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Feature Review **Open Access**

Climate-Resilient Rice Farming Techniques for Sustainable Production

Mingliang Jin, Danyan Ding
Institute of Life Sciences, Jiyang College of Zhejiang A&F University, Zhuji, 311800, Zhejiang, China
Corresponding email: danyan.ding@jicat.org

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Abstract Rice is the cornerstone of global food security, but climate change poses a major threat to its sustainable production. This study systematically explores the challenges posed by climate change to rice cultivation, including rising temperatures, water shortages, and the increasing prevalence of pests and diseases, and evaluates the corresponding solutions. We highlight the progress in breeding climate-resilient rice varieties through conventional breeding and molecular technologies, implementing innovative soil and water management practices such as alternating wetting and drying (AWD) and conservation tillage, and integrated pest and disease management strategies. In addition, we explore the role of diversified agricultural ecosystems, technological innovations such as artificial intelligence and Internet of Things-based decision support tools, and the criticality of supporting policies and farmer capacity building. Successful cases in Bangladesh, the Philippines, and Vietnam demonstrate the practical effectiveness of these approaches. This study argues that building a climate-resilient rice cultivation system must adopt a comprehensive and multidimensional strategy that combines breeding innovation, smart agronomic practices, technology application, and policy support, and calls for future research to focus on genome editing, participatory breeding, and the construction of an overall climate-smart agricultural landscape.

Keywords Climate-resilient rice farming; Sustainable rice production; Climate change adaptation; Water and soil management; Agroecological diversification

1 Introduction

Rice is the staple food for more than half of the world's population (Jat et al., 2022). Especially in Asia, where there are some areas that are particularly dependent on rice, rice almost supports most of the food security and social stability. However, its role is far more than just filling the stomach. The economic development of many countries, the livelihoods of ordinary people, and even the political situation in some regions are inseparable from the support of rice (Jamal et al., 2023).

Unfortunately, climate change is making this dependence more and more fragile. Temperatures are rising, rainfall is becoming abnormal, extreme weather is no longer surprising, and coastal and low-lying areas are also subject to salt erosion all year round (Li et al., 2023; Irwandhi et al., 2024). These problems come one after another, and rice production is naturally hit. Traditional planting methods already have some old problems, such as high greenhouse gas emissions and serious waste of resources (Mohapatra et al., 2023; Praharaj et al., 2023), and these problems will only get worse under climate pressure. Of course, climate is not the only problem. Land is shrinking, fewer people are willing to work in the fields, and farming is becoming less profitable - these problems together make the vulnerability of rice production more obvious (Li et al., 2024a).

The main purpose of this study is to sort out which rice planting technologies are more resilient and sustainable in the context of climate change. These include direct-seeding rice, rice intensive cropping system (SRI), improved irrigation and drainage methods, planting new stress-resistant varieties, and using regenerative soil conditioners. These methods not only help rice survive climate shocks, but also take into account environmental protection and economic benefits. This study will also focus on whether these technologies can be promoted, how effective they are in different regions, and what policy support may be needed behind them. Ultimately, we hope to find some reliable guarantees for rice yields and farmers' livelihoods in an uncertain future.

2 Impact of Climate Change on Rice Cultivation

2.1 Impact of rising temperatures and high temperature stress on rice yield

Rising temperatures are definitely not a good thing for rice. The growth period will be compressed, the filling period will be shortened, and the yield will naturally decline (Lv et al., 2018). The situation is particularly bad in some places, such as Africa. If no response is taken, by 2070, under a high emission scenario, rice yield may drop by 24% directly-mainly because extreme high temperatures greatly reduce the efficiency of rice photosynthesis (Van Oort and Zwart, 2017). In fact, China is no exception. Different regions are expected to see a 3.7% to 16.4% decline in yield, with the central, eastern and northwestern regions being the most affected (Zhan et al., 2023). A study conducted a meta-analysis and said that for every 1 °C increase in average temperature, rice yield will decrease by about 3.85% (Li et al., 2024a). Moreover, late rice is particularly unlucky. High temperature stress shortens the filling period even more, and yield is naturally hit harder.

2.2 Impact of water shortage and unstable rainfall patterns

In addition to temperature issues, water has also become a big problem. Climate change has made water resources more scarce, and rainfall has become increasingly unreliable. In particular, rain-fed rice systems that rely on the weather are most affected. There is too much rain at one time, and not enough at another. Extreme conditions such as droughts and floods are becoming more and more common. Rice is either short of water or flooded, and the yield fluctuates greatly (Wang et al., 2024). In China, the distribution of rainfall is becoming more and more extreme, with droughts and heavy rains taking turns. Although a moderate increase in rainfall of 20% to 25% may help rice stabilize its yield, a drop that is too sharp or too sparse will not work, but will be counterproductive (Li et al., 2024a). Therefore, how to scientifically manage water resources and find ways to adapt to this change has become a hard task facing agriculture (Arunrat et al., 2020).

2.3 Threats from increased incidence of pests and diseases

As the climate changes, pests and pathogens have also become more active. Although specific pests and diseases are not listed here, it is certain that rising temperatures, increased humidity, and increasingly unstable weather have created an excellent breeding environment for pests and pathogens (Saud et al., 2022). These biological threats are superimposed on abiotic stresses such as high temperature and drought, greatly increasing the risks of rice cultivation. To ensure yield, it is not enough to rely on only one measure. Comprehensive measures must be taken to flexibly respond to various changes brought about by the climate.

3 Climate-Adapted Rice Varieties

3.1 Development of drought-tolerant and flood-tolerant rice lines

Climate change has made rice cultivation increasingly difficult, with droughts and floods becoming the norm. To deal with these problems, breeders have developed drought-tolerant and flood-tolerant rice varieties. In Bangladesh, some flood-tolerant (such as BRRI dhan51 and BRRI dhan52) and drought-tolerant (such as BRRI dhan56 and BRRI dhan71) varieties have shown better yield performance than traditional varieties under various conditions and are gradually being accepted and used by farmers (Figure 1) (Nayak et al., 2022). Of course, this is inseparable from the help of molecular breeding technology. By introducing some key quantitative trait loci (such as qDTY1.1, qDTY2.1, qDTY3.1 and Sub1), researchers have bred lines that can withstand both drought and flood, such as CR dhan 801 and Bahuguni dhan-1 (Sandhu et al., 2019). These new varieties not only have excellent yields under stressful conditions, but also have no yield reduction under normal conditions, making them particularly suitable for areas that are extremely vulnerable to extreme weather (Dar et al., 2021).

3.2 Breeding for salt and heat tolerance

For rice cultivation in coastal and tropical areas, salinization and high temperatures have become problems that must be faced. Salt-tolerant rice varieties, such as Inpari 43 and Mendawak, have been shown to maintain good yields in high-salt and flooded environments, especially when used in conjunction with adaptive agronomic measures such as the application of biofertilizers (Simarmata et al., 2021). As for heat-tolerant breeding, the focus is on details such as early morning flowering, pollen fertility, and spikelet fertility (Senguttuvel et al., 2020). Some people may find this characteristic unintuitive, but in fact, these traits are the key to preventing a significant reduction in rice yields on hot days. Now, researchers are constantly screening and using germplasm resources with these characteristics, hoping to cultivate rice varieties with uncompromised yield and quality even under high temperature stress (Sreenivasulu et al., 2015).

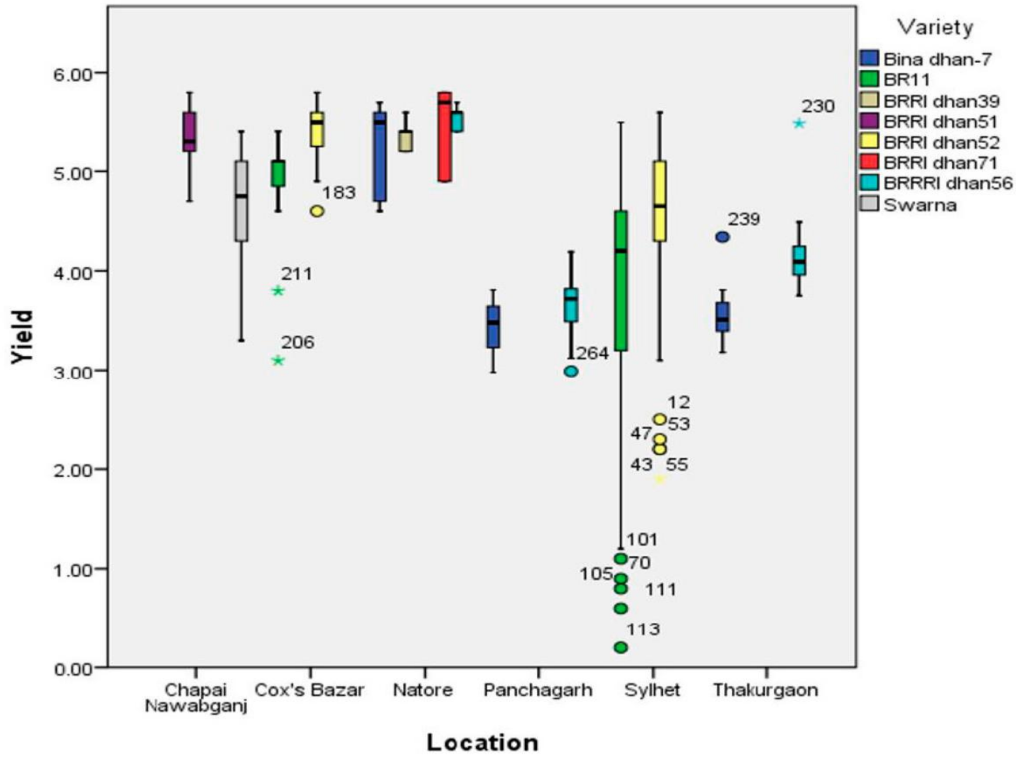

Figure 1 BRRI dhan51, BRRI dhan52, BRRI dhan56, and BRRI dhan71 yield range (t ha^{-1}), deviation, and prediction in a trial in Chapai Nawabganj, Cox's Bazar, Natore, Sylhet, and Thakurgaon districts (Adopted from Nayak et al., 2022)

3.3 The role of molecular tools and genomics in accelerating variety breeding

Traditional breeding alone is slow and risky. In recent years, molecular tools and genomics technologies have opened up new avenues for rice stress-resistant breeding. For example, molecular marker-assisted selection can accurately introduce multiple stress-resistant genes into target varieties at the same time, greatly accelerating the breeding progress (Saini et al., 2025). In addition, analyzing the genomes of traditional rice varieties has also helped scientists find many useful stress-resistant genes (McNally and Henry, 2023). Not to mention CRISPR-Cas9, a genome editing technology that can directly manipulate specific genes and quickly transform rice to make them more drought-resistant, flood-resistant, and disease-resistant (Li et al., 2024b; Riaz et al., 2025). However, the ideal approach would be to combine these molecular methods with traditional breeding in order to truly keep up with the pace of climate change and stabilize future rice production.

4 Water Management Technology to Enhance Climate Resilience

4.1 Alternating wet-dry (AWD)

Rice fields have always been soaked in water, but this old method has long exposed many problems. The alternating wet-dry (AWD) method was proposed to change this situation. Its idea is simple: irrigate when there is water in the field, let it dry for a period of time when there is no water, and then add water, instead of soaking for a long time (Srivastav et al., 2021). This practice can not only greatly reduce water consumption, but also improve water resource utilization, and sometimes even make the yield higher than traditional methods. Especially in areas with severe water shortages, AWD is particularly effective. Moreover, it can also help reduce greenhouse gas emissions, so many people list it as a typical climate-smart agricultural practice, which is very useful for dealing with rainfall variability and drought.

4.2 Adopting the system of rice intensification (SRI)

Another idea is the System of Rice Intensification (SRI). Compared with traditional planting methods, SRI does not advocate more irrigation and dense planting, but controls the amount of water, increases the distance between plants, and pays more attention to soil and nutrient management (Sikka et al., 2022). Some people initially thought this method was troublesome, but practice has proved that SRI can not only increase yields, but also improve the efficiency of land and water use, and reduce costs. More importantly, SRI makes the rice root system stronger, and enhances its drought and heat resistance. Under the various pressures brought by climate change, the overall adaptability of the planting system is stronger. It is indeed a method worth promoting.

4.3 Application of precision irrigation and intelligent water-saving technology

Of course, relying solely on experience to farm is far from enough. Now, precision irrigation and intelligent water-saving technologies are beginning to enter the fields. These technologies rely on data support, such as sensors to detect soil moisture, software to adjust irrigation according to weather forecasts, and even use automated systems to supply water on demand. This method can use water resources more finely and consume less energy, especially in the context of water shortage, the advantages are obvious. Moreover, if these high-tech methods can be combined with traditional practices and natural regulation, the resilience and sustainability of the rice system can be further improved.

5 Soil health Management Helps Rice Resilient Planting

5.1 Conservation tillage and cover crop practices

In the past, although traditional farming methods were simple, the problem of soil getting worse and worse became more and more obvious. Conservation tillage (such as reduced tillage, no-tillage combined with stubble management) came into being and is considered an effective means to improve the fertility of rice planting soil (Zahid et al., 2020). Through these practices, the level of soil organic matter can be greatly improved, the water retention capacity and nutrient utilization rate will also improve, and the content of trace elements such as copper, manganese, and zinc can also be improved. Of course, the effect is not immediate and requires long-term persistence (Shah et al., 2024). Moreover, planting some green manure crops, such as field sesbania, can not only further improve soil fertility, but also increase organic carbon content. In this way, not only the yield is stable, but also the resilience of the soil itself becomes stronger (Kumawat et al., 2024).

5.2 Application of organic amendments and biofertilizers

The method of using fertilizers to improve soil fertility is not new, but there are many requirements for what fertilizers to use and how to use them. Organic amendments such as farmyard manure, vermicompost, crop residues and green manure can significantly improve the physical, chemical and biological properties of the soil after long-term application (Sihi et al., 2017). The organic carbon content in the soil increases, nutrients are more easily absorbed by crops, and microbial activity is also booming, which is very helpful for the healthy growth of rice. In addition, biofertilizers - such as nitrogen-fixing bacteria and phosphate-solubilizing bacteria - can further promote nutrient absorption, enhance soil fertility, and improve rice yield and quality. In recent years, biochar and beneficial microorganisms have also become popular choices. They can also help rice resist environmental stresses such as salinization and drought (Hafez et al., 2021; Vanama et al., 2023).

5.3 Integrated nutrient management strategy

It is difficult to solve the problem of rice soil fertility with a single fertilizer, so integrated nutrient management (INM) has become an increasingly important practice. Simply put, INM is a combination of organic and inorganic fertilizers. The advantage is that it can not only maintain soil fertility but also stabilize crop yields (Marzouk et al., 2024). Microorganisms play an important role here. They are good at nutrient transformation, improving soil structure, and alleviating stress. After many places tried INM combined with soil testing and formula fertilization, not only did the yield increase, but farmers' income also increased (Liu et al., 2022). In particular, after the combination of chemical fertilizers, green manures and farmyard manure, the soil quality and resilience index increased significantly, laying the foundation for maintaining sustainable production under the pressure of climate change (Tripathy et al., 2023).

6 Integrated Pest Management under Climate Stress

6.1 Promote pest-resistant rice varieties

Climate change has brought many pest problems that were previously controllable to the forefront, and planting pest-resistant rice varieties has become the most direct and basic response. By introducing genes that are tolerant to pests and diseases and some abiotic stresses into new varieties through breeding, it can not only reduce the use of pesticides, but also help farmers stabilize their yields when the number of pests fluctuates with climate change (Juroszek and Tiedemann, 2011). Although this method is not a panacea, it is definitely a key link in the climate-smart pest management (CSPM) system (Bouri et al., 2023). With resistant varieties, at least when facing sudden pest disasters, the planting system will not be overwhelmed all at once.

6.2 Biological control and habitat management methods

However, seeds alone cannot withstand all threats, especially after climate change breaks the balance between pests and natural enemies. At this time, biological control becomes more important. By protecting or introducing natural enemies such as parasitic wasps and predatory insects, the number of pests can be effectively suppressed and dependence on pesticides can be reduced (Heeb et al., 2019). Of course, if you want these beneficial organisms to stay, the environment must also be adjusted, such as planting different crops and staggering planting times, so as to disrupt the pest life cycle and make room for natural enemies. Biological control and habitat management together constitute an important part of the integrated pest management (IPM) strategy, emphasizing eco-friendliness and sustainability (Masood et al., 2021).

6.3 Climate-adaptive integrated pest management (IPM) framework

It's just that traditional IPM has been unable to keep up with the changes. Now, the climate-adaptive IPM framework has become a new trend. It packages cultural, biological, mechanical, and chemical measures together to flexibly respond to pest threats (Skendžić et al., 2021). Moreover, blind guessing based on human experience is no longer effective. More and more places are beginning to use remote sensing, prediction models, and decision support systems to warn of pest outbreaks in advance and intervene precisely (Msomba et al., 2024). Climate-smart pest management (CSPM) can be said to be an upgrade on the basis of traditional IPM, with a clearer goal: not only to control pests, but also to reduce greenhouse gas emissions, enhance ecological services, and make the entire agricultural system more resilient. To achieve these, technology alone is far from enough. Continuous innovation investment, capacity building, and cooperation between researchers are all indispensable (Nitta et al., 2024).

7 Agroecology and Diversified Farming Systems

7.1 Rice-fish farming system improves ecosystem resilience

Raising fish in rice fields is an ancient practice that actually existed hundreds of years ago. Although it was marginalized under the wave of modern agriculture, it has re-entered people's vision with the emphasis on sustainability. The integration of rice-fish farming not only increases biodiversity, but also improves nutrient cycling, helps suppress pests and diseases, and reduces the use of pesticides and fertilizers (Kremen et al., 2012). The benefits of this practice are not just raising more fish, but also making the agricultural system more resilient to extreme climates. By maintaining these key ecological services, rice-fish farming has indeed supported a corner of sustainable food production. In addition, fish can eat some pest larvae and weed seeds, which invisibly maintains the ecological balance of rice fields.

7.2 Intercropping and rotation strategies

Not all places are suitable for fish farming, but to enhance the ability of farms to resist climate change, intercropping and rotation are also the "good guys" among the old methods. By planting different crops, either simultaneously or in rotation, it is possible to disrupt the reproduction rhythm of pests and diseases, improve soil fertility, and use water and nutrients more efficiently. Especially today, with the increasing frequency of extreme climate events, these diversified planting arrangements - such as crop mixtures and crop and livestock combination - have become an important line of defense for farmers against risks. Practice has shown that a variety of crop layouts not only help farms recover production faster, but also maintain overall productivity levels.

7.3 Promote agroforestry practices and carry out rice planting at the same time

If single-crop planting is a bit lonely, then agroforestry is a typical example of "grouping together for warmth". Pairing trees, crops, and even livestock together not only makes the land more fully utilized, but also significantly improves ecological benefits. Especially in rice-growing areas, introducing an appropriate amount of trees can provide shade, reduce wind and water erosion, and increase soil organic matter and bring higher biodiversity (Altieri et al., 2015). Although it is more troublesome to manage in the early stage, the agroforestry system can effectively buffer the impact of extreme temperatures or abnormal rainfall on rice fields. At the same time, farmers can increase their income and improve food security through diversified agricultural products. Overall, this diversified layout is more resilient in the face of climate change and economic fluctuations.

8 Technological Innovation and Digital Tools

8.1 Application of remote sensing and climate forecasting tools

In the past, if you wanted to understand the situation in the rice fields, you could only rely on people to observe in the fields. Now it is different. Satellites, drones, and ground sensors are all in place. Remote sensing technology is quietly changing the rules of the game for rice cultivation. They can monitor crop health, soil moisture, and environmental conditions in real time, helping farmers to obtain first-hand information. Although the investment in equipment is not small, the benefits are also obvious. For example, irrigation can be arranged more accurately, early signs of crop stress or disease can be detected in time, and flexibility in responding to climate change is improved (Goel et al., 2021; Zhang et al., 2024). If combined with climate forecasting tools, farmers can also know weather changes and potential risks earlier and adjust their planting strategies in advance. Now, multi-scale and multi-sensor monitoring has become a research hotspot for responding to climate uncertainty and is considered to be the key to ensuring stable future crop production (Storm et al., 2024).

8.2 Mobile consulting system for farmers

Although high-tech sounds cool, what can really help farmers are often some seemingly simple applications. Mobile consulting system is one of them. They can directly push weather forecasts, pest and disease warnings, and planting suggestions to farmers, which is convenient and practical. Especially in rural areas where information asymmetry is serious, this system bridges the knowledge gap, allowing farmers to make smarter decisions in a timely manner, improve production efficiency, and enhance their ability to cope with climate change (Balyan et al., 2024; Christian et al., 2024). Moreover, with the development of big data and analytical technologies, these platforms can also tailor management suggestions based on the location of farmers, which is more in line with actual needs.

8.3 The role of artificial intelligence (AI) and the Internet of Things (IoT) in climate-smart decision-making

Of course, if you want to make agricultural digitalization really work, artificial intelligence (AI) and the Internet of Things (IoT) are absolutely indispensable. Now, there are not only soil moisture sensors and meteorological microstations in rice fields, but also systems that can automatically adjust irrigation. All these devices collect data every day, but without AI to analyze, these data are basically just a bunch of numbers (Fuentes-Peñailillo et al., 2024). Artificial intelligence algorithms can help identify patterns, predict risks, and optimize decisions such as irrigation, fertilization, and pest and disease management, making farm management increasingly intelligent. The combination of AI and IoT not only improves resource utilization, but also effectively reduces environmental burdens and enhances the ability of rice farming systems to withstand climate stress (Subeesh and Mehta, 2021; Elbeheiry and Balog, 2023). Automation and remote management are also becoming more and more popular, making climate-smart agriculture truly within reach.

9 Case study: Successful Implementation of Climate-Resilient Technologies

9.1 Promotion of flood-tolerant rice varieties (e.g. “water lung rice”) in Bangladesh

In Bangladesh, floods are not a minor nuisance that comes once in a while, but a regular problem that affects millions of hectares of land, especially in recent years, when weather has become increasingly extreme and sea levels have slowly risen. In the past, farmers had no choice but to accept the losses, but the emergence of flood-tolerant rice varieties has changed the situation. People have given these rice plants a vivid name - "water lung rice" because they can hold their breath underwater for up to two weeks. In fact, this is inseparable from the introduction of the SUB1 gene, which not only retains the original excellent traits, but also makes the rice more flood-resistant. These varieties were later officially promoted in Bangladesh and India, helping farmers to withstand climate pressure, stabilize yields, and ensure their livelihoods.

9.2 Promotion of alternating wet and dry (AWD) practice in the Philippines

When talking about the promotion of the alternating wet and dry (AWD) method in Asia, the Philippines cannot be avoided. After all, the International Rice Research Institute (IRRI) is headquartered there (Stuart-Brown, 2018). IRRI has made great efforts in rice variety improvement, germplasm protection, and water resource management in recent years, and has also laid the foundation for climate-adaptive planting in the Philippines and even more countries. In particular, the practice of AWD, which saves water and increases production, is particularly important under the double pressure of water shortage and unstable climate (Figure 2). Although it is not directly named in the information, IRRI's role in promoting it can be said to be unquestionable.

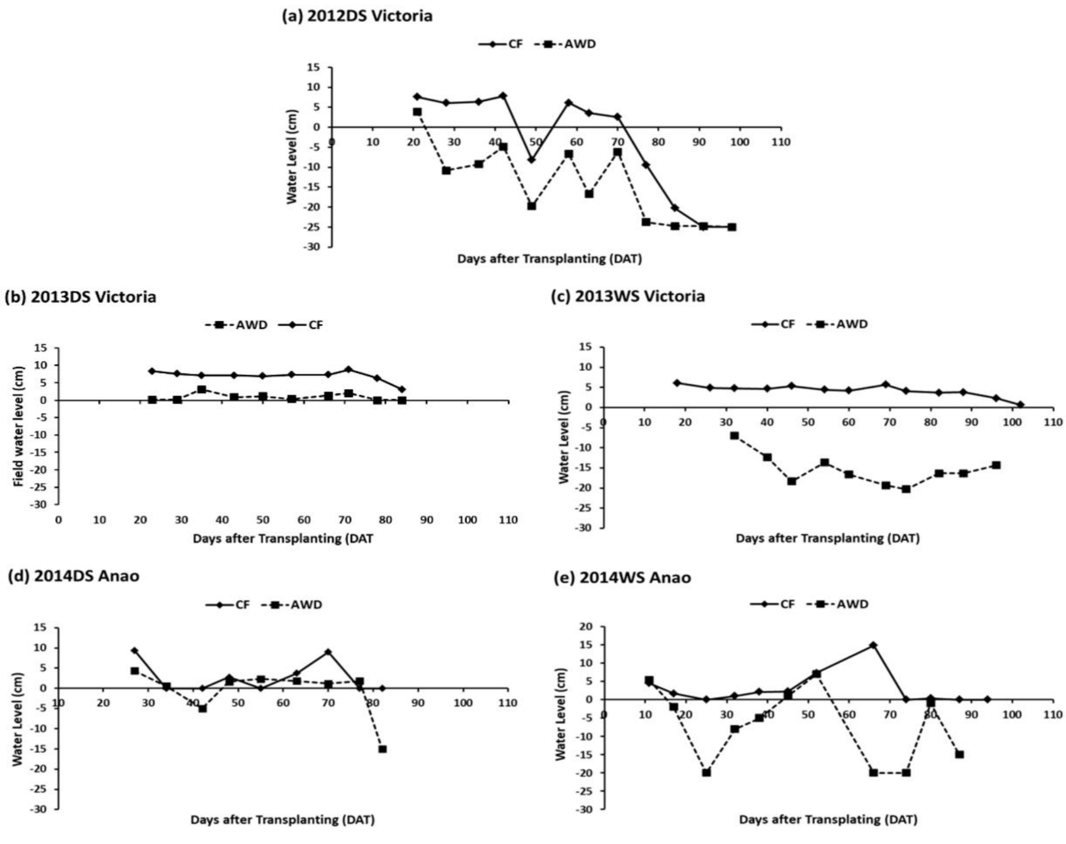

Figure 2 (a-g) Sample of daily field water level collected by farmer cooperators during the field experiments in the wet and dry seasons of 2012-2015. Water levels were collected via perforated plastic pipes in the field, except in 2013 DS when the water level was determined via the surface water level (Adopted from Sander et al., 2020)

9.3 Successful case of rice-fish farming in the Mekong Delta in Vietnam

When it comes to the importance of diversifying rice production in Southeast Asia, the first thing that comes to many people's minds is the Mekong Delta in Vietnam (Stuart-Brown, 2018). Here, rice-fish farming is not a new concept, but an ancient and practical traditional practice. Raising fish in rice fields at the same time not only increases the source of income, but also improves nutrient circulation and helps control the number of pests. Especially in an environment with frequent floods and fragile climate, the resilience of this complex system is much higher than that of single planting. The success of rice-fish farming has also become an important case for promoting ecological restoration agriculture in Southeast Asia.

10 Policy support and capacity building

10.1 Formulate climate-resilient agricultural policies

Climate-resilient agriculture (CRA) sounds like the direction of future agricultural development, but to truly implement it, technology alone is not enough. Policy is the foundation of the entire system. Many years ago, the scientific community repeatedly emphasized that it is critical to formulate a policy framework that can promote communication, knowledge sharing, and technology development, and it is best to link it with risk management and environmental protection (Lipper et al., 2014). But then again, although many local policies have been formulated, implementation and effect evaluation have not kept up, and there are relatively few cases that truly support CRA transformation. More realistic suggestions include: introducing climate forecasts in agricultural planning, promoting agricultural insurance to reduce farmers' investment risks, and formulating flexible policies that can take into account the specific needs of different agricultural systems (Zakaria et al., 2020; Manevska-Tasevska et al., 2023). Not only at the national level, but also local communities and public institutions must participate and provide strategic support, otherwise many good policies will be difficult to implement.

10.2 Farmer training and knowledge dissemination programs

No matter how good the policy is, if farmers do not understand it, implementation is still a problem. Therefore, farmer training and knowledge dissemination programs are particularly important. It has been proven that farmers who have received relevant training are more willing and easier to adopt climate-resilient practices (Zakaria et al., 2020). Most of these trainings are promoted by extension workers or farmer organizations. The content should not only include new technologies and methods, but also integrate some traditional knowledge and local experience, which is more practical (Karume et al., 2022; Ginigaddara and Kodithuwakku, 2024). Moreover, the training targets cannot only focus on farmers. Extension workers themselves must continue to learn and update, otherwise even the best knowledge cannot be passed on. Only when information is truly flowing can capacity building really play a role.

10.3 Strengthen research and extension networks

Scientific research institutions have played a great role in promoting climate-resilient agriculture, but the problem is that there is often a big gap between research and front-line application. Research can provide data support and management advice, and even develop win-win policy solutions that take into account land use, climate regulation and biodiversity (Webb et al., 2017). The extension network is responsible for translating these results into practical guidelines that farmers can understand and use (Teklu et al., 2023). However, many public institutions currently have shortcomings in funding, personnel training, and resource allocation (Khan et al., 2020). If research is to truly serve the front line, better coordination mechanisms, sufficient material support, and a more precise training system are needed (Popoola et al., 2020). Only by filling in these details can climate-resilient agriculture not only look good in papers, but also take root in the fields.

11 Future Directions and Research Focus

11.1 Innovations in Genome Editing for Climate Adaptability

If rice is to survive in the increasingly unreliable climate conditions of the future, it will certainly not be able to rely on old varieties. In recent years, genome editing and molecular breeding technologies have given breeders more tools to directly address problems under climate stress such as drought, salinity, and extreme high temperatures (Isnaini et al., 2023). Many studies have found a number of quantitative trait loci (QTLs), genes, and superior alleles related to drought and salt tolerance. How to combine these characteristics into modern varieties has become an urgent task. In order to speed up the pace, high-throughput phenotyping technology, genetic map construction, gene aggregation and other methods are being widely used to strive to cultivate climate-smart rice that can truly cope with various biological and abiotic stresses (Saini et al., 2025). However, technology alone is not enough. It is also critical to develop clearer and more efficient promotion strategies, especially for those areas that are most vulnerable to climate.

11.2 Strengthen farmer participation in breeding and local adaptation

Whether a new variety is useful or not is not up to the research laboratory to decide, but the people who work in the fields have the final say. Participatory breeding is to allow farmers to directly participate in the selection and improvement of rice varieties. Practice has shown that in the face of climate change, changing the variety itself is often more effective than simply changing water and fertilizer management, especially when the two are used together (Li et al., 2024b). Involving farmers in person can not only accelerate the implementation of climate-adaptive varieties, but also improve the acceptance and practicality of these innovative solutions at the community level (Poulton et al., 2016). This approach is especially important in the small-scale farmer environment where agricultural ecological conditions vary greatly, otherwise one-size-fits-all technology will hardly be really useful.

11.3 Construct an integrated climate-smart rice planting landscape

The rice fields of the future may no longer be single-crop fields. More and more studies are emphasizing the need to combine genetic improvement, agronomic optimization and ecological innovation to work on the entire landscape level (Irwandhi et al., 2024). For example, the use of rhizosphere microbiome engineering technology, the promotion of new salt-tolerant varieties, and improved soil moisture management can all help rice systems withstand more climate challenges. At the same time, biodiversity can be improved by adjusting crop planting calendars, rotating crops, and promoting agroforestry, and resource utilization efficiency can be improved with precision agricultural tools (Habib-Ur-Rahman et al., 2022). However, if these new methods are to be truly promoted, scientists, farmers, and policymakers must work together, otherwise it will be difficult to promote them on a large scale. After all, in the context of an increasingly unpredictable climate, food security and environmental sustainability are no longer issues that can be solved by a single sector alone.

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Conflict of Interest Disclosure

The authors affirm 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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