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Field Evidence of Eco-Friendly Pest Management for Sustainable Production of High-Quality Rice

Qifu Zhang
Hier Rice Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China
Corresponding email: qifu.zhang@hitar.org

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Abstract High-quality rice production aims not only to achieve stable and high yields but also to improve grain quality, protect the environment, and support sustainable agriculture. Insect pests are one of the main factors affecting rice yield and quality. Conventional pest control mainly depends on chemical pesticides. Although this approach can quickly reduce pest populations, it often leads to pesticide resistance, loss of natural enemies, environmental pollution, and food safety concerns. This paper reviews eco-friendly pest management practices, including pest monitoring and early warning, habitat improvement, conservation of natural enemies, ecological engineering, biological control, and integrated pest management (IPM). Typical field cases, such as green pest control demonstration fields in Zhejiang Province, rice-duck farming systems, ecological engineering in rice fields, and Farmer Field Schools, are used to explain how these practices influence pest population dynamics, plant health, yield formation, environmental protection, and farmers' economic returns. The results show that eco-friendly pest management can effectively reduce pest outbreaks, decrease the use of chemical pesticides, and protect farmland biodiversity. At the same time, it helps maintain or increase rice yield, improves grain quality, and supports a more stable agricultural ecosystem. In the future, greater efforts should be made to strengthen digital pest monitoring, expand ecological farming practices, and encourage cooperation among researchers, extension services, and farmers. These measures will promote the wider adoption of green pest management in high-quality rice production and provide scientific support for food security, ecological sustainability, and long-term agricultural development.

Keywords High-quality rice; Eco-friendly pest management; Integrated pest management (IPM); Green pest control; Sustainable agriculture

1 Introduction

Rice is one of the most important food crops in the world and provides a stable source of calories for more than half of the global population. However, rice production is facing increasing pressure from climate change, population growth, urbanization, and limited natural resources. In several major rice-producing regions, yield growth has slowed or reached a plateau, while global demand for rice is expected to continue increasing. As a result, improving production without placing greater pressure on the environment has become a major goal of rice research (Bin Rahman and Zhang, 2023). Rice is important not only as a staple food but also for its nutritional value, market value, and eating quality. It contains carbohydrates, vitamins, minerals, and many bioactive compounds. Improving rice quality can also help achieve both food security and environmental sustainability at the same time (Mohidem et al., 2022).

Rice is also one of the largest consumers of freshwater in agriculture. More than 75% of the world's rice is still grown under flooded conditions. The long-term sustainability of rice farming is threatened by water shortages, methane emissions, rising labor costs, declining soil health, and increasing biotic and abiotic stresses (Nawaz et al., 2022). High yield and efficient resource use are not mutually exclusive. An analysis of 32 rice production systems covering about half of the world's harvested rice area showed that most systems still have room to improve both yield and resource-use efficiency. By improving only the systems with the largest yield gaps or the lowest efficiency, global rice production could theoretically increase by 32% while almost eliminating excessive nitrogen use (Yuan et al., 2021). A survey conducted in five provinces of China found that wider adoption of climate-smart agricultural practices, including reduced tillage, improved rice varieties, organic manure, water-saving irrigation, and biological pesticides, was associated with an average yield increase of 94 kg/mu (about 1 410 kg/ha) (Vatsa et al., 2023). In Bangladesh, improving the broken rice rate to an acceptable market level could maintain the current food supply while reducing land use by about 170.79 thousand hectares and lowering greenhouse gas emissions by approximately 1.48 million metric tons of CO_2 equivalent (Saha et al., 2021).

Rice plants are exposed to many biological threats throughout the growing season, including bacteria, fungi, viruses, nematodes, insects, and weeds. In heavily affected regions, these stresses can cause around 30% of global rice yield losses. Among them, insect pests and weeds have long been recognized as two of the most serious biological constraints to rice production worldwide (Shi et al., 2023). Improper use of insecticides can even make pest problems worse. Frequent or excessive pesticide application destroys natural enemies and weakens the ecological balance of rice fields, making pest outbreaks more likely. Therefore, integrated pest management (IPM) and other eco-friendly pest control strategies have become important approaches for sustainable rice production. These strategies include conserving natural enemies, improving field habitats, using insect-resistant rice varieties, promoting farmer participation, and applying biological pesticides derived from plants or microorganisms (Zhou et al., 2024). Plant-based pest control materials and locally developed biopesticides have also shown good potential. Several biopesticide treatments have significantly reduced populations of green leafhoppers while causing only limited effects on non-target organisms such as spiders. Studies during grain storage have also shown that plant powders can reduce insect damage and help maintain rice quality (Polakitan et al., 2025). Because plant-based pesticides are biodegradable, have a lower environmental impact, and are compatible with biological control, resistant varieties, and other agronomic practices, they are becoming an important part of rice IPM. This paper links sustainable production of high-quality rice with eco-friendly pest management. It focuses on whether green pest control under real field conditions can achieve stable yield, better grain quality, lower pesticide use, higher production efficiency, and improved environmental protection at the same time. It also provides evidence to support future technology extension, farmer training, regional adaptation, and policy development.

2 Eco-Friendly Pest Management Practices

2.1 Early pest monitoring and timely intervention

Rice pest management is not based on spraying pesticides on a fixed schedule. Instead, it starts with regular monitoring of pest populations, crop damage, and natural enemy activity. Control measures are taken only when field conditions indicate that they are needed. Field scouting is still an important part of this process. However, traditional manual surveys are time-consuming, subjective, and difficult to track over time. Today, they are increasingly supported by modern monitoring tools, such as machine vision-based automatic light-trap identification systems, field camera monitoring systems, and augmented reality tools that can detect small pests and natural enemies. These technologies improve both the accuracy and speed of pest monitoring (Yao et al., 2020). Studies have shown that automatic light-trap identification is highly consistent with manual counting (r = 0.92). New field detection models can also identify pests accurately in real time under complex field conditions, showing that digital monitoring is becoming a practical tool for precision pest management (Hong et al., 2025; Yin et al., 2025).

In field practice, regular monitoring is not intended to spray pesticides as soon as pests are found. Instead, farmers monitor pest abundance, seasonal peaks, crop damage, and natural enemy populations together before deciding whether intervention is necessary. Light-trap studies have shown that different rice pests have distinct seasonal and daily activity patterns. Continuous monitoring provides direct information for choosing the best control timing. A four-year light-trap study identified different peak periods for six major rice pests, making it possible to manage each pest at the right time (Atta et al., 2024). For rice leaffolders and striped stem borers, studies found that trap height and operating time strongly influence monitoring efficiency. Setting light traps at canopy height and adjusting operation during the first or second half of the night improved capture rates of target pests (Uddin et al., 2025). In striped stem borer monitoring, adult moth numbers began to increase sharply in early August and continued rising until October. This result suggests that tracking adult populations allows farmers to take action before serious crop damage occurs (Arain et al., 2025).

2.2 Habitat improvement

Habitat improvement aims to maintain vegetation around rice fields, protect flowering plants, and reduce unnecessary disturbance. These practices provide food, shelter, and alternative prey for natural enemies. Agricultural fields are often disturbed by farming activities, making it difficult for predators and parasitoids to survive throughout the season. Improving ecological infrastructure can provide nectar, pollen, shelter, and alternative hosts, helping natural enemies remain active in both space and time. In rice production, ecological engineering usually includes preserving field-edge vegetation that supports overwintering parasitoids, planting flowering plants on field bunds, and reducing unnecessary insecticide applications during the early growing season to maintain the natural food web. Lower insecticide use, selective pesticides, and better habitat management are all important for conserving natural enemy populations.

Field studies have shown that planting nectar-producing flowering plants along rice field bunds increases the abundance of natural enemies, improves parasitism rates, and strengthens pest suppression while maintaining stable rice yield with less pesticide use. Flowering species such as marigold, cowpea, and sesame are highly attractive to many beneficial insects. Rice fields with flowering plants supported larger populations of lady beetles, ground beetles, rove beetles, mirid bugs, damselflies, and spiders. These fields also produced higher rice yields and better economic returns than conventional fields (Meera et al., 2026).

2.3 Conservation of natural enemies

Rice fields naturally contain a complex food web, where many predators and parasitoids help suppress herbivorous pests. Common natural enemies include spiders, predatory true bugs, parasitoid wasps, and many other beneficial insects that attack important rice pests. Surveys in early-season rice fields found that generalist predators such as spiders and mirid bugs were already abundant during the early crop stages. The application of organic materials and the maintenance of decomposer communities provide alternative prey for these predators, allowing their populations to establish before pest numbers increase (Hajjar et al., 2023).

Spiders, dragonflies, damselflies, predatory mirid bugs, and egg parasitoids have repeatedly been identified as key natural enemies in eco-friendly rice production. Rice fields planted with flowering plants consistently supported higher numbers of spiders, damselflies, dragonflies, green mirid bugs, and parasitoid wasps. These fields also showed higher egg parasitism rates of brown planthoppers, striped stem borers, and rice leaffolders. In a biological control program carried out in the Greater Mekong Subregion, IPM based on Trichogramma parasitoids increased the abundance of natural enemies. Spider populations doubled, insecticide applications were reduced by 1.5 sprays per season, and rice yield increased by 2%~10% (Babendreier et al., 2020). Different groups of natural enemies attack pests at different life stages, feeding sites, and activity periods. Their complementary roles often provide stronger pest suppression, especially when rice fields offer diverse habitats that reduce competition among beneficial species (Snyder, 2019).

2.4 Integrated eco-friendly measures

Light trapping is one of the most widely used physical control methods in rice production. Besides directly reducing pest populations, it also provides continuous monitoring information with little dependence on chemical pesticides. Solar-powered light traps can capture yellow stem borers, rice leaffolders, leafhoppers, planthoppers, rice bugs, and other important pests. Field studies showed that these traps significantly reduced pesticide applications and lowered pesticide costs by an average of 1 034 BDT per hectare (Rashid et al., 2022). Optimizing trap height and operating time further improves trapping efficiency and allows light traps to be integrated into IPM programs under different ecological conditions. Field experiments with Internet of Things (IoT)-based light-trap systems reported major reductions in both pest populations and pesticide use. In one study, pesticide use decreased by 91.67%, showing the strong potential of intelligent physical pest control technologies (Simpao et al., 2025).

Sex pheromone traps are more selective and are especially useful for monitoring and controlling lepidopteran pests. In striped stem borer field trials, pheromone traps caught more moths throughout the season than light traps. Fields using pheromone traps had the lowest rates of white heads and dead hearts and produced the highest rice yields. These results show that pheromone traps are effective not only for monitoring but also for reducing adult pest populations (Arain et al., 2025). Studies on integrated trapping systems have shown that combining colored sticky traps, sex pheromones, and ultraviolet light traps can improve the capture of several important rice pests. However, different pest species respond differently to light sources. For example, rice leaffolders show negative responses to some ultraviolet light components. Therefore, trapping systems should be selected according to the biology and behavior of the target pest (Zeng et al., 2025).

Biopesticides and biological control agents provide another important option for eco-friendly pest management. A wide range of biological control agents, including fungi, bacteria, viruses, and nematodes, have been tested against rice pests. Among them, Metarhizium, Beauveria, and Bacillus thuringiensis (Bt) have shown good activity against several important rice pests. Eco-friendly pest management does not completely exclude chemical insecticides. Instead, it recommends using selective insecticides only when pest populations reach the action threshold. This approach reduces unnecessary pesticide applications while minimizing negative effects on natural enemies and the ecological functions of rice fields (Figure 1).

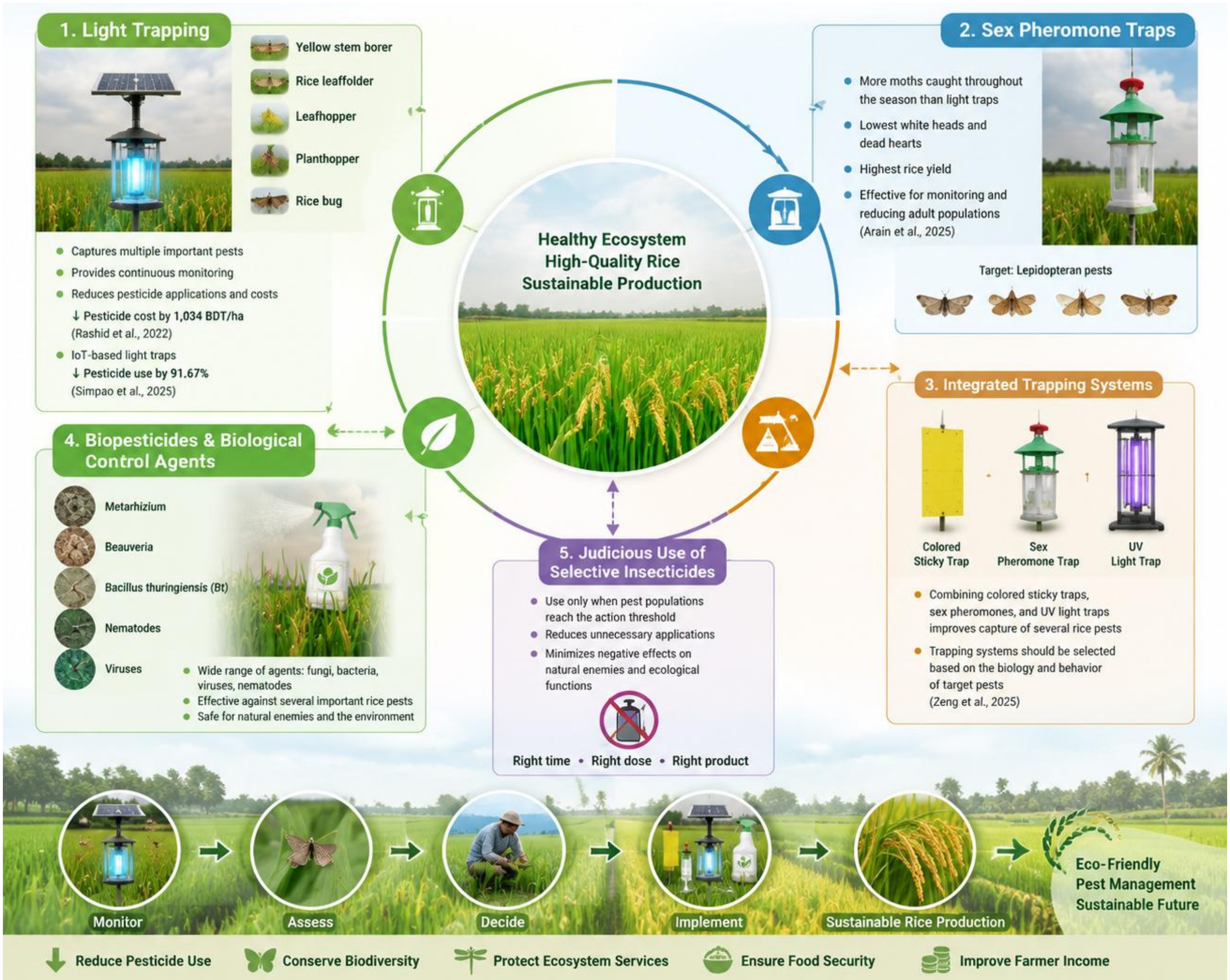

Figure 1 Field-based evidence of integrated eco-friendly pest management approaches for improving sustainability of high-quality rice production

3 Field Evidence from High-Quality Rice Production

3.1 Case study 1: green pest management demonstration fields in Zhejiang province, China

Zhejiang Province has standardized ecological engineering practices and promoted them on a large scale in rice production. The main measures include maintaining beneficial vegetation along field edges, planting nectar-producing plants on field bunds, using trap plants, releasing Trichogramma parasitoids when needed, and combining these methods with sex pheromone traps. Under this integrated system, insecticide use has been reduced by about 50% (Zhu et al., 2022) (Figure 2). Solar-powered light traps continuously capture important rice pests, including yellow stem borers, rice leaffolders, brown planthoppers, and leafhoppers. Field results showed that these traps reduced the number of pesticide applications and lowered pesticide costs without reducing rice yield. Because light traps also capture some beneficial insects, they are most effective when used together with field monitoring and selective control rather than as a replacement for all pest management practices.

Heavy reliance on chemical insecticides often reduces natural enemy populations and can lead to secondary pest outbreaks. Therefore, sustainable rice production encourages biological control and the conservation of beneficial insects. In Zhejiang rice fields, nectar-producing plants such as sesame grown on field bunds increase the activity of Trichogramma wasps, the rice planthopper egg parasitoid Anagrus, and predatory mirid bugs. Functional weeds and intercropped water bamboo (*Zizania latifolia*) also provide shelter for spiders, frogs, and parasitoid wasps, further improving natural pest control.

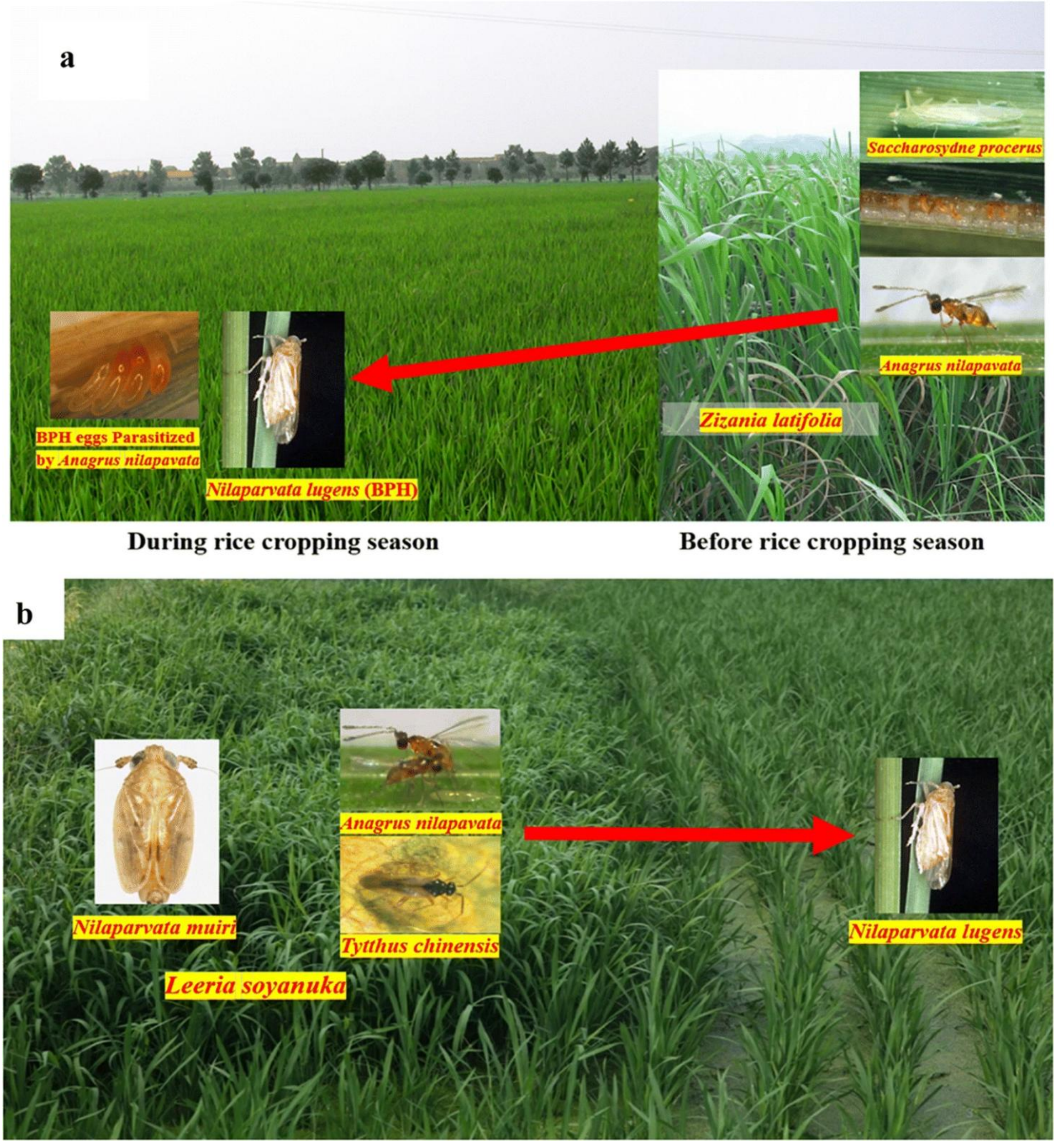

Figure 2 Banker plant systems used in rice production. a The *Zizania latifolia-Saccharosydne procerus-Anagrus* spp. (ZSA) system, BPH refers to the brown planthopper *Nilaparvata lugens*; b *Leersia sayanuka-Nilaparvata muiri-Anagrus* spp. & *Typhus chinensis* (LNA&T) system (Adopted from Zhu et al., 2022)

3.2 Case study 2: rice-duck farming system

The rice-duck farming system controls pests and weeds by allowing ducks to forage, walk, and move freely in rice fields. Their feeding behavior directly removes insects and weeds while improving the field environment, reducing the need for pesticides and herbicides. A field experiment conducted under organic management in suburban Shanghai showed that duck release significantly reduced weed density and lowered the occurrence of striped stem borers, rice leaffolders, and planthoppers. The reductions in rice leaffolder damage, sheath blight, and planthopper populations were especially significant. Duck farming also increased soil ammonium nitrogen, available phosphorus, available potassium, and the activity of several soil enzymes. Rice yield reached 1.9 times that of the control treatment, while pesticide and herbicide inputs were greatly reduced (Teng et al., 2016). Duck activities, including feeding, trampling, movement, and the addition of manure, reduced insects, diseases, and weeds, improved field conditions, and increased biodiversity. Control efficiency reached 98.47% for planthoppers and 100% for leafhoppers, while stem borers and rice leaffolders were also effectively suppressed (Long et al., 2013).

For high-quality rice production, the benefits of the rice-duck system extend beyond reducing pesticide use. Compared with conventional rice farming, ecological rice-duck systems reduce production costs, increase profits, improve grain quality, and strengthen the resilience of the farming system. They also reduce lodging during typhoon seasons and decrease rice leaffolder damage (Zhuo et al., 2025) (Figure 3). After several years of operation, ecological rice produced under this system can obtain China's Green Food certification, build a market brand, and achieve premium prices. Ducks also provide an additional source of farm income. However, the pest control effect is not always consistent under all conditions. A study from northern Zhejiang reported that rice-duck fields had higher populations of planthoppers and leafhoppers than conventional and untreated fields, while spider and dragonfly populations were lower. This finding suggests that unsuitable duck density, release timing, or poor habitat management may reduce natural enemy populations and weaken biological control. Even so, the organically certified rice-duck system still achieved net profits that were 7.6 times higher than those of conventional farming and 1.4 times higher than the untreated control (Qian et al., 2022).

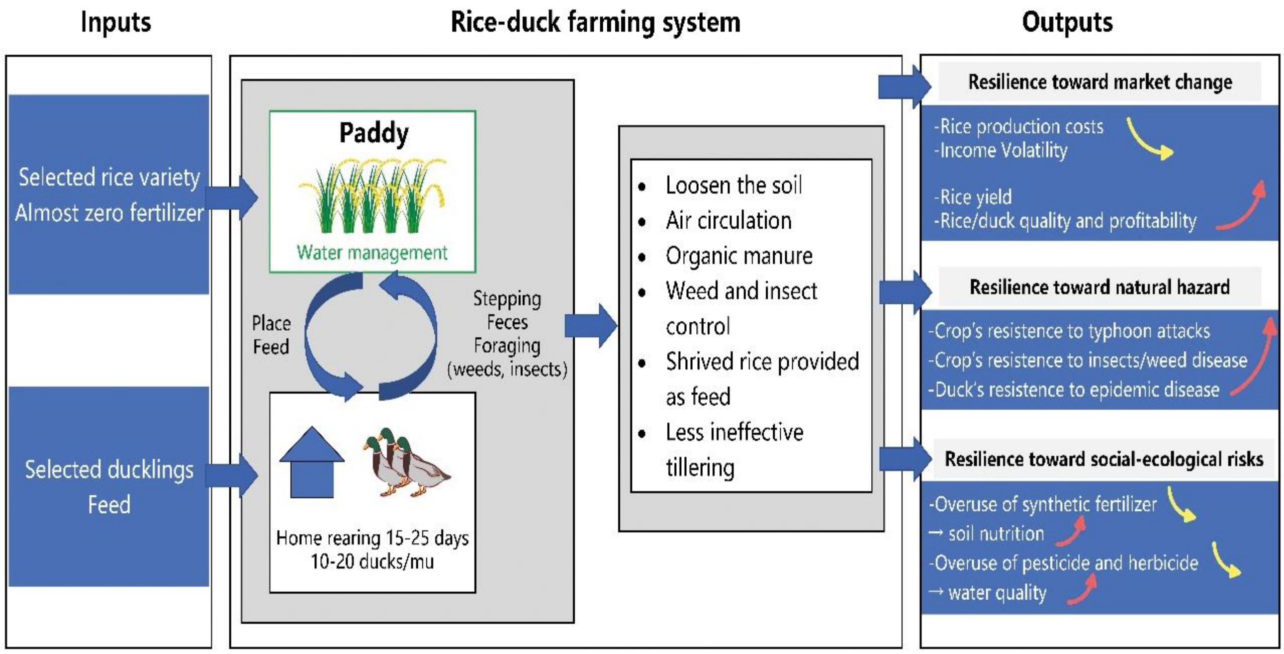

Figure 3 Ecological rice-duck integration farming system conceptualization. Notes: This figure is about the study case and drawn by the authors. At XQ farm, Shen selected "Zhe'he'xiang 2" late rice and shelducks to operate the rice-duck integration farming system. Blue thick arrows, material flow in rice-duck farming system; yellow arrows, the decrease of rice production costs, income volatility, overuse of synthetic fertilizer, pesticide and herbicide; red arrows, the increase of rice yield, rice/duck quality and profitability, soil nutrition and water quality (Adopted from Zhuo et al., 2025)

3.3 Case study 3: ecological engineering in rice fields

Ecological engineering in rice fields mainly involves establishing strips of flowering plants along field bunds and field margins. These flowering plants provide nectar, pollen, alternative hosts, and shelter for parasitoids and predators, helping natural enemies suppress pests throughout the growing season. In many rice fields, beneficial insects cannot maintain stable populations because food resources and suitable habitats are limited. Planting nectar-producing flowers along field bunds increases the abundance of predators and parasitoids, reduces pest populations, and maintains rice yield. Field studies showed that ecological engineering significantly increased predator abundance, parasitoid abundance, and parasitism rates compared with both conventionally sprayed fields and untreated fields. At the same time, major pest populations and crop damage were significantly reduced without any yield loss (Ali et al., 2019).

Another study involving eight field experiments conducted across different seasons and locations reached similar conclusions. Rice fields with flowering plants consistently supported higher populations of spiders, damselflies, dragonflies, lady beetles, ground beetles, rove beetles, green mirid bugs, and parasitoid wasps. Egg parasitism rates were also higher than those in conventional fields. Average rice yield remained almost the same as that of farmers using routine preventive insecticide applications, with yields of 5.99 t/ha and 5.93 t/ha, respectively (Bari et al., 2025).

The value of ecological engineering is not limited to pest control during a single growing season. It also improves the long-term resilience of rice ecosystems. Multi-country and multi-season studies showed that flowering-strip ecological engineering reduced insecticide use by 70%, lowered pest density by 30%, increased biological control by 45%, improved rice yield by 5%, and increased farm profits by 7.5%. In China, plants growing along rice field bunds provide shelter, nectar, alternate hosts, and pollen (SNAP) for parasitoids, cricket-like egg predators, spiders, and other beneficial organisms. When these habitat improvements are combined with avoiding insecticide applications during the early crop stage, biological control becomes even more effective (Heong et al., 2021). Planting sesame, sunflower, soybean, and marigold along field bunds significantly reduced brown planthopper populations, delayed pest outbreaks, increased the activity of spiders, mirid bugs, and rove beetles, and finally improved rice yield.

4 Effects on Pest Population Dynamics

4.1 Lower early-season pest colonization

Planting flowering plants along rice field bunds, maintaining functional vegetation, avoiding unnecessary insecticide applications during the early crop stage, and using trap plants can provide food, shelter, and alternative hosts for predators and parasitoids before pest populations become established. Many important rice pests migrate into rice fields from surrounding areas rather than overwintering locally. Therefore, the strength of local ecosystem services largely determines whether invading pests can survive and build their populations. When biodiversity and natural biological control are well maintained, invading pests often remain at low population levels instead of developing into major outbreaks.

Lower pest colonization during the early season is closely related to a better balance between pests and natural enemies. During the early growth stage, generalist predators such as spiders and mirid bugs are already abundant in rice fields. These predators gain an early advantage by feeding on alternative prey supported by the detritus food web before major herbivorous pests arrive. Applying organic matter before planting further increases decomposer organisms and predator populations. In contrast, experiments that removed natural enemies during the early season resulted in serious pest outbreaks later in the growing season. These findings show that conserving natural enemies early in the season is a key mechanism for preventing later pest population growth rather than simply being a secondary ecological effect (Settle et al., 1996). Studies also found that plant diversity along rice field bunds is positively associated with predator abundance. In ecological engineering fields, predator numbers increased significantly during the flowering period, while densities of planthoppers and leafhoppers during the early tillering stage remained similar to or lower than those in conventional fields, indicating that natural biological control had already begun to function (Qian et al., 2021).

4.2 Slower population growth during the mid-season

From the tillering stage through stem elongation and panicle initiation, eco-friendly pest management mainly slows the rate of pest population growth rather than causing immediate pest elimination. Planting nectar-producing flowering plants along field bunds increases the abundance of predators and parasitoids as well as parasitism rates. At the same time, both pest populations and crop damage decrease, indicating that biological control continues to suppress pest development throughout the growing season. Ecological engineering fields consistently support larger populations of spiders, damselflies, dragonflies, lady beetles, ground beetles, rove beetles, green mirid bugs, and parasitoid wasps than conventionally managed rice fields. Egg parasitism rates of brown planthoppers, yellow stem borers, rice leaffolders, and rice thrips are also higher. This advantage allows pest populations to remain below the economic threshold.

The suppressive effect is particularly clear for brown planthoppers and rice leaffolders, which are two of the most important pests during the middle of the growing season. Field experiments in India showed that ecological engineering reduced brown planthopper densities to 6.3 and 9.4 insects per hill in 2019 and 2020, respectively, compared with 9.8 and 14.4 insects per hill in the control treatment. Pest outbreaks also occurred later and reached lower peak levels. Researchers attributed this slower population growth to increased activity of spiders, mirid bugs, and rove beetles, which continuously suppressed brown planthopper populations throughout the season (Yele et al., 2023). Studies on green leafhoppers also found that combining ecological engineering with biopesticides resulted in much lower pest densities than either preventive insecticide spraying or untreated controls. Natural enemy populations became especially abundant during the later growth stages, suggesting that pest suppression established in the middle season continued into the late season (Rosida et al., 2025). Similar results have been reported for rice leaffolders. Diversified field margins and border planting reduced both pest populations and crop damage. In natural farming systems, border planting with aromatic rice significantly lowered rice leaffolder populations and improved the balance in favor of natural enemies (Chowdhury et al., 2023).

4.3 Reduced risk of late-season pest outbreaks

Field exclusion experiments have shown that when natural enemies are removed from rice fields, brown planthopper populations increase rapidly and cause much greater yield losses. These results demonstrate that a complete natural enemy community is one of the most important ecological safeguards against late-season pest outbreaks (Ali et al., 2023). Conserving beneficial insects while reducing unnecessary chemical disturbance helps maintain a more stable and resilient rice ecosystem. Once this ecological balance is disrupted, secondary pest outbreaks, resurgence of minor pests, and the development of pesticide resistance become much more likely.

Late in the growing season is usually the period when planthoppers, rice leaffolders, and stem borers reach their highest population levels. Therefore, the ecological stability established during the early and middle growth stages largely determines whether severe pest outbreaks occur later. Long-term monitoring studies have shown that many major rice pests reach their annual peak from late tillering through heading and grain filling. Peak populations of brown planthoppers, rice leaffolders, and stem borers generally occur between September and October (Panse and Sharma, 2026). Ecological engineering, bio-intensive integrated pest management (BIPM), and IPM all increase the diversity, evenness, and effectiveness of natural enemy communities. As a result, pest population peaks become lower and crop damage is reduced (Reddy et al., 2024). Field studies conducted in Bangladesh, China, and other countries found that ecological engineering not only reduced pest density but also lowered the occurrence of severe crop damage and decreased the risk of yield loss during the late season (Ali et al., 2019). Participatory ecological engineering demonstration programs also reported lower populations of planthoppers and stem borers together with larger populations of natural enemies. These results indicate that stable ecological regulation can replace emergency pesticide spraying as the main strategy for managing late-season rice pests (Shanmugam et al., 2022).

5 Effects on Yield Performance and Sustainable Production

5.1 Better plant health

Field studies have shown that eco-friendly pest management improves rice plant health by reducing pest damage throughout the growing season. In a two-year field experiment, IPM significantly reduced the incidence of dead hearts and white heads caused by stem borers. The lowest dead heart rates were 1.23% and 1.55% in the two study years, while the white head rate was only 2.06%, indicating more effective control of stem borer damage (Alam et al., 2016). A three-year demonstration in farmers' fields in India reported similar results. Eco-friendly management reduced dead hearts, white heads, rice leaffolder damage, and rice earhead bug injury to 2.34%, 2.42%, 4.11%, and 2.56%, respectively. All values were significantly lower than those under farmers' conventional practices (Kedarnath et al., 2024). Integrated organic nutrient management also reduced damage caused by striped stem borers, rice gall midges, and rice leaffolders while improving plant growth and yield performance. Ecological engineering reduced major pest populations and crop injury by planting nectar-producing flowering plants along field bunds, keeping pest densities below the economic threshold and protecting leaf area and canopy function. In integrated rice production systems, combinations of green manure, fish, ducks, and Azolla produced the best plant growth and physiological performance while reducing pest infestation.

5.2 Improved yield components

Field experiments have shown that combining ecological farming practices with biological inputs can significantly improve important yield components, including productive panicle number, panicle length, panicle weight, and the number of filled grains per panicle. The treatment combining green manure, fish, Azolla, ducks, and liquid biofertilizer or nano-urea produced 457 panicles per m², a panicle length of 31.26 cm, a panicle weight of 3.94 g, and 331.5 filled grains per panicle. These values were clearly higher than those under conventional management (Ranjith et al., 2024). In rainfed aromatic rice, the combined use of green manure, vermicompost, biofertilizer, rock phosphate, and Azolla produced 276.3 panicles per m², 25.50 grains per panicle, and a panicle weight of 3.37 g, resulting in the highest grain yield. These findings suggest that eco-friendly farming practices can consistently improve traits related to grain filling and yield formation (Medhi et al., 2024).

Environmentally friendly cultivation systems combined with proper water management also improve grain development. A three-year study found that a two-week mid-season drainage period followed by alternate wetting and drying consistently produced the highest proportion of mature grains. In contrast, continuous flooding resulted in the highest proportion of immature and unfilled grains (Oh and Cho, 2025). Ecological engineering and IPM reduced white heads, leaf rolling, and panicle damage, lowering the risk of poor grain filling caused by pest injury. Plant-based pesticides further contribute by reducing feeding, slowing insect development, preventing egg laying, and killing insect eggs, while causing little damage to non-target organisms. These actions interrupt the pest life cycle and protect rice production.

5.3 Stable grain yield

Eco-friendly pest management not only reduces pest damage but also helps maintain stable or even higher rice yields. In a two-year field study conducted in Barisal, Bangladesh, IPM produced grain yields of 7.3~7.5 t/ha, compared with 6.28~7.02 t/ha under non-IPM management (Alam et al., 2016). A three-year demonstration in farmers' fields in India reported an average grain yield of 47.23 q/ha under eco-friendly management, representing a 16.99% increase over farmers' conventional practices (Kedarnath et al., 2024). IPM based on economic threshold levels (ETLs) was more effective than routine preventive insecticide spraying because it reduced pest outbreaks while avoiding problems such as pesticide resistance, destruction of natural enemies, and pest resurgence. By reducing dependence on chemical pesticides and strengthening ecosystem health and agricultural resilience, IPM supports sustainable rice production under the pressures of climate change and biodiversity loss. Eco-friendly management also maintains rice quality. Studies showed that environmentally friendly water management consistently produced a higher proportion of mature grains and better grain quality over three consecutive years, while continuous flooding resulted in poorer grain quality (Oh and Cho, 2025).

5.4 Environmental benefits

Conventional pesticides and fumigants can leave harmful residues that threaten human health, reduce the natural quality of rice, and pollute the environment. In contrast, IPM, ecological engineering, biological control, and biopesticides reduce dependence on chemical pesticides and lower the risk of pesticide residues from the source

(De Sousa et al., 2023). Planting flowering plants along rice field bunds can replace routine preventive insecticide spraying while maintaining rice yield and improving environmental quality and safety for both people and animals. Endophytic entomopathogenic fungi and bacterial biopesticides are also considered environmentally friendly because they leave fewer residues, have lower impacts on non-target organisms, and are highly compatible with agricultural ecosystems (Mantzoukas and Eliopoulos, 2020; Tomar et al., 2024).

Excessive pesticide application often kills beneficial insects and can trigger secondary pest outbreaks. In contrast, flowering plants established along field bunds significantly increase predator abundance, parasitoid populations, and parasitism rates. Multi-location field studies consistently reported larger populations of spiders, damselflies, dragonflies, lady beetles, ground beetles, rove beetles, mirid bugs, and parasitoid wasps in ecological engineering fields. Integrated rice farming systems that combined fish, ducks, and ecological management also supported greater numbers, richness, diversity, and evenness of natural enemies. In these systems, pest control efficiency reached 52.24%, demonstrating the strong ecological benefits of integrated and eco-friendly rice production (Ranjith et al., 2024).

6 Practical Lessons for Family Farms

6.1 Monitor pests before applying insecticides

For family farms, the first practical lesson is to observe the field before deciding to spray insecticides. Rice IPM begins with accurate pest identification and regular field monitoring. Farmers need to know which pest species are present, when they appear, and whether their populations are approaching damaging levels before taking control measures (Pegalepo et al., 2025). Therefore, IPM decisions are based on pest population density, economic thresholds, and the growth stage of the rice crop rather than on a fixed spraying schedule.

Routine preventive spraying is often unnecessary. Studies in smallholder rice fields showed that applying insecticides every 15 days without considering actual pest populations resulted in pest densities similar to those in fields where no insecticides were used. By adopting IPM practices such as installing perching poles, conducting sweep-net sampling, and spraying only when necessary, farmers reduced insecticide use by 75% without reducing rice yield (Ali et al., 2017). Decision-support studies for smallholder farming also found that scientific pest monitoring reduced average pest control costs by 25.4% and pesticide use by 58.8% (Kopton et al., 2025).

6.2 Protect natural enemies throughout the growing season

Beneficial insects should be protected throughout the entire rice growing season rather than only after pest outbreaks occur. Rice IPM depends heavily on predators and parasitoids, and conserving these native natural enemies is essential for effective biological control. Excessive insecticide use not only kills beneficial insects but also increases the risk of pest resurgence and secondary pest outbreaks, weakening the natural regulation capacity of the rice ecosystem. For this reason, many green pest management programs recommend reducing the use of broad-spectrum insecticides, especially during the early growth stage when natural enemy populations are still becoming established.

Planting nectar-producing flowering plants along field bunds provides food and shelter for predators and parasitoids. These plants increase natural enemy abundance and parasitism rates, reduce pest populations, and maintain rice yields comparable to those achieved under chemical control. Other practices, including planting flowering plants, using trap crops, installing pheromone traps, releasing parasitoid wasps, and adopting rice-duck or rice-fish farming systems, also strengthen biological control while reducing the need for insecticides (Gontijo, 2019). For family farms, protecting natural enemies means avoiding unnecessary early-season spraying, preserving field refuges and flowering plants, and managing the rice field as a complete ecosystem rather than trying to eliminate every insect.

6.3 Combine multiple green pest management practices

No single method can solve every pest problem in rice production. IPM is an integrated management strategy that combines biological control, cultural practices, physical control, and selective chemical control when necessary. Combining natural enemy conservation with other eco-friendly practices is much more sustainable than relying on a single method, especially repeated use of chemical insecticides (Iftikhar et al., 2023). Because pest populations vary among years, crop growth stages, and local environments, family farms should use flexible combinations of control measures instead of following one fixed management approach.

In Bangladesh, an IPM program that combined egg mass collection, sweep-net monitoring, perching poles, and insecticide applications based on economic thresholds achieved better pest control and higher rice yield than routine preventive management. In India, combining proper plant spacing, natural enemy conservation, botanical pesticides, entomopathogenic fungi, sticky traps, and selective insecticides significantly reduced planthopper damage compared with traditional farming practices. The benefit-cost ratios reached 1:7.6 and 1:6.85 in two consecutive years (Longkumer et al., 2024). Family farms should therefore establish integrated management systems that combine pest monitoring, habitat management, resistant rice varieties, physical control, and selective chemical control instead of relying on a single "universal solution."

6.4 Keep simple field records

Effective IPM depends on connecting pest occurrence with rice growth stages, weather conditions, field history, and previous management practices. Decisions based on field records are generally more reliable than decisions based only on experience. Even when intensive monitoring is not possible, recording simple information such as pest species, crop damage, survey date, rice growth stage, rainfall, and control measures can help farmers better understand pest patterns and avoid unnecessary pesticide applications (Husin et al., 2024).

Using monitoring records to guide management decisions improves the accuracy of pest control. When monitoring information is shared among farmers, its value becomes even greater than when it is used by individual farms alone. A pest early-warning program involving more than 4 000 smallholder farmers in Africa showed that access to pest warning information increased IPM adoption by 8~32 percentage points and improved both yield and farm income by 18%~26% (Khonje et al., 2026). Rice pest forecasting and early-warning systems are also becoming more advanced. When pest populations exceed the economic threshold, these systems can quickly alert farmers and support timely pest management decisions.

7 Future Perspectives

7.1 Wider adoption of eco-friendly pest management

The wider adoption of eco-friendly pest management in high-quality rice production should focus not only on increasing yield but also on improving grain quality, food safety, and ecological sustainability. IPM shares many of the same goals as sustainable agriculture. Its main strength lies in combining biological control, habitat management, insect-resistant rice varieties, plant-based pesticides, and precise intervention to reduce pesticide residues while maintaining important ecosystem services. Plant-based pesticides are biodegradable, have a lower environmental impact, and are generally safer for non-target organisms. These characteristics make them an important alternative for reducing chemical pesticide use in high-quality rice production (Ganesan et al., 2025). At the same time, conserving and using natural enemies should remain a major priority. Rice fields already contain abundant beneficial organisms that can naturally suppress many pests. Unnecessary insecticide applications often disrupt this ecological balance and increase the risk of pest resurgence.

7.2 Digital monitoring technologies

Modern technologies, including sensors, intelligent trapping devices, drones, remote sensing, and data analysis systems, can continuously monitor crop health, environmental conditions, and pest population dynamics. These technologies support early warning, hotspot detection, and timely intervention based on economic thresholds (Mansoor et al., 2025). Combining Internet of Things (IoT) technologies with unmanned aerial vehicles (UAVs) allows pest monitoring at both ground level and field scale. By integrating field images with weather information, these systems can better explain the relationship between environmental conditions and pest outbreaks. When combined with artificial intelligence, machine learning, and remote sensing, digital monitoring systems can identify damaged areas, predict future pest outbreaks, determine the best control timing, and support more precise pest management with lower pesticide inputs.

Digital technologies are especially valuable for high-quality rice production because they reduce unnecessary preventive pesticide applications, improve input efficiency, and help achieve high yield, good grain quality, and environmental protection at the same time. However, several challenges still limit their wider adoption, including high infrastructure costs, poor internet connectivity in rural areas, limited data compatibility, concerns about data privacy and management, and the difficulty of applying these technologies on small family farms (Miller et al., 2025). Future research and extension should therefore focus on developing low-cost sensor networks, edge-computing technologies, shared UAV service platforms for farmer cooperatives, and simple decision-support tools that farmers can easily use. These improvements will help ensure that digital monitoring strengthens eco-friendly IPM rather than becoming another technical barrier.

7.3 Development of ecological farming systems

Sustainable rice production in the future requires not only better field-level pest management but also the wider development of ecological farming systems. Diversified and ecological farming practices can improve soil fertility, nutrient cycling, carbon sequestration, and ecosystem services while maintaining stable rice production. In many cases, these practices create benefits for both agricultural production and the environment. A global analysis showed that diversified rice farming increased biodiversity by 40%, improved economic returns by 26%, and reduced crop damage by 31%. These findings indicate that ecological farming is important not only for environmental protection but also for improving productivity and farm profitability (He et al., 2023). Therefore, future production of high-quality rice should make greater use of intercropping, crop rotation, habitat management, buffer zones, and integrated rice farming systems.

Organic rice farming and rice-lotus production systems in the Mekong Delta of Vietnam have demonstrated long-term ecological, social, and economic advantages. These systems improve water quality, increase soil fertility, and support greater diversity of birds, fish, and plants (Tran et al., 2024). Integrated rice-fish-duck farming systems improve nutrient cycling, strengthen ecological interactions, enhance soil and water quality, support microbial and aquatic ecosystems, and increase both total production and farm income (Nayak et al., 2018). Similarly, rice-aquatic animal farming systems reduce environmental pollution, lower greenhouse gas emissions, maintain soil fertility, and protect biodiversity in rice ecosystems. However, wider adoption is still limited by an incomplete understanding of their ecological mechanisms (Ge et al., 2023). Future research should combine ecological studies, region-specific management strategies, and modern technologies to promote the standardization and large-scale application of ecological rice farming systems.

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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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