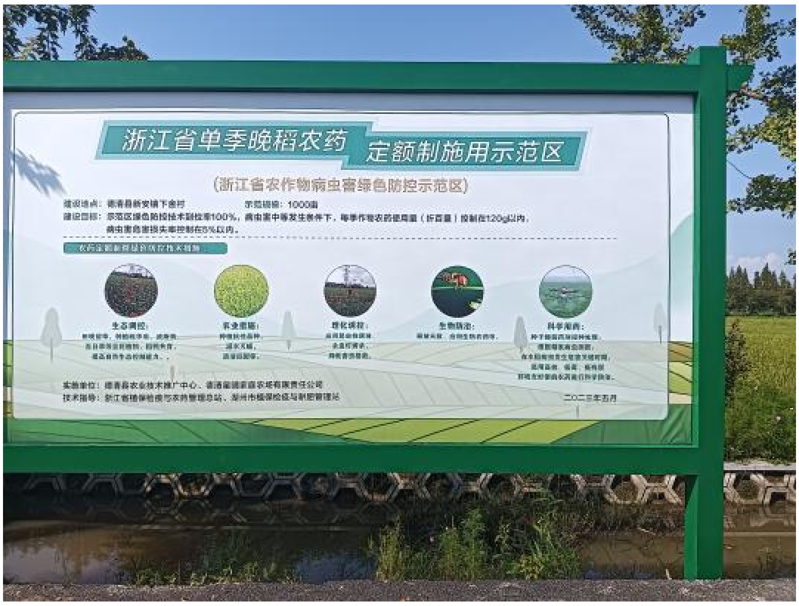

Figure 1 Rice-duck farming reduces pesticide dependence and builds a new model of ecological rice fields (Photographed by Yuchao Shen)

This reduction effect is more ecologically significant when applied on a large scale: if a region promotes rice-duck farming on a large scale, a considerable amount of total fertilizer and pesticide application can be reduced each year, which will have a far-reaching impact on regional soil and water environment protection. It should be emphasized that reducing the frequency of input does not mean no application at all. When serious pests and diseases outbreaks or soil deficiency occur, appropriate chemical means are still needed. Rice-duck farming has achieved the transformation of rice field production from "high input and high output" to "low input and high efficiency" through biological substitution. This not only improves resource utilization efficiency, but also conforms to the current policy direction of reducing fertilizers and pesticides and sustainable agricultural development.

4.2 Reduced environmental burden on soil and water bodies

Rice-duck co-cultivation reduces the pollution and harm of agricultural chemicals to water and soil environment from the source by reducing the use of pesticides and fertilizers. In conventional rice cultivation, a large amount of nitrogen and phosphorus fertilizers are easily lost into field ditches and groundwater, causing eutrophication of water bodies. Frequently sprayed pesticides and herbicides will accumulate in the soil and enter the surrounding waters with farmland runoff, endangering aquatic organisms and ecosystem health. In the rice-duck co-cultivation model, since ducks feed on Cordyceps and return their feces to the fields, there is almost "zero input" of chemical pesticides and herbicides during the planting process, and the demand for chemical fertilizers is also significantly reduced. The study by Xu et al. (2024) specifically measured the water environment and found that in the experimental fields in the Erhai Lake Basin where rice-duck co-cultivation was practiced and 25% of chemical fertilizers were replaced by organic fertilizers, the total nitrogen and total phosphorus concentrations in the field drainage were reduced by more than 30% compared with the conventional fertilized fields. This shows that the co-cultivation model effectively reduces the nutrient load in rice field runoff, which has positive significance for preventing lake eutrophication and protecting regional water quality.

Similarly, the study by Li et al. (2020) pointed out that the rice-duck mixed farming model can alleviate agricultural non-point source pollution in rice fields, and can significantly reduce the chemical oxygen demand and pesticide residue concentration in rice field drainage compared with single planting. In terms of soil, reducing the application of pesticides makes the soil ecological environment safer. Long-term excessive use of pesticides will destroy the soil microbial community and lead to soil functional degradation. In rice-duck co-cultivation fields, since biological control replaces chemical control, the diversity and number of beneficial microorganisms (such as actinomycetes, nitrogen-fixing bacteria, etc.) in the soil are often higher than those in conventional rice fields. The survey by Shi and Jiang (2022) also showed that the detection rate of pesticide residues in farmland soil using rice-duck ecological farming was close to zero, and the pesticide concentration in field water was lower than the national environmental standard limit. This means that the rice-duck co-cultivation model can fundamentally avoid the generation of difficult-to-degrade organic pollutants in agricultural non-point sources, which is conducive to maintaining the cleanliness and health of the agricultural ecosystem. Rice-duck farming promotes the circulation of nutrients in the field, allowing more nitrogen and phosphorus nutrients to remain in the crop-soil system instead of being lost. While ensuring agricultural output, rice-duck farming minimizes the negative impact of chemical inputs on the environment, achieving a win-win situation for agricultural production and environmental protection.

4.3 Sustainable transition through eco-friendly inputs

Rice-duck farming has explored a feasible path of "replacing chemistry with biology" for sustainable agricultural development, that is, controlling weeds, pests and diseases and providing nutrients through ecological means, partially replacing the functions of herbicides, pesticides and fertilizers. It is specifically reflected in the following two aspects: First, using ducks to weed instead of chemical herbicides. Weed control has always been a difficult problem in rice production. In the past, large-scale spraying of herbicides was not only costly but also polluted the environment. In rice-duck farming, ducks have a significant inhibitory effect on common weeds in rice fields such as barnyard grass and duck tongue grass. Practice has proved that as long as the stocking time and density of ducks are controlled, there is basically no need to apply herbicides separately within a growing season to control weed damage to a level that does not affect yield. This not only saves pesticide expenses, but also avoids herbicide damage and residue problems, which can be said to be "killing two birds with one stone". Second, duck manure is used to replace some chemical fertilizers. Duck manure is a high-quality organic fertilizer with a comprehensive nitrogen, phosphorus and potassium nutrient ratio and good slow-release properties. Rice-duck farming allows duck manure to be directly returned to the field, which is equivalent to continuously applying a small amount of organic fertilizer to rice. It is estimated that each duck can produce about 0.05 kg of nitrogen per day, which is equivalent to applying 0.1 kg of urea. If calculated based on 20 ducks per mu, the nutrients provided by duck manure during a growing period can replace about 30%-50% of the amount of chemical nitrogen fertilizer used. Moreover, the organic matter in duck manure is conducive to improving soil fertility and soil structure, which is incomparable to chemical fertilizers. This "raising instead of applying" organic fertilizer source recycling model improves nutrient utilization, reduces fertilizer input, and is more environmentally friendly. Rice-duck farming has taken a sustainable path to reduce external input and reduce environmental pressure by developing ecological circular agriculture. As Wang (2019) pointed out, a series of rice farming and breeding models (including rice-duck farming) reflect the shift of agricultural input from external dependence to internal potential, making agricultural production more dependent on ecological processes and biological functions rather than simply relying on chemicals. This model is in line with the current direction of green agricultural development and has good prospects for promotion.

5 Case Studies

5.1 Xingqing Family Farm (Deqing): model of rice-duck co-culture

As a successful practice case of rice-duck co-cultivation, the experience of Xingqing Family Farm in Deqing County, Zhejiang Province is representative. The family farm began to explore the rice-duck symbiotic breeding model in the 2010s. After years of practice, it has formed a complete set of standardized and large-scale rice-duck co-cultivation operation models (Figure 2). In the planting stage, high-quality rice varieties (such as "Zhehexiang No. 2" and other fragrant japonica rice) are selected for green planting, and chemical pesticides and herbicides are not used during the entire growth period. After the seedlings are planted, about 1 000 mountain ducklings are evenly released into the rice fields according to the fields. The ducks are free to forage for insects and weeds in the rice fields to achieve ecological pest control and weed control.

Figure 2 Rice-duck co-cultivation model at Xingqing Family Farm (Photographed by Yuchao Shen)

According to farm statistics, after adopting rice-duck co-cultivation, there is basically no need for manual weeding, and the average annual reduction of pesticide application per mu of land is 23 times, and the cost of pesticides is almost zero. This reduces the cost of rice planting by about 17.6%, and the rice produced fully meets the standards of pollution-free and green food. After market promotion, "Xingqing" brand duck rice is widely popular for its fragrant and sticky taste and safe quality. The price is about 15% higher than ordinary rice. In the breeding stage, the paddy ducks on the farm are not fed with compound feed. They are only fed with rice grains and broken rice in the evening. The ducks mainly grow by foraging in the fields. On average, 45 paddy ducks can be harvested per mu of paddy field. Because ducks grow in a natural environment and exercise a lot, their duck meat has a unique flavor and a high lean meat rate. They are recognized by the market as high-quality native ducks, and the price is about 30% higher than that of ordinary farmed ducks. The farm has realized the business model of "rice-duck symbiosis, rice-duck double excellence". One season of rice production can obtain both rice and meat duck income, which greatly increases the income per unit of land.

It is reported that Xingqing Family Farm has successfully embarked on a path of ecological agricultural income generation through the development of rice-duck co-cultivation and rice deep processing, with an annual output value of more than 5 million yuan. While achieving economic benefits, the ecological benefits of the farm are also very significant. Since no pesticides or chemical fertilizers are used, the soil and water quality of the farm area remain good; the fields are rich in biodiversity, with frogs croaking and birds flying, creating an ecologically harmonious scene. The success of the rice-duck co-breeding model on the farm is due to several factors: first, the operator is far-sighted, adheres to the concept of ecological planting, and pays attention to product quality and brand building; second, it introduces scientific research cooperation, and has long-term on-site guidance from experts from Zhejiang University and the Provincial Academy of Agricultural Sciences to carry out experiments such as variety selection and fertility improvement, and continuously optimizes breeding techniques; third, it timely promotes mechanization and digital management, purchases rice transplanters, harvesters, plant protection drones, etc., which improves operating efficiency and makes up for the lack of manpower. The case of Xingqing Family Farm shows that as long as rice-duck co-breeding is scientifically managed and operated on a large scale, it can also obtain considerable economic returns and achieve the unity of ecological and social benefits.

5.2 Integration of saffron + rice-duck system: economic and ecological impact

Based on the practice of rice-duck co-breeding, some farmers and enterprises have also explored combining it with other high-efficiency economic crops to further improve land utilization and economic benefits. Deqing Xingqing Family Farm has been experimenting with a "saffron + rice-duck" fusion model since 2024, and has achieved remarkable results. Saffron (*Crocus sativus*) is a precious Chinese medicinal material and spice. Its style (i.e. saffron) is extremely valuable, but its planting season is staggered with rice, which can be complementary to rice-duck co-cultivation rotation. The specific approach is: plant saffron bulbs on the high ridges of the rice field immediately after the rice is harvested, and use the idle fields in winter and spring for saffron production; in early summer, plant rice and raise ducks to achieve "two harvests a year". The paddy field soil is fertilized with duck manure from the previous crop, providing rich nutrients for the growth of saffron, and the saffron residues after harvest can be returned to the field as organic matter for absorption by rice next year, which can be said to complement each other. Under this fusion model, the annual output of dried saffron per mu of land is about 0.5 kg. Together with the income from duck rice and paddy ducks, the average economic benefit per mu exceeds 20 000 yuan, which is far higher than the income from single rice planting. This shows that integrating high-value cash crops into the rice-duck co-cultivation system can greatly increase land output and farmers' income. At the same time, the saffron + rice-duck model continues to maintain the characteristics of ecological farming, without the use of chemical pesticides and fertilizers throughout the process. The saffron produced is of pure quality, and the duck rice and duck meat are green and safe, which has a unique selling point in the market.

The successful exploration of this model shows the great potential of "hybridization" of rice-duck co-cultivation with other agricultural models. In addition to saffron, other regions have also tried to combine rice-duck co-cultivation with aquaculture. For example, some places in Jiangsu raise aquatic animals such as loaches and shrimps in the ditches of rice-duck fields to achieve "three-habitat co-cultivation", and the economic benefits are also considerable. Ji et al. (2021) reported that the implementation of rice-duck integrated farming for many years has helped to continuously improve the fertility of rice field soil and reduce the cycle of pests and diseases, creating good conditions for the introduction of diversified operations. In the future, through scientific and technological innovation, more three-dimensional agricultural models like "saffron + rice-duck" can be designed to give full play to the multifunctional attributes of rice fields, promote agricultural efficiency and increase farmers' income.

5.3 Dual-market value: premium rice quality and free-range duck meat production

The success of the rice-duck co-cultivation model is inseparable from the simultaneous development and marketization of high-quality rice and duck meat products. Since the rice and duck meat produced by this model are of high quality, pollution-free and nutritious, how to jointly promote these two types of products to the high-end market is the key to improving overall benefits. On the one hand, create a "duck rice" brand. By packaging and promoting rice, highlighting its advantages of growing in the ecological environment of duck fields and not applying pesticides and fertilizers, consumers' awareness of its safety and flavor is enhanced. For example, Xingqing Family Farm registered the "Sufan Youxiang" trademark and made duck rice a well-known regional brand. It has won gold medals at the Zhejiang Agricultural Expo many times and is sold well throughout the province. In Huai'an District, Jiangsu Province, the government took the lead in creating a unified brand image for rice produced by ecological integrated breeding and certified it as green food, thereby increasing market recognition. According to statistics, the market price of high-quality and delicious rice produced by the rice-duck co-cultivation model is generally more than 20% higher than that of ordinary rice. The realization of high premiums provides a direct impetus for farmers to adopt this model. On the other hand, it promotes the commercialization of rice field ducks. The native ducks raised in rice fields are known for their large amount of exercise and firm meat, and can be sold as special livestock and poultry products. Many farmers who raise rice and ducks have promoted freshly slaughtered free-range ducks and duck eggs in rice fields to urban consumers through e-commerce, fresh supermarkets and other channels, which are very popular.

Some regions have also developed deep-processed foods using rice field ducks as raw materials, such as Hunan's cured duck and Zhejiang's sauce duck, to further increase the added value of products. The rice-duck model realizes the "two-wheel drive" of plant and animal products, and improves the risk resistance and profitability of the entire industrial chain. It is worth mentioning that the coordinated marketing of rice and duck meat can often promote each other. For example, customers who buy duck rice are likely to be interested in rice field duck meat, and vice versa. Many ecological farms have launched a "rice + duck" combination package, which has achieved good sales results.

Shi and Jiang (2022) analyzed that the overall benefits of rice-duck farming can only be maximized when both rice and duck products are sold at a good price. Therefore, when promoting this model, it is necessary to do a good job in market cultivation in both aspects, including quality standard formulation, brand certification, publicity and promotion, etc. In summary, through brand building and market linkage, the improvement of rice quality and the commercialization of duck meat are promoted in a coordinated manner in the rice-duck farming model, forming a benefit superposition of 1+1>2, setting an example for the virtuous cycle of ecological agriculture.

6 Challenges and Strategic Recommendations

6.1 Constraints in labor and mechanization

Currently, when rice-duck co-breeding is promoted on a large scale, a prominent problem is the high labor demand and low degree of mechanization. Compared with monoculture, rice-duck co-breeding increases the duck-raising process and requires someone to regularly feed, release and collect ducks, which places additional requirements on labor. There is a relative shortage of modern rural labor, especially young and middle-aged labor, and many farmers are unwilling to try it because they are worried that co-breeding rice and ducks is "too troublesome" and "the cost of watching ducks is high". It is difficult to promote mechanized operations in rice-duck co-breeding (Suh, 2015). At present, most aspects of rice production (seedling transplanting, plant protection, harvesting, etc.) have mechanization plans. However, when ducks are active in the rice fields, some machinery cannot be operated in the fields and must wait for the ducks to withdraw. This restricts the planting schedule. At the same time, some machinery and equipment specifically suitable for comprehensive rice farming are not yet perfect, such as automatic duck feeders in the field and self-propelled harvesters with fences, etc., which are still under development.

In response to the problems of labor force and mechanization, the following countermeasures are recommended: First, reduce labor costs through policy support and service organizations. A professional agricultural socialization service team can be developed to provide duck management and other services to large grain farmers who are willing to carry out rice-duck co-breeding, so that farmers can "raise rice-ducks without raising ducks." Agricultural cooperatives in some places have explored unified stocking and centralized management of duck flocks, achieving intensive utilization of labor. Secondly, speed up the development and promotion of machinery and equipment related to rice-duck co-breeding. For example, the development of automatic patrol robots or drones in the field can assist in the care of ducks to achieve intelligent management; the improvement of rice transplanters and spraying drones so that they have working modes that do not harm ducks, etc. We can learn from the experience of Xingqing Family Farm and introduce a digital agriculture platform to remotely monitor and regulate the rice field environment and duck activities. Farmer Shen Yuchao plans to build a digital large-screen system that integrates smart irrigation and smart prevention and control. Farmers can check the water level in the field, the location of the ducks and other information in real time on their mobile phones and remotely operate the equipment. These measures will greatly reduce the manual intensity and attract more young people to participate. Finally, in the long run, it is necessary to cultivate a new team of compound farmers who understand both planting and breeding to improve labor productivity and technical level. The government can organize special training and technical competitions to enhance farmers' confidence and skills in rice-duck co-breeding. Only when the degree of mechanization and intelligence improves and the labor problem is alleviated can rice-duck co-breeding be promoted and applied on a larger scale.

6.2 Consumer perception and value recognition

Although rice-duck co-breeding products have high quality and ecological added value, they often face the problem of insufficient market recognition in the early stages of promotion. First, consumers have limited knowledge. Many consumers lack understanding of the concept of "duck rice" and find it difficult to understand why it is more expensive than ordinary rice. Some people think that rice is just rice, and it is difficult to tell the difference between ecologically grown and non-ecologically grown rice, so they are unwilling to pay high prices. This has led to the embarrassing situation of some farmers who adopt the rice-duck model of "good rice cannot be sold at a good price". Second, sales channels are limited. Under the rice-duck co-breeding model, the yield per unit area is often slightly reduced. If the products are not sold at a good price, it is impossible for farmers to increase their income. The current market for ecologically high-quality rice and free-range native ducks is not broad enough, and corresponding production and marketing channels need to be established and improved. For example, some regions promote duck rice through e-commerce live broadcasts, agricultural products exhibitions and other methods, which has increased product visibility, but overall, this type of market promotion is still insufficient.

In order to solve the problem of market acceptance, a multi-pronged approach is needed: First, increase the science popularization of rice-duck co-breeding products. Use news media and new media platforms to tell the story of "rice-duck co-production" and promote its eco-friendly, healthy and delicious features, so that consumers can realize that "you get what you pay for" and are willing to support green products. The government and industry associations can take the lead in formulating and certifying product standards for "duck rice" and "paddy duck" to enhance consumer trust. For example, a unified ecological planting and breeding product logo should be issued, and the source of rice-duck co-breeding should be clearly identified on the packaging to improve recognition. Secondly, expand marketing models and create brand effects. Support leading enterprises or cooperatives to register regional public brands, sell products from scattered farmers under a unified brand, and open up the market with scale effects (Somsong et al., 2019). Taking Hunan as an example, the local government launched the "Dongting Duck Rice" brand and protected it as a geographical indication, significantly increasing the added value of the product. Thirdly, the government can provide appropriate market incentives, such as giving "green consumption vouchers" rewards to units or individuals who purchase ecological products, or promoting government canteens and school canteens to prioritize the purchase of ecological rice and rice field duck products to demonstrate and drive consumption. Some people in the industry suggest developing rice-duck co-breeding experiential agriculture and adoption agriculture. For example, urban residents adopt a "duck field" to receive a certain amount of rice and duck meat every year, thereby increasing consumer participation and recognition. As long as consumers are fully aware of the advantages of rice-duck co-breeding products in terms of quality and social value, their market acceptance will naturally gradually increase. It is foreseeable that as people's awareness of health and environmental protection increases, the market demand for green organic agricultural products will continue to expand, and the high-quality rice and ducks bred by rice and duck will also have a broader market space.

6.3 Need for technical standards and policy support

In the process of promoting rice-duck co-breeding, perfect technical standards and strong policy support are also indispensable. First of all, there is still a lack of unified technical specifications for rice-duck co-breeding in some areas. Farmers mainly rely on experience, resulting in uneven production results. Therefore, there is an urgent need to standardize the planting and breeding technology system. For example, what kind of ducks are suitable for stocking in which rice growing areas, how to control stocking density and time, what are the requirements for water and fertilizer management and disease prevention and control, etc. Mature experience should be summarized and upgraded to regional technical regulations or industry standards to guide large-scale promotion. Scientific research institutions and extension departments should strengthen collaboration, conduct systematic research on rice-duck co-breeding models in different ecological zones, develop standard manuals and distribute them to farmers through training. Secondly, policy support must keep up. The initial investment in developing rice-duck co-breeding is relatively large, such as purchasing duck-proof facilities, building duck sheds, purchasing duck seedlings, etc., which all require a certain amount of funds. The government can reduce the burden on farmers through project subsidies, loan discounts, etc., and encourage them to adopt ecological farming models. For example, a certain amount of reward per mu will be given in lieu of subsidy to the certified rice-duck co-breeding demonstration base to mobilize the enthusiasm of farmers. In Zhejiang and other places, there are special subsidy policies for comprehensive rice farming, and farmers have responded well. The policy should also include insurance and risk protection measures. Since the introduction of rice-duck co-breeding into the breeding process, natural risks and market risks have increased. The government can explore the pilot program of rice-duck co-breeding insurance and provide compensation for losses caused by natural disasters or epidemics to reduce farmers' concerns. Finally, a collaborative promotion mechanism must be established. Rice-duck co-breeding involves two departments: planting and breeding. In the traditional agricultural management system, the two often belong to different departments (for example, the planting industry belongs to the agricultural technology extension station, and the animal husbandry belongs to the animal husbandry and veterinary station).

Therefore, departmental collaboration should be strengthened and a joint technical team should be established to jointly promote the promotion services of rice-duck co-breeding technology (Vipriyanti et al., 2021). Agricultural and rural departments at all levels can organize cross-field expert tours to provide guidance and go to the front line of production during key farming seasons to help farmers solve technical problems. Give full play to the leading role of new business entities and demonstration households, and establish a number of rice-duck co-breeding demonstration areas so that surrounding farmers can visit and learn on the spot and enhance their confidence in the model. Through a "two-pronged approach" of technical standardization and policy support, the rice-duck co-breeding model is expected to accelerate from sporadic exploration to large-scale promotion, forming a sound development situation with government guidance, expert support, and farmer participation.

7 Concluding Remarks

As a modern ecological agricultural model, rice-duck symbiotic farming is of great significance to the current green transformation of agriculture. It combines the traditional experience of duck farming in rice fields with modern scientific farming techniques to explore a path for the coordinated development of food production and ecological environment. Studies have shown that compared with single planting, the rice-duck symbiotic farming system can reduce the input of pesticides and fertilizers, control agricultural non-point source pollution, improve biodiversity and soil fertility, and realize the transformation of the agricultural production system from "high input and high pollution" to "low input and low pollution" without significantly reducing rice yields. This is highly consistent with the country's strategy of promoting high-quality agricultural development and building a beautiful China. Rice-duck symbiotic farming is not only a simple combination of farming and breeding, but also represents a new agricultural value and production paradigm: emphasizing the use of biological reciprocity and ecological cycles to replace dependence on industrial chemicals. This has a demonstrative significance for solving the problem of agricultural non-point source pollution and repairing damaged farmland ecology. In addition, the safe and high-quality agricultural products produced by rice-duck symbiotic farming meet people's growing demand for healthy food and provide a new path for farmers to increase their income. Some practices have proved that farmers who adopt rice-duck symbiotic farming have significantly increased their income and embarked on the road to ecological prosperity. Therefore, the promotion of the rice-duck co-cultivation system will help my country's agriculture shift from a production-oriented to a quality-oriented approach, and accelerate the green transformation of achieving a "win-win" situation for agricultural production and ecological benefits.

Based on the experience of rice-duck co-cultivation, the improvement of the service function of the rice field ecosystem requires systematic measures based on the overall agricultural ecosystem. First, the integrated rice field farming model, including rice-duck co-cultivation, should be vigorously promoted. Integrated farming can provide food while outputting other ecological products (such as poultry meat and aquatic products) and service functions (such as insect control and fertile land) by optimizing the food chain structure and material circulation pathway of farmland. This is seen as an important way to improve the multifunctionality of agricultural ecosystems. Secondly, strengthen the research and development and application of ecological inputs, such as organic fertilizers, biological pesticides, and biological traps, to gradually replace chemical inputs and reduce disturbances to the environment. At the same time, use information technology and the Internet of Things to dynamically monitor farmland ecological indicators (insect population density, soil nutrients, water quality, etc.), achieve precise regulation, and ensure that ecological measures are implemented in place. Thirdly, build a good policy support system to encourage farmers to adopt ecological farming and raise their enthusiasm through subsidies and technical services. Furthermore, it is possible to consider incorporating the improvement of farmland ecological services into the assessment of agricultural subsidies, rewarding farmers who reduce fertilizers and pesticides and protect habitat diversity, and guiding the transformation of production methods from a policy perspective. Finally, cultivating the market for ecological agricultural products is also an indispensable part. When consumers are willing to pay a premium for eco-friendly products, the external value of ecological agriculture can be internalized as producer benefits. Therefore, it is necessary to improve ecological certification and carry out publicity and education to make the whole society aware of the importance of farmland ecological services, thereby forming a good atmosphere for supporting ecological agriculture. The successful practice of the rice-duck co-cultivation model proves the feasibility of the above path. As long as the government, scientific research, and the market work together, a sustainable development path that gives equal importance to improving farmland ecological services, ensuring food security, and increasing farmers' income can be found.

Looking to the future, the rice-duck co-cultivation system will achieve greater development in the direction of scale and intelligence. On the one hand, with the advancement of technology and the maturity of the model, rice-duck co-cultivation is expected to break through the current small-scale decentralized operation and move towards regionalized and intensive development. In suitable areas, a rice-duck co-cultivation demonstration area of 10 000 mu can be established to form an integrated industrial chain of production, processing, and sales to enhance competitiveness. Through large-scale operation, unified varieties and unified management, it is easier to achieve mechanization and standardization, which will help reduce costs and improve production stability. On the other hand, modern information technology and equipment will deeply empower rice-duck co-cultivation and achieve intelligent upgrading. For example, develop an intelligent duck flock monitoring system based on image recognition to understand the distribution and behavior of ducks in real time; use big data analysis to optimize the duration and density of duck release; use drones to spray biological pesticides and robots to clean up field debris to reduce human intervention. In some cutting-edge explorations, there are even bionic "machine ducks" used for paddy field weeding to make up for the lack of live ducks or avoid damage to crops. The application of these technologies will greatly improve the production efficiency and adaptability of rice-duck co-cultivation, making it more competitive in modern agriculture. In addition, the progress of breeding and biotechnology is also worth looking forward to. In the future, it may be possible to cultivate rice varieties that are more in line with the ecology of rice fields (such as varieties that are resistant to lodging and suitable for symbiosis with ducks) and domestic duck varieties (such as special meat ducks that do not peck at rice ears) to further optimize the co-cultivation effect. At the policy level, as the country attaches great importance to the green development of agriculture, the support policies for integrated rice farming may be improved, providing a good external environment for the expansion and development of the model. In short, as a product of the integration of traditional wisdom and modern technology, rice-duck farming has broad prospects. Through continuous innovation and improvement, this model is expected to achieve the unity of economic, ecological and social benefits on a larger scale, become an important part of future smart agriculture and sustainable agriculture, and make greater contributions to ensuring food security, increasing farmers' income and building an ecological civilization.

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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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