CropSci Publisher©

Field Crop 2025, Vol.8, No.3, 154-165
http://cropscipublisher.com/index.php/fc

Research Insight Open Access

Impact of Alternate Wetting and Drying (AWD) Irrigation on Rice Yield and Greenhouse Gas Emissions

Dapeng Zhang

Hier Rice Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572025, Hainan, China

Corresponding email: dapeng.zhang@hitar.org

Field Crop, 2025, Vol.8, No.3 doi: 10.5376/fc.2025.08.0015

Received: 18 Apr., 2025

Accepted: 29 May, 2025

Published: 21 Jun., 2025

Preferred citation for this article:

Zhang D.P., 2025, Impact of alternate wetting and drying (AWD) irrigation on rice yield and greenhouse gas emissions, Field Crop, 8(3): 154-165 (doi: 10.5376/fc.2025.08.0015)

Abstract The optimization of rice field irrigation methods is of great significance for alleviating water resource shortages and reducing agricultural greenhouse gas emissions. This study systematically reviews the impact of alternating dry and wet irrigation (AWD), a water-saving irrigation technology for rice, on rice yield and greenhouse gas emissions from paddy fields. The results show that AWD effectively reduces methane emissions from rice fields through periodic dry-wet alternations, significantly reducing methane flux by 20% to 70%, while only accompanied by a slight increase in nitrous oxide emissions. Moderate AWD treatment (such as a soil water potential threshold of approximately-15 kPa) will not significantly reduce rice yield. In some cases, it can promote root development and improve nitrogen use efficiency, thereby achieving stable and increased yields. Excessive drought stress (such as soil water potential below-30 kPa) may inhibit root growth and photosynthesis, leading to a significant decrease in yield. Both field trials and large-scale demonstrations have demonstrated that implementing AWD while ensuring yield can save 25% to 30% of irrigation water, enhance water use efficiency and reduce irrigation costs. The promotion of AWD helps to reduce the comprehensive warming potential of rice fields and achieve emission reduction and efficiency improvement in rice production. This article simultaneously discusses the adaptability and limitations of AWD in different ecological regions, its synergistic effect with other low-carbon agricultural measures, and looks forward to future research directions and policy support priorities. Research suggests that the scientific implementation of AWD technology is of great significance for ensuring grain production, conserving water resources, and reducing greenhouse gas emissions in the field of rice production.

Keywords Alternating dry and wet irrigation; Rice yield; Methane emissions; Nitrous oxide; Water use efficiency

1 Introduction

More than half of the world's population regards rice as their staple food. However, growing rice consumes a lot of water, with irrigation alone accounting for over 30% of agricultural water usage. Nowadays, water resources are becoming increasingly tight. The traditional rice fields that are always submerged for cultivation are indeed finding it hard to sustain. But then again, saving water is not that simple-you have to consider the output and also take the environment into account. Moreover, perhaps many people are not aware that rice fields are also a major source of greenhouse gases: being constantly flooded can easily produce methane, and if they are sometimes dry and sometimes wet, they will release nitrous oxide (Towprayoon et al., 2005). In some rice-growing countries, methane emissions from rice fields can account for about 10% of the total agricultural emissions, which is really a considerable proportion (Khalil and Shearer, 2006). So now, ensuring the harvest while reducing the emissions caused by rice cultivation has become a core challenge for the sustainable development of rice planting. Especially in the context of promoting carbon neutrality in agriculture, this issue has become even more urgent.

Traditional rice cultivation always involves soaking in water. Although this can suppress weeds, it consumes a lot of water and also generates a large amount of methane due to soil oxygen deficiency. The mid-term sun-drying of fields commonly used in Asia can strengthen roots and prevent lodging, but it does little to help reduce emissions. Alternating wet and dry irrigation (AWD), which has become popular in recent years, is a good approach. It alternates between flooding and draining, allowing the soil to breathe air from time to time. This can effectively inhibit methanogens and reduce methane emissions by an average of 30% to 50% (Zhao et al., 2024). Although this might lead to a slight increase in nitrous oxide emissions, the overall reduction effect is still very prominent

(Chidthaisong et al., 2018). Therefore, AWD is regarded as a key technology for water conservation and emission reduction. Countries like China and the Philippines are promoting it. However, due to the different conditions in various regions, the specific effects still need further research.

Given the potential of AWD in water conservation and emission reduction and the complexity of its application, this study aims to systematically review its impact on rice yield and greenhouse gas emissions from paddy fields. Based on field experiments and promotion experiences, this article explores the applicability and limitations of AWD in different ecological and management scenarios. The analysis focuses on its basic principles and operation methods, as well as the differences from traditional irrigation. It explains the mechanisms of action on root growth, nutrient absorption, photosynthesis and yield composition, assesses the dynamic emissions of CH_4 and N_2O in paddy fields and the trade-off relationship between methane reduction and nitrous oxide increase (Loaiza et al., 2024), and discusses its impacts on soil properties, water resource utilization and the ecological environment (Echegaray-Cabrera et al., 2024). Meanwhile, the research focuses on the economic benefits of AWD, farmers' willingness to adopt it and the obstacles to its promotion. It proposes application strategies by combining policies and international experiences, and draws on typical empirical studies in Southeast Asia to summarize regional promotion experiences. Finally, we look forward to its challenges in different ecological zones and the prospects of synergy with other low-carbon technologies, with the aim of providing a scientific basis for optimizing the irrigation system and achieving green production increase.

2 The principle and Implementation of Alternating Irrigation (AWD)

2.1 Basic concepts and operational methods of AWD

Alternating wet and dry irrigation (AWD), in essence, means no longer keeping the rice fields flooded all the time. Instead, it involves draining the water and then refilling it, alternating this process. Generally, when the seedlings are still small at the beginning, a little shallow water is maintained. Once they stabilize, the water is allowed to fall slowly until it is about 15 centimeters lower than the field surface-this is the "Safe AWD" standard recommended by the International Rice Research Institute (Mote et al., 2021). At this point, if water is applied, it is less likely that the rice will suffer from drought. Of course, it depends on the period: during the tillering stage, it should not be too dry, otherwise it will affect the division. By the time of panicle formation and heading, if it is too dry, there will be fewer grains produced. Overall, however, through this cycle of "shallow water-drying-rewatering", AWD can indeed save water and the output is not likely to drop much (Chu et al., 2016). The soil is sometimes dry and sometimes wet, but it is more breathable, and the root system and microorganisms are also more active. Nowadays, there are also mild and severe AWD types. Generally, mild AWD has almost no impact on yield, but when operating, it is still necessary to consider the location, weather, and even the variety to select the appropriate standard.

2.2 Comparison with traditional irrigation methods

Compared with continuous flooding, AWD shows differences in soil moisture, nutrient cycling and ecological processes, thereby affecting the paddy field environment and crop performance. Studies show that AWD can reduce irrigation water by approximately 20% to 30%, saving 1 000 to 1 500 tons per hectare and significantly improving water use efficiency. However, continuous flooding leads to low efficiency due to seepage and evaporation. In terms of the soil environment, continuous flooding keeps the soil anaerobic for a long time, which is conducive to methane production. AWD increases the REDOX potential through periodic drying, inhibits methane production and promotes nitrification. For crops, although continuous flooding provides stable moisture, it is prone to restricting root development due to oxygen deficiency. Moderate AWD promotes root penetration and enhances vitality without affecting the growth of the above-ground parts. Multiple experiments have shown that the output of AWD is not significantly different from that of continuous flooding, with an average reduction of only about 3%. If not managed properly, it may lead to a reduction in production. Moderate alternation of dry and wet conditions during the tillering stage is conducive to nutrient absorption, while during the heading and flowering stage, it is necessary to maintain moisture to prevent a decrease in seed setting rate. Overall, the rational implementation of AWD can not only save water but also stabilize yields, providing a feasible approach for rice-growing areas to alleviate water resource pressure and reduce emissions.

2.3 Applicability and current status of regional promotion

The AWD irrigation method is most suitable for rice fields with convenient irrigation and drainage and good infrastructure, where water can be flexibly controlled. However, if it is rain-fed fields that rely on the weather or low-lying and flood-prone plots, it is very difficult to implement because water cannot be drained at all. In recent years, some high-standard farmlands in southern China have been promoting the "shallow and wet alternation" model, and the agricultural department has also encouraged farmers to adopt it through training subsidies. Countries like the Philippines and Vietnam are also demonstrating and promoting this. In many places, after using it, water savings have been significant, production has not decreased, and methane emissions have been reduced by more than 30% (Chidthaisong et al., 2018). Farmers' acceptance is actually quite high, especially in areas that are often short of water or under pressure to reduce emissions (Duong et al., 2024). Nowadays, there are still some auxiliary means, such as using simple water pipe measurement or mobile phone apps to indicate the irrigation time, which is more convenient to use. In conclusion, AWD is a practical and feasible technology. However, in the initial stage of promotion, local trials should be conducted first to establish appropriate operational standards and prevent farmers from worrying about reduced yields. As conditions get better and better in the future, there will definitely be more places where it can be used (Tanaka et al., 2025).

3 The Influence of AWD on Rice Yield

3.1 Physiological and morphological mechanisms

The AWD irrigation method is quite different from continuous flooding. It makes the fields sometimes dry and sometimes wet. You may know that if the soil is constantly flooded, it will lack oxygen and the roots won't grow well. However, when AWD dries up, it is actually providing oxygen to the root zone. As a result, the roots will grow deeper, distribute more, have stronger vitality and oxidation capacity, and have a wider range of nutrients to find. Moderate use of AWD can increase the root-to-crown ratio, expand the surface area of the roots, and make the absorption of nutrients such as nitrogen and phosphorus more effective (Sun et al., 2025). Moreover, the alternation of dry and wet soil can accelerate the decomposition of organic matter and release more nitrogen elements. Even a slight water pressure is not a bad thing. It will stimulate the roots to grow deeper and actually enhance the resilience. When it comes to photosynthesis, mild AWD actually has little impact on the photosynthetic rate of leaves. Sometimes, due to better ventilation and light penetration in the field, there is even a slight improvement, and both transpiration and photosynthetic efficiency can be maintained well (Yang et al., 2020). Of course, this thing should not be overdone either-if it is too dry, the stomata will close, photosynthesis will weaken, carbon assimilation will not keep up, and the yield may drop. In conclusion, AWD mainly works by improving the oxygen and nutrient conditions in the root zone, enabling roots and leaves to grow more harmoniously and achieving what is called "strong roots and thick stems". Even if water is saved, the yield can still be stable or even increased. The key is to prevent it from being too dry.

3.2 Differences in yield performance at different growth stages

The impact of AWD on rice yield cannot be generalized. It depends on the type of rice and when it is used. For instance, in single-cropping rice, if a mild AWD is applied, the yield is basically not affected. The number of panicles and grains is similar to that of those that have been constantly flooded. Sometimes, the number of grains per panicle may even be a little higher-because a little drying can actually control ineffective tillering and concentrate nutrients on the longer panicles. However, if it is double-cropping rice, the situation for early rice and late rice is different: early rice has more rainfall, and appropriate drainage is actually beneficial to the growth of the group and can also maintain the yield. Late rice is prone to high temperatures and drought. If the alternations between dry and wet conditions are too frequent at this time, it may lead to insufficient tillering and less fruit production. Therefore, it is best to keep the soil moist during the panicle formation and grain filling periods. The variety is also quite crucial. For instance, many hybrid rice varieties nowadays have strong roots and are resistant to adverse conditions, so their yields remain stable under AWD conditions (Wang et al., 2024). However, some old varieties experience a significant reduction in yield as soon as there is a drought. Overall, as long as the operation is proper and the drought is not excessive during critical periods, AWD can actually achieve no reduction in yield. In fact, due to a better population structure and higher nutrient utilization, it can even slightly increase yield (Shaibu et al., 2014).

3.3 Summary of yield results from field trials and large-scale promotion

Indeed, many experiments and field demonstrations have shown that the AWD irrigation method does not affect the yield. Whether in the Philippines, Bangladesh or China, farmers have actually found that the yield is about the same as that of those who have been constantly flooded. Sometimes, due to less lodging and diseases, the yield can even be slightly higher (Hossain and Islam, 2022). Of course, the results may fluctuate a little depending on the region and year, but in most cases, the output variation is within 5%, which is not very significant. In some places, even when AWD is used in combination with soil improvement measures, the output can be further increased (Neogi et al., 2018). Although in particularly dry and hot years, improper operation may affect the formation of ears, it can generally be avoided by adjusting management. Overall, as long as the water pipes are used reasonably, AWD basically will not cause a reduction in rice yield. At the same time, it can save water, reduce emissions, and has good stability. This also makes farmers more willing to accept it. After all, they don't have to worry about a significant drop in harvest, and it will be easier to promote.

4 The Impact of AWD on Greenhouse Gas Emissions

4.1 Sources and dynamics of major greenhouse gases (CH_4, N_2O, CO_2) in rice fields

Rice fields are actually a major source of greenhouse gases, among which methane and nitrous oxide are the most troublesome. You may not know that if the field is constantly flooded and the soil is deprived of oxygen, methanogenic bacteria will be particularly active, and methane will be discharged through soil pores and rice plants-usually most obviously during the peak tillering period and the later stage of heading. If the fields are dried in the middle, the discharge will temporarily stop, but once water is reapplied, it may rebound. Nitrous oxide is quite different. It is related to the nitrification and denitrification processes. It hardly occurs when the water is constantly flooded. Instead, it tends to suddenly peak when the water dries up or when the water and soil alternate (Jiang et al., 2014; Chidthaisong et al., 2018). As for carbon dioxide, although it does exist, its cycle is short and its impact is small. What people are more concerned about are still methane and nitrous oxide. Overall, fields that have been constantly flooded emit more methane and have a stronger greenhouse effect. Although the alternation of dry and wet conditions may cause a slight increase in nitrous oxide, it leads to a greater reduction in methane, and the overall warming potential actually decreases. So, irrigation methods like AWD, by adjusting water content, are indeed an effective way to control rice field emissions and mitigate climate impacts.

4.2 The mechanism of AWD in reducing methane (CH_4) emissions

When it comes to greenhouse gases in rice fields, one of the most obvious advantages of (alternating dry and wet irrigation) AWD is that it can significantly reduce methane emissions. This is mainly because AWD makes the fields sometimes dry and sometimes wet. When the soil is dry and there is oxygen, methanogens are less active-they prefer an environment that is constantly flooded. Meanwhile, aerobic conditions can also promote the oxidation of methane, allowing some of the methane that has already been produced to be consumed. Actual field data shows that after the application of AWD, methane emissions throughout the growing season can be reduced by 30% to 70%, and in some areas, it can even reach 90% (Karki et al., 2022; Zhao et al., 2024). Of course, this effect is related to the duration and frequency of drying. Generally speaking, the longer and more frequently it is dried, the more obvious the reduction in emissions will be. However, on the other hand, when operating, one should not only focus on reducing emissions but also ensure that the rice gets enough water. If it is too dry, the yield may be affected. Overall, AWD can significantly reduce methane emissions with little impact on yield, greatly improving the carbon efficiency of rice cultivation. It can be regarded as a practical approach towards low-carbon agriculture.

4.3 Potential impact on nitrous oxide (N_2O) emissions and trade-off relationship

Unlike the significant reduction of methane, the emissions of nitrous oxide (N_2O) are often higher under AWD. This is mainly because the alternation of dry and wet conditions activates the nitrification and denitrification process in the soil, causing some nitrogen fertilizers to escape in the form of N_2O. The fields that have been constantly flooded actually have very low N_2O emissions due to lack of oxygen. However, during the process of AWD drying up and rewatering, the soil is alternately rich in oxygen and deficient in oxygen, which makes it easy for a peak in N_2O emissions to occur at this time. Overall, the total amount of N_2O in AWD fields is indeed higher than that of continuous flooding, but its absolute amount is much smaller than that of methane. The increase in N_2O is far from offset by the reduction in methane, so the overall greenhouse effect is still reduced. However, it should also be noted that if too much nitrogen fertilizer is used or the dry and wet alternations are too frequent, the peak value of N_2O may be particularly high. To control this risk, it is best to optimize nitrogen fertilizer management, such as applying less fertilizer, using slow-release fertilizer or adding some nitrification inhibitors, and at the same time, prevent the fields from being too dry. In fact, as long as water and fertilizer are well combined, AWD can not only reduce methane but also control N_2O. In most cases, the overall emission reduction effect is better than continuous flooding. It can be regarded as a practical emission reduction method (Abid et al., 2019; Wang et al., 2025).

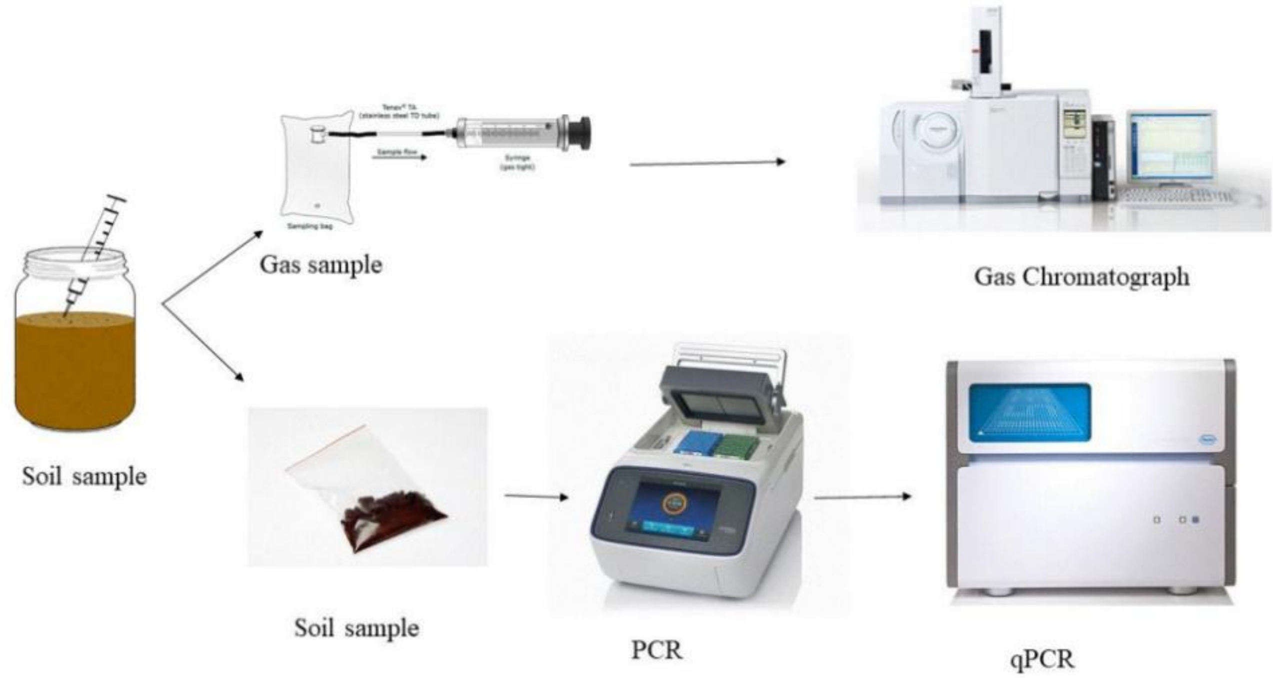

Figure 1 Schematic diagram of whole study plan (Adopted from Abid et al., 2019)

5 Ecological and Environmental Effects

5.1 The influence of AWD on the physical and chemical properties of soil

A change in irrigation methods not only affects greenhouse gases and crops, but also makes the soil itself different. Take AWD for example. The field is dry and wet, and the soil repeatedly shrinks and expands, undergoes oxidation and reduction, which actually makes the structure more stable and breathable, reduces the bulk density, and some cracks may appear-this is actually beneficial for the root system to grow deeper, and the entire plough layer will also be looser. In terms of chemical properties, AWD reduces the accumulation of reducing substances such as ferrous and manganese, alleviates the toxicity to crops, and also promotes the conversion of ammonium nitrogen into nitrate nitrogen, enhancing the supply capacity of nitrogen. However, if not managed properly, nitrogen is also prone to loss. The activation of phosphorus under AWD is slightly lower, while potassium has little effect. In terms of microorganisms, AWD will make aerobic bacteria more active, accelerate the decomposition of organic matter, and increase the release of nutrients in the short term. However, in the long term, it may lead to a decrease in organic carbon (Islam et al., 2020). This can be compensated for by returning straw to the field. There is an advantage in terms of elements: AWD can reduce the arsenic content in rice, making it safer to eat, but it may slightly increase the activity of cadmium (Hu et al., 2023). Overall, AWD is mostly positive for soil structure and nutrient environment. However, it is best to combine it with fertilization and tillage measures, which can not only nourish the land but also reduce emissions.

5.2 Water resource utilization efficiency and water-saving potential

The greatest advantage of AWD is actually water conservation, which is particularly useful in alleviating the pressure on water resources caused by rice cultivation. The traditional rice fields have been flooded all along, and a lot of water has actually seeped or evaporated, which is quite a waste. AWD reduces unnecessary water accumulation in the fields, allowing more water to be truly used for crop transpiration. This means maintaining yields with less water and sometimes even allowing for more grain production. Research shows that AWD can generally save 15% to 30% of irrigation water, and in some areas, it even exceeds 40%, and water use efficiency is also increased by 10% to 30% (Rejesus et al., 2011). Especially in areas that frequently suffer from water shortages, AWD can also reduce the frequency of water pumping, and electricity and fuel costs can be saved by 20% to 30% (Husain et al., 2010). This directly means cost reduction and income increase for farmers. From a broader perspective, due to the reduced water consumption per unit area, the same amount of water can irrigate more fields, and the overall grain output can also increase. At the same time, it can alleviate the over-exploitation of groundwater and save energy for pumping water. Therefore, AWD not only performs well in farmers' fields but also plays a role in water resource allocation throughout the region. It can be regarded as an effective approach to addressing water shortages and promoting sustainable agricultural development.

5.3 Role in biodiversity and ecosystem services

Rice fields are actually quite unique. They are not only farmlands but also have the characteristics of wetlands, and their ecological functions change with the way water is managed. The AWD, which alternates between dry and wet irrigation, alters the hydrological conditions in the fields through periodic drying, exerting considerable influence on animals, plants and ecological services. When the water keeps flooding, the fields are more like wetlands, suitable for living creatures such as apple snails and aquatic insects-some of which are pests and some are beneficial. However, AWD will break this aquatic environment, reducing snail damage and some weeds, and at the same time making it easier for some terrestrial natural enemies to enter the fields to catch pests. As a result, the effect of ecological pest control is enhanced (Chapagain et al., 2011). The fields being dry and wet can also reduce fungal diseases like rice blast and inhibit the reproduction of rice planthoppers, but it may also make field mice more active. For soil microorganisms, AWD enhances the diversity of aerobic bacteria and nitrifying and denitrifying bacteria, making the nitrogen cycle more active. At the same time, methanogens are less active, which is helpful for emission reduction (Brito et al., 2021). As for carbon sinks, the situation is a bit more complicated: AWD may accelerate the decomposition of organic matter, but if combined with straw returning to the field, it can actually increase net carbon sinks. Overall, while AWD saves water and reduces emissions, it also improves some ecological functions. However, it is necessary to pay attention to the possible problems it may bring and try to balance production and ecology through optimized operation.

6 Considerations at the Social, Economic and Policy Levels

6.1 Economic benefit analysis of AWD

When it comes to promoting agricultural emission reduction technologies, whether they are economically feasible is actually very crucial. The greatest advantage of the AWD field management approach is that it can save money and even earn more. It directly reduces the cost of oil, electricity or water by cutting down on irrigation water and the frequency of pumping. In some places, it can save several hundred yuan per hectare. Moreover, the output was basically not affected. Sometimes, the harvest was even slightly higher, truly achieving "saving money without reducing production" (Suwanmaneepong et al., 2023). As a result, the actual income of farmers increased instead. There are also some less obvious benefits, such as fewer pests and diseases and less money on pesticides. The root system grows better and there are fewer cases of lodging. In the long run, AWD can alleviate the problem of over-exploitation of groundwater and is beneficial to the sustainable development of agriculture. If it is a larger farm, more land can be cultivated with the same amount of water, and the potential income will be even more considerable (Uddin et al., 2020). Although using AWD requires more effort in field patrol and management, it is still more convenient overall. Many farmers, seeing that it can indeed save money without affecting the harvest, are willing to follow suit and use it. As a result, the promotion of AWD becomes much easier, laying a good foundation for its wide application.

6.2 Obstacles to farmers' acceptance and technology promotion

Whether farmers are willing to use AWD is directly related to whether this technology can be widely promoted. Although AWD can indeed save water and money, it still encounters many obstacles in actual promotion. Some farmers are worried that their yields will drop, especially during the crucial growth period. When they see the fields dry, they feel insecure. Therefore, they still insist on the old method of flooding the land. This requires real demonstrations and training to gradually change their mindset. The irrigation system is also a problem. In areas where water is uniformly released, if no one coordinates, it is very difficult for individual households to alternate between dry and wet irrigation on their own. There are also technical operation thresholds. In some low-lying fields, drainage is already inconvenient, or farmers are not good at measuring water levels, so they are naturally not very willing to try. In fact, with some simple water measurement tools and the guidance of a technician, it's not difficult to learn. Another key point is the distribution of benefits: if the saved water cannot be converted into actual income, farmers' enthusiasm will be low, so incentives such as policy subsidies or water rights trading may be needed (Mahadi et al., 2018). Besides, the older generation of farmers are relatively conservative. However, if village cadres or large-scale grain producers take the lead in using it, the effect will be much better. Overall, the main obstacles are the lack of understanding among the public, the lack of supporting systems, and the absence of incentives (Alauddin et al., 2020). However, as long as farmers can see with their own eyes that "it saves money without reducing production", many people will still accept it. Only in this way can the water conservation and emission reduction goals of AWD be truly achieved.

6.3 The role of policies and international organizations in low-carbon agriculture

For low-carbon agricultural technologies like AWD to be widely applied on a large scale, the support of governments and international organizations is truly crucial. In fact, the government has already done a lot. For instance, it has included AWD in the agricultural emission reduction plan. By formulating technical standards, conducting pilot projects, and providing subsidies, it has helped farmers install water level pipes and improve irrigation and drainage facilities. In some places, water price reforms and water rights trading have been carried out to enable farmers to earn more directly by saving water. Only in this way can people be more motivated to use water. The agricultural technology department has also been conducting training and demonstrations to enable more farmers to master this technology. International organizations like IRRI and FAO have long been promoting AWD in various countries. They have formulated operational guidelines, provided both technology and funds. Institutions such as the World Bank have also regarded AWD as an important indicator in agricultural loan projects (McKinley et al., 2020). All these have contributed to the promotion of AWD among different countries. If the reduction of emissions from rice fields can be included in the carbon market in the future, farmers can still earn some money from carbon sinks through AWD, and their enthusiasm will definitely be higher. Overall, with the joint efforts of policies, funds, markets and technologies, the risks for farmers to try new technologies have been reduced, and the environmental benefits of water conservation and emission reduction have been transformed into real economic driving forces (Trang et al., 2022). Only in this way can AWD gradually become the mainstream rice-growing method and promote the green transformation of agriculture.

7 Empirical Analysis of AWD Application in Southeast Asia

7.1 Research area and method design

Southeast Asia is home to one of the world's largest rice varieties and is an important granary. However, it is also increasingly short of water and faces considerable pressure to reduce emissions. Take the Mekong Delta in Vietnam as an example. The rice fields have been flooded for a long time, which not only consumes a lot of water but also leads to a decreasing amount of groundwater and soil salinization. At the same time, methane emissions are also quite serious. To address these troubles, in recent years, Vietnam, the Philippines and Thailand have all conducted numerous demonstrations and trials of AWD, comparing its output, emissions and water-saving effects with the old methods that have always been flooded. These experiments spanned different seasons and locations. Some conducted precise measurements in small plots of land, while others directly compared large fields in collaboration with farmers. The results were closer to reality. Overall, AWD has performed well in water conservation and emission reduction, with almost no impact on production. Moreover, adjustments have been made based on local conditions. For instance, during the rainy season, the rice is naturally drained by rainwater, while during the dry season, regular drainage is carried out but timely re-irrigation is ensured to prevent the rice from being left dry. They also took the opportunity to look at the pests and diseases and changes in rice quality that farmers were concerned about. After a comprehensive assessment, it was found that AWD has considerable promotion value in Southeast Asia and also has practical significance for the sustainable development of agriculture (Tirol-Padre et al., 2018; Duong et al., 2024).

7.2 Monitoring results of rice yield and greenhouse gas emissions

Many experiments have been conducted in Southeast Asia, and it has been found that as long as it is managed properly, the AWD irrigation method can indeed significantly reduce emissions and save water without basically affecting the output. In terms of output, studies from multiple countries have shown that the output of AWD is similar to that of continuous flooding. Sometimes it is slightly higher or lower, but the difference is not significant. Even if the weather is relatively hot, the output remains quite stable. Farmers actually don't need to worry too much about reduced production. The effect of emission reduction is more obvious. AWD can reduce methane emissions by 45% to 50% (Chidthaisong et al., 2018). Although there will be a slight increase in nitrous oxide, the amount is very small, and the overall greenhouse effect is still reduced. Overall, the greenhouse gas emission intensity of AWD fields is one-third or even half lower than that of continuous flooding (Figure 2) (Deepagoda et al., 2024). At the same time, it can also save a considerable amount of water. About 1 000 cubic meters of water can be saved per hectare per season, and the water use efficiency has increased by nearly 20%. To put it this way, AWD has achieved stable production, reduced emissions and water conservation in the rice-growing areas of Southeast Asia. It ensures food supply while alleviating environmental and resource pressures, providing a reliable reference for promoting climate-smart agriculture.

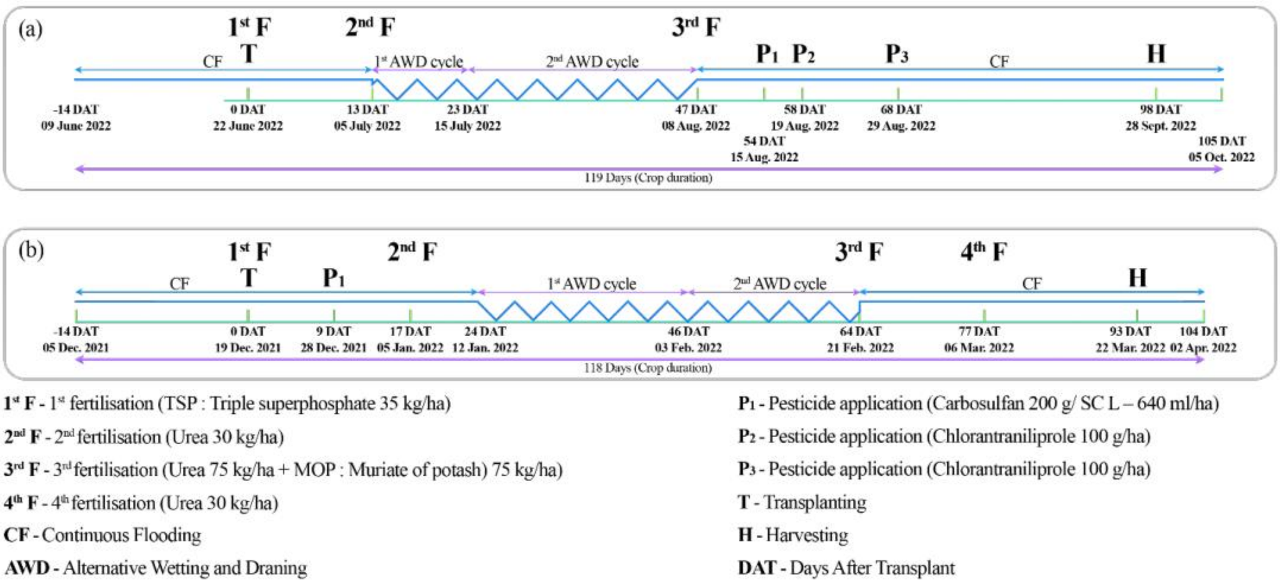

Figure 2 Cultivation practice calendar for (a) wet and (b) dry season at the Bathalagoda/Sri Lanka site (Adopted from Deepagoda et al., 2024)

7.3 Experience summary and implications for regional agricultural policies

The experience of promoting AWD in Southeast Asia has actually brought a lot of inspiration to agricultural policies and technology promotion. In practice, it was found that to apply it on a large scale, it still depends on the local conditions. Take it slow. First, set up some demonstration fields. Once the effect is seen, expand it. This way, the risk will be smaller. The promotion effect also depends on whether the supporting measures can keep up. For instance, if AWD, good varieties, scientific fertilization and pest and disease prevention are promoted together, farmers will be more likely to accept them. Cooperation between grassroots organizations and farmers is also quite crucial. For instance, cooperatives or water-using groups can manage water uniformly, measure water levels, and exchange information, which is much easier than individual households doing it on their own. Some countries have also tried subsidies and rewards, such as providing some carbon reduction subsidies and giving away some equipment, which has made people more enthusiastic. More importantly, AWD has demonstrated that increasing production and reducing emissions can actually be achieved simultaneously (Allera et al., 2024). This has led policies to no longer focus solely on output but to start considering win-win goals. Nowadays, some countries have incorporated AWD into their climate action plans and set specific usage ratios (Wassmann, 2016). This indicates that the promotion of technology must be well coordinated with aspects such as systems, organizations, and incentives in order to be truly rolled out. In the future, as the consensus among people increases, AWD may become a major direction for rice emission reduction and sustainable development in Southeast Asia.

8 Challenges and Future Prospects

Although AWD has performed well in many places, when it comes to promoting it to different regions, the issue of suitability still needs to be considered. Firstly, there are significant differences in climate and hydrology across regions. For instance, in monsoon areas, there is abundant rainfall, and AWD can be implemented simply by natural drying. However, if it is placed in arid or semi-arid areas, forcing it might actually lead to even greater water shortages. In such cases, it might be necessary to consider planting drought-tolerant varieties or even switching to upland rice. There are still some areas prone to waterlogging where the drainage conditions are not up to standard, making it difficult for the water to dry up. The type of soil is also crucial. Clay is prone to cracking and sand seeps water too quickly. If not managed properly, the water-saving effect may be compromised. The varieties also need to be carefully selected. Some traditional varieties have shallow roots and are not drought-tolerant. They cannot tolerate alternating dry and wet conditions. It is best to use new varieties that are both drought-tolerant and wet-tolerant. In addition, the water conservancy facilities and the management level of farmers must also keep up. Small-scale farmers have scattered plots of land, and it is not easy to operate uniformly. Ultimately, the policy priorities and food security demands of different countries vary, which also affects whether they are willing to promote AWD. In conclusion, AWD cannot be applied in a one-size-fits-all manner. It is necessary to consider the local water, soil and variety conditions, conduct an adaptability assessment, and find an appropriate approach to ensure its wide promotion and long-term use.

To enhance the practical effect of AWD, it is best to combine it with some other low-carbon and efficient agricultural measures, so that they can promote each other. First of all, the variety is crucial. Choose those with strong roots, drought tolerance and low fertilizer consumption. Combined with AWD, it is easier to achieve both stable production and emission reduction. Fertilizer management should also keep up. For instance, some slow-release fertilizers, organic fertilizers or returning straw to the field can be used. This can not only enhance the utilization of nitrogen but also reduce the emission of nitrous oxide. In addition, soil conditioners like biochar are also quite useful. They can help retain soil water, promote microbial activity, and further reduce emissions and stabilize production on the basis of AWD. AWD can also be combined with shallow wet irrigation and mid-term sun-drying methods to flexibly adjust water usage based on local conditions, thus forming a more suitable water-saving model for the local area. Some adjustments can also be made to the planting system, such as rotating rice and dryland crops, or planting some green manure, which can not only improve the soil but also reduce emissions. Overall, packaging measures such as AWD, good varieties, scientific fertilization, soil improvement, and reasonable crop rotation into a "water-saving and emission reduction technology package" has the best comprehensive effect and can truly promote the green and efficient development of rice cultivation.

The research and application of AWD in the future still need to make more efforts in several aspects. First, some long-term positioning tests need to be conducted to see exactly what long-term impacts it has on soil carbon and nitrogen, microorganisms, as well as yield and quality. Secondly, it is necessary to optimize the operation threshold, such as using sensors and models to find the most suitable degree of drying under different conditions, and developing a "dynamic AWD" that can be adjusted in real time. Digital agricultural technologies can also be of assistance. For instance, the Internet of Things and automatic irrigation systems can make control more precise and save labor. In addition, it is best for AWD to be integrated into the entire agricultural production system. This way, its ability to cope with climate change will be stronger. Even if the irrigation water is reduced by 20% in the future, the output can still be maintained. From a global perspective of emission reduction, if more than half of the rice fields were to use AWD, the amount of methane that could be reduced each year would be considerable, making a tangible contribution to achieving climate goals. Therefore, AWD is not only a water-saving and emission-reducing technology, but also an important tool for the green transformation of agriculture and ensuring food security.

Acknowledgments
I would like to express my heartfelt thanks to all the teachers who have provided guidance for this study.

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.

References
Abid A.A., Zhang Q., Afzal M., and Di H., 2019, Nitrous oxide emission and production pathways under alternate wetting-drying conditions in rice paddy soils, Applied Ecology & Environmental Research, 17(6): 13777-13792.
https://doi.org/10.15666/aeer/1706_1377713792

Alauddin M., Sarker M., Islam Z., and Tisdell C., 2020, Adoption of alternate wetting and drying (AWD) irrigation as a water-saving technology in Bangladesh: economic and environmental considerations, Land Use Policy, 91: 104430.
https://doi.org/10.1016/j.landusepol.2019.104430

Allera M., and Flores L., 2024, Adoption of climate-smart rice production practices and technologies: a tool towards rice production efficiency and agricultural sustainability, Journal of Interdisciplinary Perspectives, 2(8): 255-265.
https://doi.org/10.69569/jip.2024.0267

Brito G., Concenço G., Costa V., Fagundes P., Silva-Filho J., Parfitt J., Magalhães A., Silva G., Jardim T., Luccas N., and Scivittaro W., 2021, Genetics components of rice root architecture and carbon isotopic fractionation parameters: a tracer for breeding in a water-saving irrigation management, Journal of Crop Science and Biotechnology, 25(1): 19-32.
https://doi.org/10.21203/RS.3.RS-187585/V1

Chapagain T., Riseman A., and Yamaji E., 2011, Achieving more with less water: alternate wet and dry irrigation (AWDI) as an alternative to the conventional water management practices in rice farming, The Journal of Agricultural Science, 3(3): 3.
https://doi.org/10.5539/JAS.V3N3P3

Chidthaisong A., Cha-Un N., Rossopa B., Buddaboon C., Kunuthai C., Sriphirom P., Towprayoon S., Tokida T., Padre A., and Minamikawa K., 2018, Evaluating the effects of alternate wetting and drying (AWD) on methane and nitrous oxide emissions from a paddy field in Thailand, Soil Science and Plant Nutrition, 64(1): 31-38.
https://doi.org/10.1080/00380768.2017.1399044

Chu G., Zhan M., Zhu K., Wang Z., and Yang J., 2016, Effects of alternate wetting and drying irrigation on yield and water use efficiency of rice, Acta Agronomica Sinica, 42(7): 1026-1036.
https://doi.org/10.3724/SP.J.1006.2016.01026

Deepagoda T., Lakshani M., Nissanka S., Weragoda S., Senanayake D., Babu G., Chanakya H., Hamamoto S., Sander B., Clough T., Elberling B., Smits K., and Kumari K., 2024, Impact of water management on methane and nitrous oxide emission dynamics in Asian paddy ecosystems, APN Science Bulletin, 14(1): 77-92.
https://doi.org/10.30852/sb.2024.2565

Du S., Tanaka K., and Yagi H., 2025, Farmers' adoption of water management practice for methane reduction in rice paddies: a spatial analysis in Shiga, Japan, Sustainability, 17(8): 3468.
https://doi.org/10.3390/su17083468

Duong N., Pham V., Le H., Nguyen S., and Huynh D., 2024, Evaluating the performance of alternate wetting and drying irrigation technology: an on-farm rice case study in an Giang Province, the Mekong Delta of Vietnam, Pertanika Journal of Tropical Agricultural Science, 47(3): 605-619.
https://doi.org/10.47836/pjtas.47.3.02

Echegaray-Cabrera I., Cruz-Villacorta L., Ramos-Fernández L., Bonilla-Cordova M., Heros-Aguilar E., and Flores del Pino L., 2024, Effect of alternate wetting and drying on the emission of greenhouse gases from rice fields on the northern coast of Peru, Agronomy, 14(2): 248.
https://doi.org/10.3390/agronomy14020248

Hossain M., and Islam M., 2022, Farmers' participatory alternate wetting and drying irrigation method reduces greenhouse gas emission and improves water productivity and Paddy yield in Bangladesh, Water, 14(7): 1056.
https://doi.org/10.3390/w14071056

Hu R., Cooper J., Daroub S., Kerl C., Planer-Friedrich B., and Seyfferth A., 2023, Low levels of arsenic and cadmium in rice grown in southern Florida histosols-impacts of water management and soil thickness, Science of the Total Environment, 869: 161712.
https://doi.org/10.1016/j.scitotenv.2023.161712

Husain M., Alam M., Kabir M., Khan A., and Islam M., 2010, Water saving irrigation in rice cultivation with particular reference to alternate wetting and drying method: an overview, The Agriculturists, 7: 128-136.
https://doi.org/10.3329/AGRIC.V7I1.5591

Islam S., De Neergaard A., Sander B., Jensen L., Wassmann R., and Van Groenigen J., 2020, Reducing greenhouse gas emissions and grain arsenic and lead levels without compromising yield in organically produced rice, Agriculture, Ecosystems & Environment, 295: 106922.
https://doi.org/10.1016/j.agee.2020.106922

Jiang W., Fang X., Huang Z., Chen Z., Xiang W., Chen M., Yang S., and Du X., 2014, Greenhouse gas emissions and agronomic performances were affected by different irrigation methods in rice field, Journal of Food, Agriculture and Environment, 12: 559-565.

Karki S., Adviento-Borbe M., Runkle B., Moreno-García B., Anders M., and Reba M., 2022, Multiyear methane and nitrous oxide emissions in different irrigation management under long-term continuous rice rotation in Arkansas, Journal of Environmental Quality, 52(3): 558-572.
https://doi.org/10.1002/jeq2.20444

Khalil M., and Shearer M., 2006, Decreasing emissions of methane from rice agriculture, In: International congress series, Elsevier, 1293: 33-41.
https://doi.org/10.1016/J.ICS.2006.03.003

Loaiza S., Verchot L., Valencia D., Guzmán P., Amezquita N., Garcés G., Puentes O., Trujillo C., Chirinda N., and Pittelkow C., 2024, Evaluating greenhouse gas mitigation through alternate wetting and drying irrigation in Colombian rice production, Agriculture, Ecosystems & Environment, 360: 108787.
https://doi.org/10.1016/j.agee.2023.108787

Mahadi M., Rahman Z., and Sarker A., 2018, A climate resilient management practice in rice farming: adoption of alternate wetting and drying in Bangladesh, International Journal of Agricultural Extension, 6(1): 25-32.
https://doi.org/10.33687/IJAE.006.01.2432

Mckinley J., Sander B., Vuduong Q., Mai T., and LaFrance J., 2020, How expectations, information, and subsidies influence farmers' use of alternate wetting and drying in Vietnam's River Deltas, In: 2020 Conference (64th), Australasian agricultural and resource economics society (AARES), Perth, Western Australia, pp.1-2.
https://doi.org/10.22004/AG.ECON.305255

Mote K., Rao V., Ramulu V., Kumar K., and Devi M., 2021, Performance of rice (*Oryza sativa* (L.)) under AWD irrigation practice—A brief review, Paddy and Water Environment, 20(1): 1-21.
https://doi.org/10.1007/s10333-021-00873-4

Neogi M., Uddin A., Uddin M., and Hamid M., 2018, Alternate wetting and drying (AWD) technology: a way to reduce irrigation cost and ensure higher yields of Boro rice, Journal of The Bangladesh Agricultural University, 16(1): 1-4.
https://doi.org/10.3329/JBAU.V16I1.36471

Rejesus R., Palis F., Rodriguez D., Lampayan R., and Bouman B., 2011, Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: evidence from rice producers in the Philippines, Food Policy, 36(2): 280-288.
https://doi.org/10.1016/J.FOODPOL.2010.11.026

Shaibu Y., Banda H., Makwiza C., and Malunga J., 2014, Grain yield performance of upland and lowland rice varieties under water saving irrigation through alternate wetting and drying in sandy clay loams of Southern Malawi, Experimental Agriculture, 51(2): 313-326.
https://doi.org/10.1017/S0014479714000325

Sun Y., Wu Q., Chi D., Chen,H., Zhu S., and Liu Q., 2025, Water-saving irrigation combined with N-loaded clinoptilolite enhances nutrient yield, and water productivity by improving rice root characteristics: a combined PCA-SEM analysis, Agricultural Water Management, 307: 109203.
https://doi.org/10.1016/j.agwat.2024.109203

Suwanmaneepong S., Kultawanich K., Khurnpoon L., Sabaijai P., Cavite H., Llones C., Lepcha N., and Kerdsriserm C., 2023, Alternate wetting and drying as water-saving technology: an adoption intention in the perspective of good agricultural practices (GAP) suburban rice farmers in Thailand, Water, 15(3): 402.
https://doi.org/10.3390/w15030402

Tirol-Padre A., Minamikawa K., Tokida T., Wassmann R., and Yagi K., 2018, Site-specific feasibility of alternate wetting and drying as a greenhouse gas mitigation option in irrigated rice fields in Southeast Asia: a synthesis, Soil Science and Plant Nutrition, 64(1): 2-13.
https://doi.org/10.1080/00380768.2017.1409602

Towprayoon S., Smakgahn K., and Poonkaew S., 2005, Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields, Chemosphere, 59(11): 1547-1556.
https://doi.org/10.1016/J.CHEMOSPHERE.2005.02.009

Trang V., Nelson K., Samsuzzaman S., Rahman S., Rashid M., Salahuddin A., and Sander B., 2022, Institutional analysis for scaling alternate wetting and drying for low-emissions rice production: evidence from Bangladesh, Climate and Development, 15(1): 10-19.
https://doi.org/10.1080/17565529.2022.2036088

Uddin M., and Dhar A., 2020, Assessing the impact of water-saving technologies on *Boro* rice farming in Bangladesh: economic and environmental perspective, Irrigation Science, 38(2): 199-212.
https://doi.org/10.1007/s00271-019-00662-2

Wang C., Fa X., Meng Q., Zhang Y., Wang W., Zhu K., Zhang W., Gu J., Liu L., Zhang J., and Zhang H., 2024, Comparison of agronomic and physiological characteristics for rice varieties differing in water use efficiency under alternate wetting and drying irrigation, Agronomy, 14(9): 1986.
https://doi.org/10.3390/agronomy14091986

Wang J., Jin W., Xie N., Che Z., Zhang C., Li X., Wu G., Yang S., Dong Z., and Song H., 2025, Oxygen availability governs the mitigating effect of 3,4-dimethylpyrazole phosphate on nitrous oxide emissions from paddy soils under various water managements, Journal of Agricultural and Food Chemistry, 73(10): 5781-5791.
https://doi.org/10.1021/acs.jafc.4c09965

Wassmann R., 2016, Climate-smart rice production for combining adaptation and mitigation: technological options within the context of Southeast Asia, BANWA Supplements, 3: 49387.

Yang X., Fu Y., S., Gan H., Xu W., and Shen H., 2020, The class III peroxidase gene *OsPrx24* is important for root Iron plaque formation and benefits phosphorus uptake in rice plants under alternate wetting and drying irrigation, Plant and Soil, 448(1): 621-646.
https://doi.org/10.1007/s11104-020-04455-x

Zhao C., Qiu R., Zhang T., Luo Y., and Agathokleous E., 2024, Effects of alternate wetting and drying irrigation on methane and nitrous oxide emissions from rice fields: a meta-analysis, Global Change Biology, 30(12): e17581.
https://doi.org/10.1111/gcb.17581