

# **Green Asia** Report Series

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**No.9**

## **Guidelines for Improving Rice Yield through Climate-Smart Water Management in the Asia-Monsoon Region**

**Kazunori Minamikawa, Shintaro Kobayashi, Ai Leon,  
Kenichi Uno, Toshiyuki Takai, Yasuhiro Tsujimoto**



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**Kazunori Minamikawa<sup>1</sup>, Shintaro Kobayashi<sup>1</sup>, Ai Leon<sup>1</sup>, Kenichi Uno<sup>1</sup>,  
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**Green Asia**

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## Preface

Rice farming is a major source of methane (CH<sub>4</sub>), a potent greenhouse gas (GHG), yet it remains a cornerstone of food security in the Asia–Monsoon region. Climate-smart water management offers an opportunity to address both challenges simultaneously. Still, there is a significant gap in scientific evidence to guide locally applicable water-management practices that can maintain or even improve food production while reducing GHG emissions. Although practices such as Alternate Wetting and Drying (AWD) and midseason drainage followed by intermittent irrigation (MiDi) have gained traction in some areas, their adoption remains limited in the region. Concerns over yield loss, weed pressure, and insufficient technical support continue to pose barriers, while existing incentives focusing mainly on water saving and cost reduction often fall short of motivating behavioral change among farmers.

In response to the urgent need to enhance rice productivity while reducing GHG emissions, the *Guidelines for Improving Rice Yield through Climate-Smart Water Management in the Asia–Monsoon Region* were developed by the Japan International Research Center for Agricultural Sciences (JIRCAS). The Guidelines emphasize yield improvement as a tangible incentive for farmers. Yield improvement, in this context, refers to increasing actual yields by narrowing the gap with attainable yields—those achievable under optimal agronomic practices.

Drawing on evidence from field trials and scientific studies, the Guidelines offer context-specific advice on how appropriate drainage can enhance rice yields without compromising environmental benefits. The Guidelines are not a prescriptive manual but a flexible reference adaptable to a wide range of agro-environmental conditions by supporting farmers, researchers, extension officers, and policymakers in:

- Planning extension programs and demonstration plots
- Developing locally adapted water-management calendars
- Informing training materials for field officers and farmers
- Providing scientific backing for policy development and investment planning

Ultimately, this document aims to contribute to decision making for national climate goals, such as the Nationally Determined Contributions (NDCs), while supporting resilient and productive rice-farming systems in the Asia–Monsoon region.

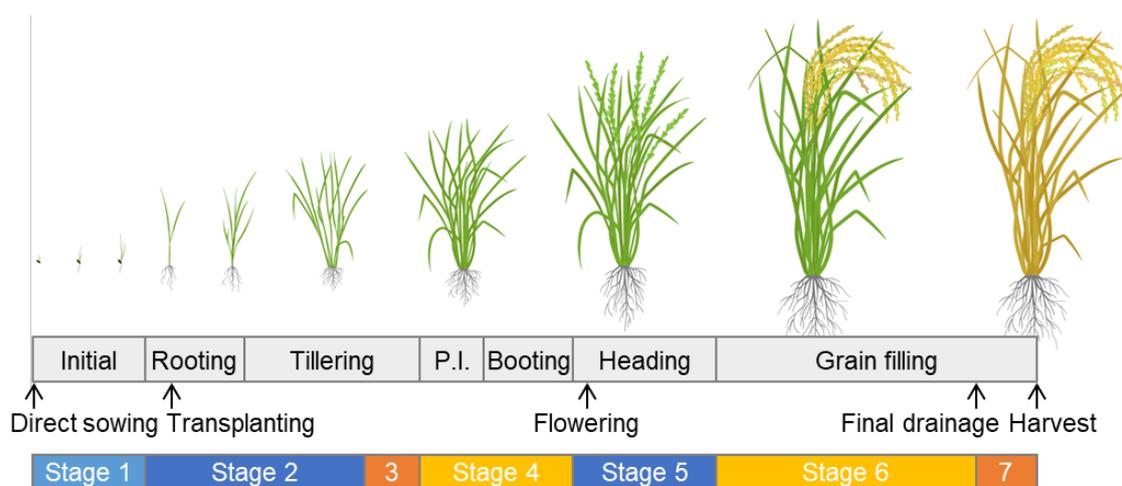
On behalf of the authors,  
Kazunori Minamikawa  
JIRCAS  
March 2026

## Summary of recommendations

Below is an overview of recommended MiDi-based water management practices by growth stage to achieve higher yields and reduce CH<sub>4</sub> emissions compared to continuous flooding (CF). These practices can be adjusted in timing and intensity to suit local agro-environmental conditions. Drainage is generally managed at moderate intensity; severe drainage may be used during the midseason drainage period if feasible. See Chapter 5 for details on optimizing the practices.

**Table S1. MiDi-based recommended practices by rice growth stage**

Stage	Objective	Recommendation	Note
1. Initial	Promote germination and emergence	Maintain saturated soil or shallow water levels	The same as the conventional direct sowing system
2. Rooting to tillering	Protect seedlings	Maintain flooded conditions	Light drainage if strong soil reduction occurs
3. Late tillering	Restore and stimulate root growth	Midseason drainage for 5–7 days	Adjust duration depending on field water conditions
4. Panicle initiation to booting	Promote translocation of photosynthates	Intermittent irrigation: (e.g., 4-day flooding → 3-day natural drainage)	Adjust drainage duration considering field water conditions
5. Heading	Ensure spikelet fertility and grain filling	Resume flooded conditions	To avoid drought stress
6. Grain filling	Promote assimilate remobilization	Intermittent irrigation: (e.g., 4-day flooding → 3-day natural drainage)	Adjust drainage duration considering field water conditions
7. End of grain filling	Facilitate harvest	Final drainage	From 1–2 weeks before harvest



**Figure S1. MiDi-based, recommended water management practices by growth stage (modified from Minamikawa, 2025). P.I., panicle initiation**



# 1. Introduction

## 1.1. Rice production and environmental challenges

Much of the world's rice is produced in the Asia–Monsoon region, where abundant rainfall and irrigation systems in many areas support flooded paddy cultivation, although the degree of irrigation infrastructure varies across regions (Figure 1). The region accounts for around 90% of global rice output, underpinning food security for a large share of the world's population (Iiyama et al., 2023). Over recent decades, the adoption of modern rice varieties with shorter growth durations has enabled intensification, especially in tropical areas such as the Mekong Delta, where rice cultivation has shifted from single- to double- or triple-cropping. While this intensification has supported stable food production, shortened fallow periods and prolonged flooded conditions can lead to chronically reduced soil environments, which may limit yield formation even under adequate fertilization and management.



**Figure 1. Diverse rice environments in the Asia–Monsoon region**

Under flooded conditions, soils become anaerobic, and methanogenic archaea produce methane ( $\text{CH}_4$ ), a potent greenhouse gas (GHG), which is released mainly through plant-mediated transport. Consequently, rice cultivation is a major anthropogenic source of  $\text{CH}_4$  emissions, with the Asia–Monsoon region contributing the majority of these emissions due to its extensive flooded paddy systems.

Strategic water management has gained attention for reducing  $\text{CH}_4$  while maintaining yield. Approaches such as Alternate Wetting and Drying (AWD) and midseason drainage followed by intermittent irrigation (MiDi) include periods of soil drying, which can help reduce  $\text{CH}_4$  production. However, if the field is dried too much and/or for too long, rice can suffer water stress, and emissions of nitrous oxide ( $\text{N}_2\text{O}$ )—another potent GHG—can increase due to enhanced microbial nitrification and denitrification under alternating aerobic–anaerobic conditions. These trade-offs need to be considered carefully when planning water management.

Rice water requirements differ across growth stages. Flooded conditions support plant establishment and initial tiller development, while planned aeration during late tillering promotes root activity and limits excessive tiller production. Controlled

drainage during grain filling can support assimilate remobilization to the grain. The drainage intensity can range from light to moderate or severe (see Chapter 2.2), and its effects depend strongly on when the drainage occurs.

## **1.2. Water management and the rationale for MiDi and AWD**

Building on this understanding, MiDi and AWD can be viewed as approaches that introduce planned periods of soil aeration into otherwise flooded systems. By incorporating drainage at specific growth stages, these practices help restore root activity, improve nutrient uptake, and maintain plant vigor in fields where prolonged flooding can lead to chronically reductive soil conditions. At the same time, avoiding excessive drying is essential to prevent water stress. Achieving this balance—introducing aeration without over-drying—is key to climate-smart rice water management.

MiDi has long been practiced in Japan and is still widely used as a common water-management approach to optimize rice yields. In promoting its application across the Asia–Monsoon region, the Japan International Research Center for Agricultural Sciences (JIRCAS) has tested and refined MiDi under diverse field conditions, emphasizing yield improvement, CH<sub>4</sub> mitigation, and water saving. MiDi is defined as a growth-stage-specific water-management practice primarily designed to improve rice yields, with additional co-benefits for CH<sub>4</sub> mitigation and water saving (Minamikawa et al., 2019). It consists of planned drainage and reflooding events adjusted according to growth stage, with the drainage intensity and timing adapted to field conditions while avoiding over-drying. Alongside MiDi, AWD was developed by the International Rice Research Institute (IRRI) and tested across Asia as a water-saving approach, providing insights into region-specific water management.

Recent multi-country field trials in the Asia–Monsoon region demonstrated that MiDi can enhance rice yields and reduce CH<sub>4</sub> emissions compared with continuous flooding (CF), particularly in irrigated paddy fields that experience long-term flooded and reductive soil conditions (Minamikawa et al., in preparation). These conditions are commonly observed in intensively cultivated areas with short fallow periods, where planned drainage timed to growth stages helps restore root activity.

The central message of the Guidelines is that the yield-optimal level of soil drying is context-dependent and is rarely achieved by severe drainage alone; rather, it emerges from matching drainage timing and intensity to growth stage, soil redox status, and local water-control capacity. The Guidelines proceed as follows. Chapter 2 introduces the principles of MiDi and AWD. Chapter 3 synthesizes evidence from meta-analyses on multiple aeration practices and highlights remaining evidence gaps, particularly regarding drainage intensity and frequency. Chapter 4 integrates lessons from multi-country field trials, showing how outcomes vary across sites and identifying cross-site patterns. Chapter 5 provides growth-stage recommendations for implementing MiDi-based practice. Chapter 6 outlines research needs and dissemination pathways, including incentive options to support wider adoption.

## **2. Concepts and principles of MiDi and AWD**

### **2.1. Physiological and environmental basis of water management**

Rice is typically cultivated under flooded conditions, as is common practice in the Asia–Monsoon region, but it can tolerate short periods of soil drying when properly managed. This subchapter briefly explains the physiological and soil environmental mechanisms that underlie how water management affects rice growth and GHG emissions. Water management regulates plant–soil interactions by controlling soil redox conditions, root oxidation, and water availability. The physiological water requirement of rice varies among growth stages: ample moisture is needed during establishment and tillering, whereas carefully timed soil drying during the later vegetative and reproductive phases supports root activity (Yoshida, 1981). When soil drying remains within the crop’s physiological tolerance, it can maintain root activity and promote the movement of assimilates toward the developing grains, thereby supporting grain filling. However, when soil drying exceeds the crop’s physiological limits or continues for too long, root activity and assimilate movement can be suppressed, resulting in potential yield loss. In other words, soil drying is beneficial only when it is kept within the crop’s physiological limits.

The soil redox environment, governed by these hydrological conditions, also determines the balance of GHG emissions. CF maintains reductive conditions that promote CH<sub>4</sub> emissions, whereas intermittent drainage—as applied in MiDi and AWD—creates alternating oxidized and reduced phases that suppress CH<sub>4</sub> emissions. However, when soil aeration increases and mineral nitrogen is available, N<sub>2</sub>O emissions may increase due to enhanced microbial nitrification and denitrification. The extent and timing of aeration therefore play a decisive role in balancing crop performance and environmental outcomes.

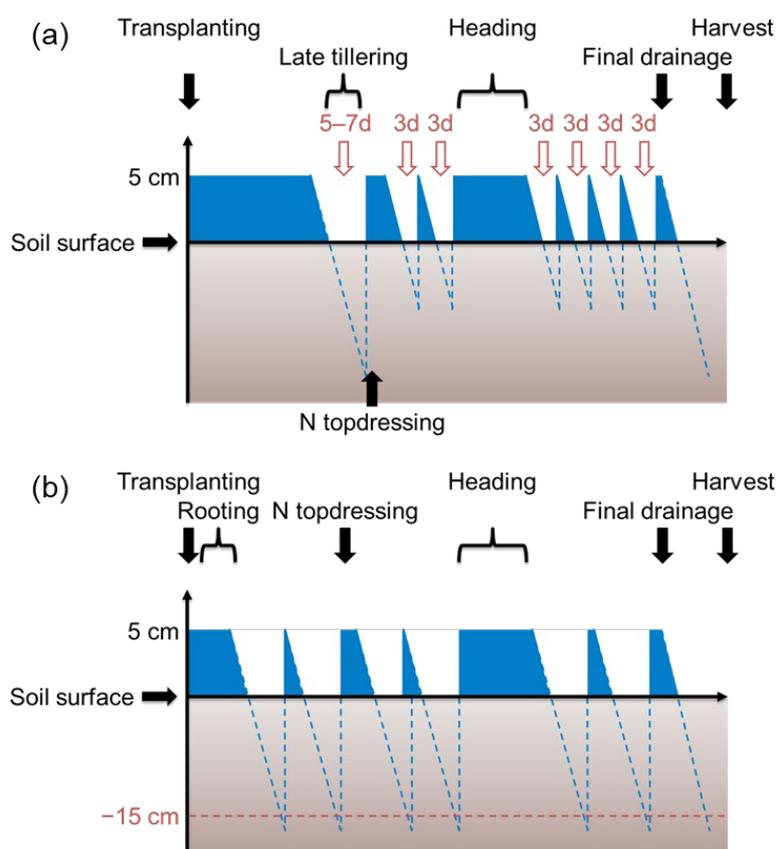
Understanding these hydro-physiological and environmental mechanisms provides the scientific foundation for both MiDi and AWD. The following subchapter describes their underlying principles and design concepts, while operational recommendations are provided separately in Chapter 5.

### **2.2. MiDi and AWD practices**

MiDi and its predecessor, midseason drainage, have long been practiced in Japan and remain widely adopted there to stabilize or improve rice yield. Midseason drainage is typically conducted during the late tillering stage by releasing surface water for a short period (typically 5–7 days) (Figure 2a), using the appearance of shallow surface cracks as a practical guideline (Figure 3a). This operation helps moderate excessive tillering, restore root activity, and prevent excessive soil reduction.

Following midseason drainage, intermittent irrigation is practiced until the final drainage before harvest (Figure 2a). In Japan, a simple weekly irrigation rhythm is commonly used, for example, a pattern of 4-day flooding followed by 3-day natural

drainage (drawdown), though the exact duration is adjusted according to field water conditions and the crop’s stage-specific water requirements. An important exception occurs during the heading and flowering period, when rice has its highest water requirement and is most sensitive to water and heat stress. Flooded conditions are therefore maintained during this stage to secure spikelet fertility. Final drainage generally begins 7–14 days before harvest to facilitate ripening and field access.



**Figure 2. Typical variations in surface water levels in (a) MiDi and (b) AWD (modified from Minamikawa et al., 2019)**

In contrast, AWD, originally developed by IRRI, is designed to reduce irrigation water use in tropical and subtropical regions. Under AWD, the field is allowed to drain down through natural drawdown (with irrigation withheld) until the soil water level falls to a preset threshold, commonly 15 cm below the soil surface (“safe AWD”) (Figure 2b). This threshold is often implemented using a perforated field water tube, which indicates the soil water level relative to the surface (Figure 3b). The field is then reflooded. As with MiDi, flooding is maintained during the heading stage to protect reproductive development. The performance of AWD depends strongly on the ability to control and adjust field water levels in a timely manner, including securing water supply and drainage when required. See Allen and Sander (2019) for the detailed background and methods of AWD.

Although both MiDi and AWD introduce intermittent soil aeration, their design principles differ. MiDi is defined as a growth-stage-specific water-management practice aimed primarily at improving or stabilizing yield under continuously flooded and reductive soil conditions, while also providing benefits for CH<sub>4</sub> mitigation and water saving. AWD, in contrast, is water-saving-driven, using a quantitative soil drying threshold as the principal decision rule. Thus, the two approaches can diverge or converge depending on cropping intensity, soil redox status, and irrigation control capacity. Operational details, including water management during N topdressing, are presented in Chapter 5.



**Figure 3. Soil cracks development (a) and monitoring surface water level using a perforated tube and a ruler (b) during a drained period**

Hereafter in this document, “drainage intensity” refers to the management strength of each drainage event. For consistency, intensity is described primarily by the maximum drawdown depth (a practical indicator), while acknowledging that its effective intensity often depends on how long the drawdown persists (drying duration). “Moderate” drainage intensity corresponds to a drawdown of ~15 cm below the soil surface (sometimes deepening over several days). “Light” drainage intensity corresponds to a shallower drawdown, whereas “severe” drainage intensity corresponds to a deeper drawdown and/or a longer duration than moderate. Because field water level is constrained by lowland topography, soil properties, and drainage infrastructure, drawdown depth alone may not represent plant-available water. Plant responses are therefore discussed separately in terms of drying stress, for which soil water potential can provide useful additional context. “Frequency” refers to the number and spacing of drainage events over the season.

### **2.3. Knowledge gaps and remaining challenges**

While multiple aeration practices, including MiDi and AWD, have proven effective in reducing CH<sub>4</sub> emissions, large uncertainties remain regarding their yield responses. Reported yield changes range from modest increases to small decreases, depending on the timing, intensity, and frequency of drainage. Across studies, such variation is largely explained by differences in drainage design and its interaction with site conditions (e.g., water-control capacity and soil properties).

Existing meta-analyses have typically pooled MiDi and AWD into a single category of “multiple aeration,” making it difficult to distinguish how specific designs, such as drainage intensity and frequency, affect yield outcomes. In many cases, data on these drainage parameters are missing or inconsistently reported. As a result, it remains challenging to translate pooled meta-analysis results into practical guidance for field implementation across diverse regions.

To clarify these relationships, the next chapter summarizes recent meta-analyses on multiple aeration practices and highlights remaining evidence gaps, with particular attention to the role of drainage intensity. This provides the foundation for subsequent chapters that synthesize results from multi-country field trials and develop stage-specific recommendations for MiDi-based management.

### **3. Effects of multiple aeration practices (meta-analysis synthesis)**

This chapter summarizes the average effects of multiple aeration practices relative to CF, based on 11 recent meta-analyses (Minamikawa, 2025). Here, MiDi, AWD, and related practices are treated collectively as multiple aeration, because most meta-analyses do not distinguish among individual approaches, and therefore evaluate their pooled effects, rather than the effects of MiDi or AWD individually.

#### **3.1. Effects on GHG emissions**

CH<sub>4</sub> emission reductions achieved by multiple aeration practices ranged from 31% to 62% with mean and median values of 50.9% and 52.7%, respectively ( $n = 10$ ; Table 1). Relatively low reduction rates reported in Japan (39%, Kajiura et al., 2018) and Asia (31%, Tirol-Padre et al., 2018) were partly due to datasets that included cases with only a single drainage event (midseason drainage) or wet-season conditions where opportunities for soil aeration were limited (i.e., light drainage). In contrast, higher reduction rates reported in China (62%, Feng et al., 2013) and in global syntheses (59%, Liao et al., 2021) partly reflect the inclusion of datasets involving severe drainage events.

Increase in N<sub>2</sub>O emissions due to multiple aeration practices varied widely, ranging from 37% to 445% with mean and median values of 180% and 105%, respectively ( $n = 7$ ; Table 1). The highest increase observed in Asia (445%, Linquist et al., 2012) was likely exaggerated by the inclusion of datasets involving high synthetic N-fertilizer application rates in China.

In irrigated rice systems, N<sub>2</sub>O typically contributes less than 5% of the combined Global Warming Potential (GWP, i.e., carbon dioxide (CO<sub>2</sub>)-equivalent emissions) of CH<sub>4</sub> + N<sub>2</sub>O, provided that soil drying is not prolonged and nitrogen inputs are not excessive. Consistent with this, the current synthesis indicates that GWP reduction rates achieved by multiple aeration practices (ranging from 33.6% to 56.2%, with mean and median values of 47.1% and 47.3%, respectively;  $n = 6$ ; Table 1) are comparable to or slightly lower than those in CH<sub>4</sub> emissions alone.

#### **3.2. Effects on rice yield**

Rice yield responses to multiple aeration practices ranged from -5.4% to +11% with mean and median values of +1.3% and +0.7%, respectively ( $n = 8$ ; Table 1). These changes are often statistically insignificant and may be difficult to detect in field studies due to the considerable spatial variability in rice yield, particularly under direct sowing conditions. Noticeable yield increases were reported in two studies conducted in China (+11% in both Feng et al., 2013 and Guo et al., 2017). In contrast, Carrijo et al. (2017) reported a global mean yield loss of 5.4%, which has been attributed to datasets involving severe drainage events that were sometimes imposed as experimental extremes. Carrijo et al. (2017) also found that rice yield was generally not significantly reduced under moderate drainage conditions.

Similarly, the global mean yield loss of 3.6% reported by Jiang et al. (2019) was also linked to severe drainage data.

**Table 1. Summary of recent meta-analyses on the effect of multiple aeration practices, expressed as percent changes relative to CF.**

Reference	Scale	CH <sub>4</sub>	N <sub>2</sub> O	GWP <sup>a</sup>	Rice yield
Bo et al. (2022)	Global	-54.2% (459)	+92.0% (325)	-56.2% (309)	+0.4% (548)
Carrijo et al. (2017)	Global				-5.4% (524)
Feng et al. (2013)	China	-62% (8)	+278% (8)	-54% (8)	+11% (8)
Guo et al. (2017)	China	-57% (62)			+11% (62)
Jiang et al. (2019)	Global	-53% (180)	+105% (122)	-44% (128)	-3.6% (160)
Kajiura et al. (2018)	Japan	-39% (43)			
Liao et al. (2021)	Global	-59% (344)	+58% (249)	-48% (270)	-4.2% (347)
Linguist et al. (2012)	Asia	-49.5% (7)	+445% (7)	-33.6% (7)	+0.95% <sup>ns</sup> (7)
Liu et al. (2019)	Global	-52.4% (70)	+242% (45)	-46.6% (31)	+0.9% <sup>ns</sup> (61)
Livsey et al. (2019)	Asia	-52.3% (16)	+37.0% (16)		
Tirol-Padre et al. (2018)	Asia	-31% (20)			

Modified from Minamikawa (2025).

In parentheses, the number of seasonal observations.

All reported percentages were statistically significant at  $p < 0.05$ , except for ns, non-significant.

<sup>a</sup> CO<sub>2</sub>-equivalent emissions for CH<sub>4</sub> + N<sub>2</sub>O calculated using the metrics in Foster et al. (2007), except for Bo et al. (2022) using Foster et al. (2021).

### 3.3. Effects on water use

Bo et al. (2022) reported a 39.7% reduction in irrigation water use ( $n = 208$ ), whereas Carrijo et al. (2017) reported a 25.7% reduction in total water use (irrigation + rainfall) ( $n = 451$ ).

### **3.4. Overall interpretation and implications**

Taken together, the meta-analyses indicate that multiple aeration practices consistently reduce CH<sub>4</sub> emissions and irrigation water use, while yield responses are generally small. Cases reporting yield losses were mainly associated with drying sustained for longer periods (i.e., severe drainage events), rather than with multiple aeration itself. The feasibility and performance of multiple aeration largely depend on the ability to control irrigation and drainage under local water conditions. The next chapter examines how outcomes vary under different field conditions and management contexts, drawing on evidence from multi-country field trials. Because meta-analyses often pool diverse designs under “multiple aeration,” the next chapter turns to multi-country field trials to examine how specific design elements (timing and drainage intensity) interact with site constraints to shape yield and GHG outcomes.

## 4. Lessons and insights from multi-country field trials

### 4.1. Overview of multi-site field trials and the evolution of research objectives

This chapter synthesizes evidence from multi-site field trials conducted under international research projects that evaluated AWD and MiDi across diverse agro-environmental conditions in the Asia–Monsoon region (Table 2). Implemented by Japanese and regional research organizations including JIRCAS, these trials shared a common objective: to clarify how water management strategy affects CH<sub>4</sub> and N<sub>2</sub>O emissions and rice yield.

**Table 2. Summary of reviewed field trials evaluating MiDi and AWD**

Project	Country	Treatment	Primary objective	Reference
MIRSA-2	Indonesia; the Philippines; Thailand; Vietnam	CF; AWD15	CH <sub>4</sub> reduction without yield loss	Chidthaisong et al. (2018); Sibayan et al. (2018); Setyanto et al. (2018); Tran et al. (2018)
MIRSA-3	Indonesia; Vietnam	CF; AWD15; organic amendment	CH <sub>4</sub> reduction and yield improvement	Hoang et al. (2023); Pramono et al. (2024)
JIRCAS-A1	Vietnam	CF; AWD15; MiDi	Maintaining or improving yield while reducing CH <sub>4</sub>	Arai et al. (2021); Minamikawa et al. (2021); Uno et al. (2021)
Green Asia	Bangladesh; Indonesia; Thailand; Vietnam	CF; AWD15; AWD25; MiDi	Exploring practices for yield improvement	Minamikawa et al. (in preparation)

Treatment explanation:

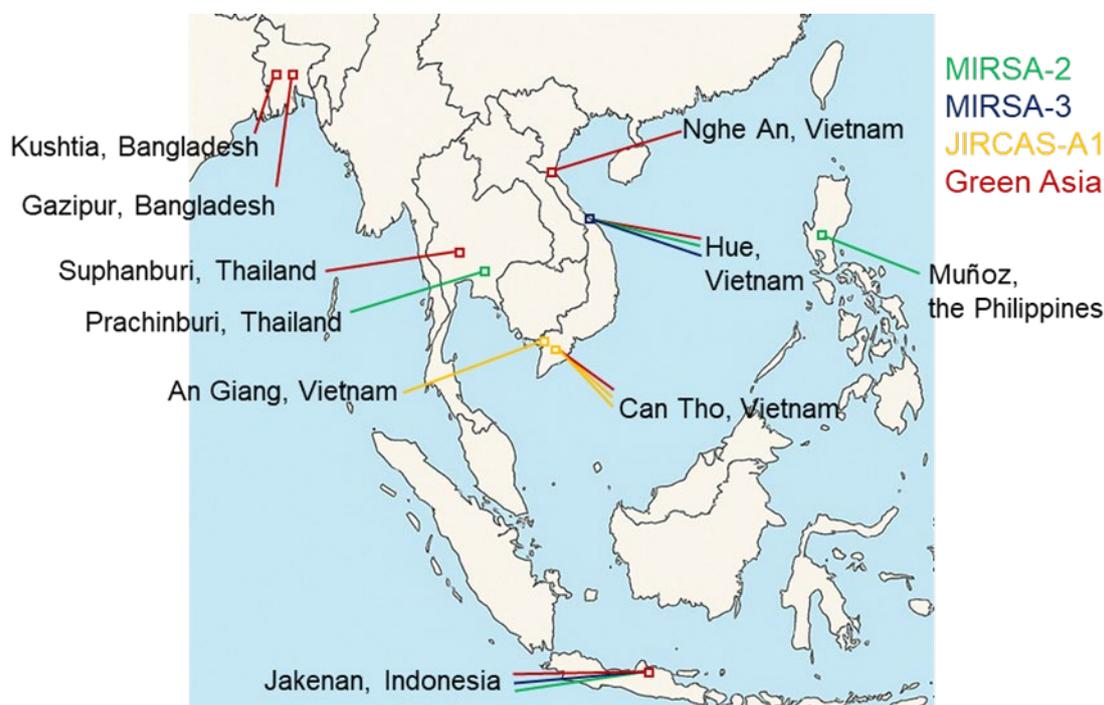
- CF: Continuous flooding from establishment to final drainage.
- AWD15: AWD with reflooding when water level reaches –15 cm (Figure 2b). Soil drying was not allowed during heading or after N topdressing.
- AWD25: Same as AWD15, but with reflooding at –25 cm (a more severe water-level threshold than AWD15).
- MiDi: Midseason drainage during late tillering followed by intermittent irrigation, except during heading and after N topdressing (Figure 2a).

The research focus evolved iteratively as observations accumulated across sites. Early trials primarily tested whether conventional AWD could reduce CH<sub>4</sub> without yield penalties. Subsequent multi-site evidence suggested that well-timed soil drying can increase yield in some environments, prompting hypotheses on underlying agronomic and physiological mechanisms and on the site conditions that enable yield gains. As attention shifted toward dissemination and social implementation, yield improvement also became a practical incentive for farmer uptake alongside mitigation benefits. This broader scope was enabled by

coordinated multi-country trials, cross-site synthesis, and stakeholder engagement to translate findings into implementable options.

MIRSA-2 (Mitigation in Irrigated Rice in Southeast Asia; FY2013–FY2017), funded by the Secretariat of the Agriculture, Forestry and Fisheries Research Council of the Ministry of Agriculture, Forestry and Fisheries of Japan, primarily aimed to demonstrate CH<sub>4</sub> mitigation without compromising yield under conventional AWD. MIRSA-3 (FY2018–FY2022) built on this foundation by evaluating improved AWD-based options to reduce combined CH<sub>4</sub> and N<sub>2</sub>O emissions more robustly, while expanding attention to yield outcomes across sites.

In parallel, JIRCAS conducted field trials under its program “Development of comprehensive agricultural technologies for climate change mitigation and adaptation in Monsoon Asia” (JIRCAS-A1; initiated in FY2011 and continued through subsequent phases). Over time, this work broadened from mitigation performance to productivity responses under diverse site constraints. Green Asia (“Accelerating application of agricultural technologies which enhance production potentials and ensure sustainable food systems in the Asia–Monsoon region”; FY2022–FY2025) further tested a wider range of drainage intensities to examine productivity–mitigation trade-offs. Together, these efforts provide a progressive evidence base supporting regionally adaptive, MiDi-centered guidelines. An overview of trial sites and evaluated treatments is provided in Table 2 and Figure 4. Across trials, CF and AWD15 served as common references, while additional treatments (e.g., AWD25, MiDi, and organic amendments) were introduced depending on objectives and site conditions.



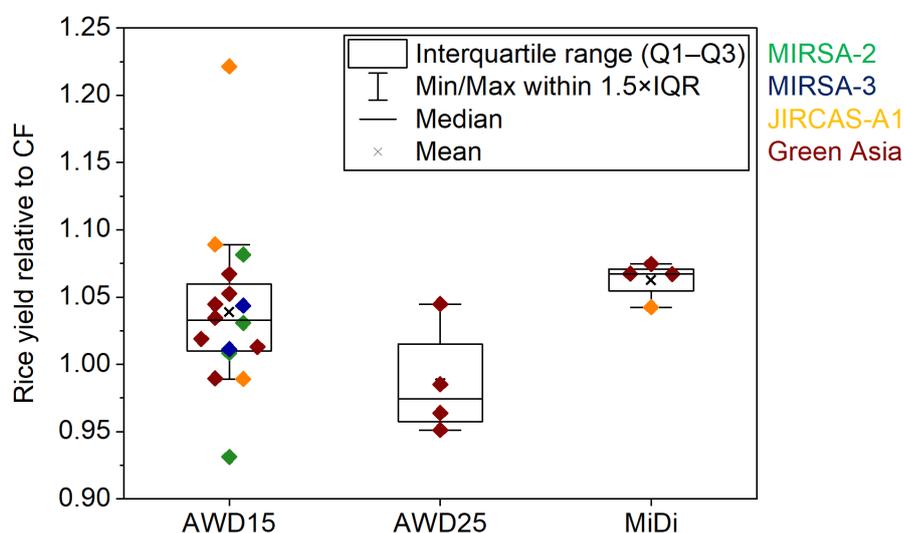
**Figure 4. Locations of field trial sites included in the reviewed projects. Each color indicates a different project**

## 4.2. Results and implications

Before synthesizing cross-site outcomes, it is useful to note that most early trials evaluated AWD relative to CF, whereas direct MiDi-AWD comparisons became available later. The first direct field comparison between MiDi and AWD was conducted in Can Tho, Vietnam (Minamikawa et al., 2021), providing a reference point for interpreting subsequent multi-site evidence.

Yield effects were evaluated using yield ratios calculated for each treatment relative to the corresponding CF control within each trial (Figure 5). Values > 1.0 indicate yield increases under the treatment (AWD15, AWD25, or MiDi), whereas values < 1.0 indicate yield reductions relative to CF. Across trials, the overall mean (median) yield ratios were 1.039 (1.033) for AWD15 (n = 16), 0.986 (0.974) for AWD25 (n = 4), and 1.063 (1.067) for MiDi (n = 4). Within the Green Asia trials, AWD25 consistently performed worse than AWD15, whereas MiDi outperformed AWD15 (Minamikawa et al., in preparation). These patterns align with the meta-analysis in Chapter 3, indicating that yield responses depend strongly on drainage intensity.

Yield losses (yield ratio < 1) were mainly associated with water stress, particularly under AWD25 (Green Asia) and in acid sulfate soils (MIRSA-2; described below). In contrast, CH<sub>4</sub> reductions generally increased with more intensive drainage across the range tested in the field, with no clear evidence of saturation.



**Figure 5. Box plots for rice yields (AWD15, AWD25, and MiDi relative to CF) across the reviewed field trials. Each dot color indicates a different project**

Below is a brief summary of implications from the reviewed field trials:

- Drainage duration as a practical indicator: The number of drainage days is an effective indicator of CH<sub>4</sub> reduction. Under moderate drainage designed to protect yield, mitigation remains substantial but may not reach its maximum

potential.

- Site- and season-dependent drainability: Drainability varies with weather (dry vs. wet seasons), topography (e.g., low-lying fields), and proximity to irrigation/drainage canals. Even where complete drainage is difficult, partial soil aeration (light drainage) can still reduce CH<sub>4</sub> while supporting yield formation.
- Feasibility in wet seasons: Intentional drainage can be implemented in wet seasons where gravity drainage or pumping is available.
- Pitfalls of water-level thresholds: In poorly drained soils, thresholds may lead to unintended prolonged drying and higher yield-loss risk. A fixed drainage duration (as in MiDi) can serve as a safeguard against over-drying. Field water level does not always reflect plant-available soil moisture.
- Advantages of MiDi over AWD: Growth stage-specific drainage can induce transient, controlled drying without hindering yield formation when appropriately managed.
- Acid sulfate (thionic) soils: Avoid excessive drainage. Depending on conditions, yield loss may be driven by oxidative acidification during drawdown (low pH itself suppressing root growth and mobilizing toxic aluminum and iron) and/or hydrogen sulfide toxicity under reducing conditions after reflooding.

Therefore, from the perspective of yield improvement, the Guidelines highlight MiDi as a particularly effective water management practice under a wide range of conditions. At the same time, water-level monitoring remains valuable for avoiding excessive drying stress—particularly when scheduling intermittent irrigation. For those with limited experience, regular water-level monitoring is strongly recommended. Before proceeding to Chapter 5, the following two columns provide supplementary insights into practical and measurement aspects of multiple aeration practices. Chapter 5 then outlines the MiDi-centered, growth-stage water-management approach.

## Column I. Why do farmers adopt AWD?: A case in Bangladesh

In contrast to MiDi, which remains little known in Southeast and South Asia, the term “AWD” is better recognized among farmers, researchers, and government officers across these regions, largely owing to its international promotion by IRRI and various national programs. AWD is known to have both advantages and disadvantages in rice cultivation (Table C1). Overall, the positive effects often outweigh the negative ones, but voluntary adoption by farmers has been observed only in limited areas.

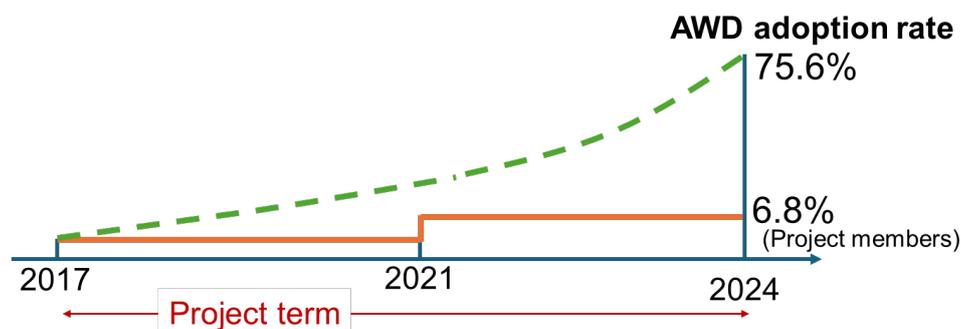
**Table C1. Expected positive and negative effects of AWD on rice cultivation, compared with CF**

Positive effects	Negative effects
<ul style="list-style-type: none"> <li>• Saving water</li> <li>• Reducing irrigation cost</li> <li>• Mitigating lodging</li> <li>• Improving fertilizer efficiency</li> <li>• Increasing rice yield under moderate-intensity drainage</li> </ul>	<ul style="list-style-type: none"> <li>• Encouraging weed growth</li> <li>• Increasing workload</li> <li>• Reducing rice yield under severe-intensity drainage</li> </ul>

Source: Minamikawa et al. (2019).

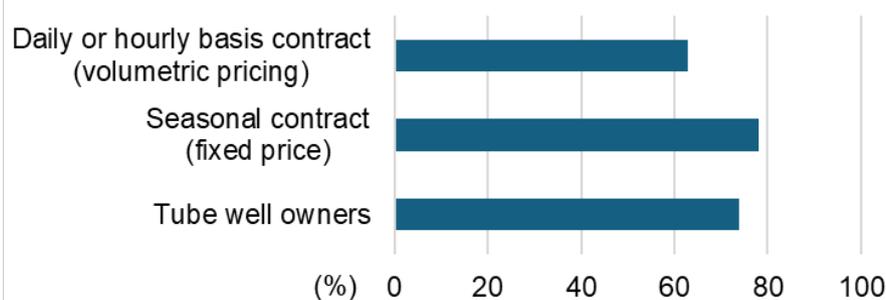
One notable case observed in the Green Asia project comes from Jhenaidah District, Bangladesh, where AWD spread rapidly among farmers, despite only a small portion—about 6.8% of all farm households—having participated in an NGO-led AWD project (Figure C1). In this region, as in most of Bangladesh, irrigation water is supplied almost entirely from groundwater through diesel or electric pumps, with few surface irrigation canals available. Under such conditions, the potential to save fuel costs provided a strong incentive for farmers to adopt AWD. Survey results showed that the adoption rate across the community reached as high as 75.6%, including farmers who practiced AWD without using perforated field water tubes. This pattern indicates that the practice expanded rapidly beyond the original project participants, reaching neighboring farmers through informal channels.

Then, why is AWD readily embraced in some places but not in others? What actually motivates farmers to adopt this practice?



**Figure C1. Change in AWD adoption rate in Jhenaidah District**

Conventional thinking in the Asia–Monsoon region suggests that volumetric water pricing should encourage AWD adoption more effectively than fixed-price contracts. Surprisingly, survey results showed the opposite: adoption rates were actually higher among farmers under fixed-price contracts (Figure C2). Interviews revealed that tube-well owners and client farmers often chose to cooperate in order to save fuel costs through AWD. Their motivation was not purely economic; it also reflected social ties and a shared sense of purpose in saving water and coping with rising fuel prices.



**Figure C2. AWD adoption rates by irrigation contract type in Jhenaidah District**

Farmers further assessed AWD in terms of their own field experiences (Table C2). The vast majority highlighted “increasing yield” and “mitigating lodging” as important benefits. Some also mentioned reduced algae growth and water saving. At the same time, several farmers pointed out drawbacks such as additional workload and the promotion of weed growth. These diverse perspectives underline that adoption decisions are made by weighing both advantages and disadvantages in practice.

**Table C2. Positive and negative effects of AWD as reported by 2,500 farmers in Jhenaidah District**

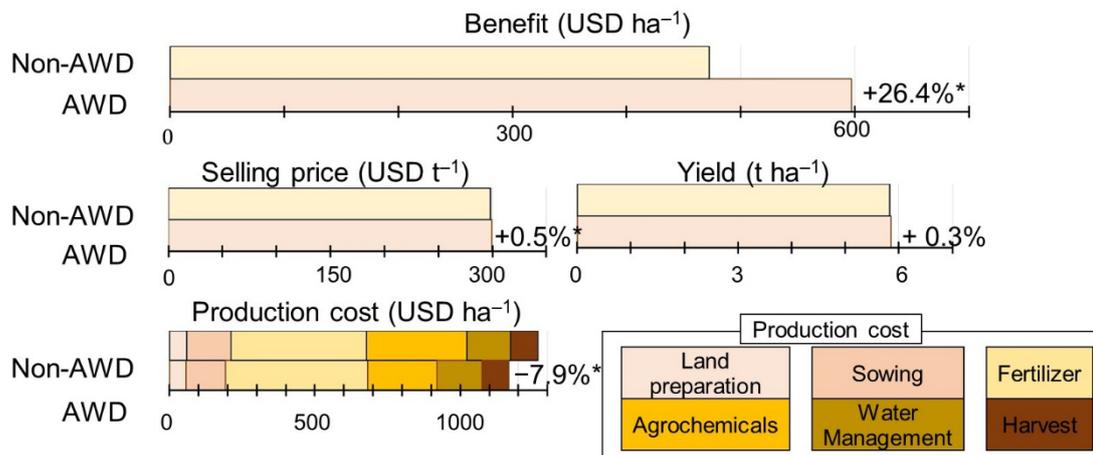
Positive effects	(%)	Negative effects	(%)
• Increasing yield	94.6	• Increasing workload	42.8
• Mitigating lodging	92.8	• Encouraging weed growth	39.7
• Reducing algae	72.6	• Increasing water leakage	0.6
• Saving water	53.3	• Decreasing yield	0.5
• Improving fertilizer efficiency	18.3		

Taken together, the evidence from Jhenaidah suggests that AWD adoption was driven by a combination of practical gains—such as reduced fuel costs and yield benefits—and social factors, including community cooperation and a shared awareness of the need to save water. These outcomes were observed where AWD was practiced in a controlled and context-appropriate way, rather than under severe-intensity drainage. This aligns with the MiDi principles outlined in the Guidelines and indicates that similar conditions may similarly encourage voluntary adoption in other regions.

## Column II. Do farmers get benefits from AWD?: A case in Vietnam

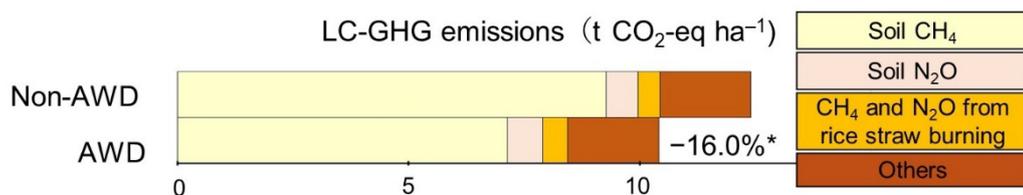
In Can Tho City, Vietnam, some farmers already practice single drainage during the rice-growing season. This observation raises an important question of whether AWD adoption provides greater economic returns and helps reduce GHG emissions compared with single drainage. In this column, farmers adopting AWD are referred to as AWD farmers, and those practicing only single drainage as non-AWD farmers. Under the Green Asia project, this column draws on farm survey data from the late wet (autumn–winter) rice season of 2024, covering 194 non-AWD farmers and 106 AWD farmers.

Turning first to economic outcomes, AWD farmers increased their net benefits by reducing production costs—particularly those for agrochemicals—compared with non-AWD farmers (Figure C3).



**Figure C3. Economic outcomes of non-AWD farmers and AWD farmers. Values are derived from regression analysis. \*,  $p < 0.05$**

From an environmental perspective, AWD farmers also contributed to climate mitigation. Using a life cycle assessment (LCA) that covers from material production to rice cultivation, life-cycle GHG (LC-GHG) emissions were estimated and found to be significantly lower for AWD farmers than for non-AWD farmers (Figure C4).



**Figure C4. LC-GHG emissions from non-AWD farmers and AWD farmers. Values are derived from regression analysis. \*,  $p < 0.05$**

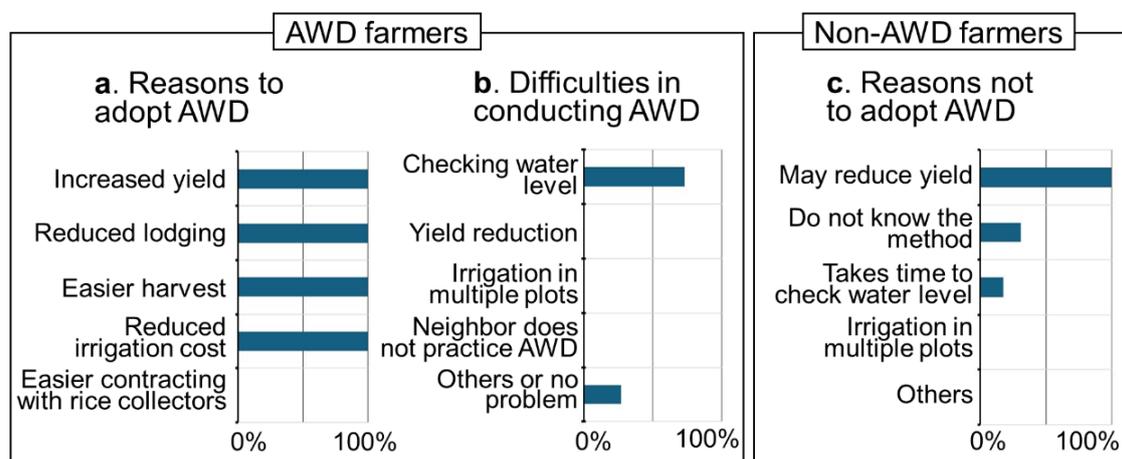
Differences were also evident in water management practices. While both groups owned irrigation pumps, AWD farmers conducted soil drainage more frequently and for longer durations, but with fewer irrigation events overall (Table C3). Both groups checked water levels regularly, often linking this task with other fieldwork such as weeding.

**Table C3. Differences in water management operations between non-AWD farmers and AWD farmers**

	Non-AWD farmers	AWD farmers
Number of soil drainage (times)	1.0	2.0*
Total drainage duration (d)	5.4	17.8*
Number of irrigation (times)	6.5	6.2*
Total irrigation duration (h)	54.7	53.4
Number of water level check (times)	5.6	5.9

The numbers are based on regression approach. \*,  $p < 0.05$

As for motivations and challenges, all AWD farmers reported adopting the practice for yield improvement and lower irrigation costs (Figure C5a). At the same time, 72% noted that checking water levels was a difficulty (Figure C5b). By contrast, non-AWD farmers cited concerns over possible yield loss, lack of knowledge about AWD, and the additional time required for water monitoring as reasons for not adopting it (Figure C5c).

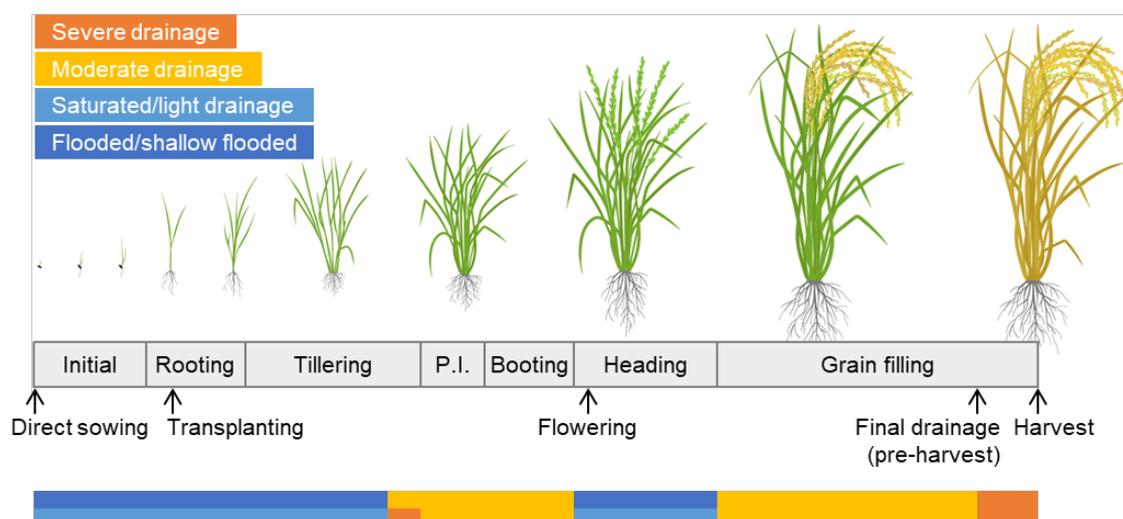


**Figure C5. Farmers' motivations and challenges regarding AWD (multiple responses)**

Taken together, the results indicate that AWD farmers not only improved their financial returns but also reduced life-cycle GHG emissions compared with non-AWD farmers. This evidence suggests that, where feasible, AWD can provide farmers with tangible benefits while contributing to climate mitigation. Such outcomes were achieved where drainage was moderate-intensity and well-timed, rather than severe drainage, consistent with the MiDi-centered water-management approach introduced in Chapter 5.

## 5. Stage-specific guidelines for implementing MiDi-based practice

This chapter presents MiDi-based recommended water management practices by growth stage, along with their scientific rationale. Drainage intensity should be adjusted according to cultivation conditions in order to optimize performance. Farmers and extension staff are encouraged to refine these practices over multiple cropping cycles. The Guidelines do not rule out the use of AWD. When implementing a water-level-based AWD approach for intermittent irrigation, it is important to manage drainage duration carefully to avoid excessive drying stress.



**Figure 6. Rice calendar and MiDi-based recommended water management practices for each growth stage (modified from Minamikawa, 2025). The bottom bar shows the recommended practices: one color for a single practice, two colors for a range. P.I., panicle initiation**

### 5.1. Initial stage

In wet direct-seeded rice, water-saturated (but not flooded) soil conditions are essential for successful germination, while shallow-flooded conditions (e.g., 1–3 cm water depth) are suitable for emergence and early seedling growth (Figure 6). This is a general requirement in a wet direct sowing system, not unique to MiDi or AWD.

### 5.2. Rooting and tillering stages

Flooded conditions are recommended as a protective measure against adverse weather conditions during the rooting and tillering stages (Figure 6). At these stages, a major concern is that rice straw incorporation prior to planting may lead to the transient production and accumulation of organic acids, as well as microbial N immobilization in flooded soils, thereby inhibiting initial growth (Ponnamperuma, 1984). This situation is often unavoidable in multiple rice cropping systems with

short fallow periods. Therefore, light drainage is desirable to address this issue (Figure 6). However, plant growth may recover after the initial inhibition, and the accumulation of organic acids can also suppress weed emergence (Nozoe et al., 2022). Accordingly, the overall impact of temporary organic acid accumulation and N immobilization on rice growth and yield depends on environmental and agronomic conditions. This underscores the need for location-specific tuning of water management practices.

### **5.3. Late tillering stage**

Midseason drainage should be implemented during the late tillering stage by intentionally removing surface water for 5–7 days, depending on weather conditions (Figure 6). The timing for reflooding should be adjusted according to soil surface cracking or surface water levels (see Figure 3), so as to avoid excessive drying and water leakage. This event corresponds to a single drainage with moderate to severe drainage intensity.

Midseason drainage has several positive effects on rice growth and yield as mentioned below (Minamikawa et al., 2019).

1. It controls non-productive (excessive) tillers and over-luxuriant growth caused by excess N uptake, thereby strengthening the remaining productive tillers and increasing their proportion. However, it can also promote N mineralization from soil organic matter. Which process becomes dominant therefore depends on the inherent soil fertility and N-fertilizer application rate.
2. It prevents canopy lodging by inhibiting the elongation of the lower internodes of the remaining tillers.
3. It promotes healthy root development by supplying oxygen to the drained soil and reducing toxic substances, such as organic acids and hydrogen sulfide.

### **5.4. Panicle initiation and booting stages**

Multiple aeration practices with moderate drainage intensity are recommended from the panicle initiation to the booting stage (Figure 6). In Japan, intermittent irrigation is conducted to maintain healthy root development and to prevent premature senescence of the lower leaves until the final drainage, except during the heading stage (Minamikawa et al., 2019).

Typically, a weekly irrigation cycle—such as 4 days of flooding followed by 3 days of natural drainage—is adopted as a standard form of intermittent irrigation. The duration of natural drainage phase (e.g., 2–4 days) should be adjusted depending on local climatic and soil conditions. Managing intermittent irrigation based on water levels, as in AWD, can also be effective, particularly for farmers less experienced with intermittent irrigation.

## 5.5. Heading stage

Rice exhibits high water demand, and elevated temperatures can lead to spikelet sterility during the heading stage (e.g., Matsui et al., 2021). Therefore, maintaining flooded conditions is recommended as a protective measure during this stage, particularly at flowering (Figure 6). Although CH<sub>4</sub> emissions often peak around heading, adequate water supply must take precedence. If a CH<sub>4</sub>-mitigation drawdown is considered, it should be light (i.e., brief and shallow), avoided during peak flowering and heat stress, and implemented only under careful monitoring of crop water uptake and field conditions.

## 5.6. Grain filling stage

Grain filling relies on two nutrient sources: current assimilates and those redistributed from reserves in vegetative tissues (Yang and Zhang, 2010). Drought stress during this stage accelerates leaf senescence, reduces photosynthesis, and shortens the grain filling period, although it also enhances the remobilization and transfer of pre-stored assimilates from vegetative tissues to the grain (Yang and Zhang, 2006). Moderate drainage after flowering can stimulate the phytohormonal regulation of enzymes responsible for carbon remobilization and carbohydrate metabolism in grains, thereby improving yield (Yang and Zhang, 2006; 2010). Accordingly, controlled drainage with moderate drainage intensity—such as intermittent irrigation and AWD—is recommended during this stage (Figure 6). Final drainage is generally implemented 1–2 weeks before harvest.

## 5.7. Implementation notes

Drainage intensity should be adjusted according to both the growth stage and degree of soil reduction in the field to optimize the performance of MiDi-based practice. While midseason drainage can range from moderate to severe depending on field and seasonal conditions, subsequent intermittent irrigation should generally maintain moderate drainage intensity, while avoiding excessive drying stress. During heading and flowering, flooded conditions should be maintained as the default to protect spikelet fertility; if a CH<sub>4</sub>-mitigation drawdown is considered, it should be light (i.e., brief and shallow), avoided during peak flowering and heat stress, and implemented only under careful monitoring of crop water uptake and field conditions.

Although it is difficult to isolate the specific cause of yield increase from a series of drainage events, previous field trials reviewed in Chapter 4 indicate that multiple aeration with moderate to severe drainage intensity enhances rice yields under chronically reductive soil conditions, such as those in double- or triple-rice cropping systems. Such conditions may reduce yield by suppressing root respiration and promoting the accumulation of toxic substances. Therefore, mitigating chronically reductive soil conditions should be prioritized in affected areas (Minamikawa, 2025). In contrast, under non-chronically reductive soil conditions—such as single-

cropping fields and paddy–upland rotation fields—well-planned MiDi-based practice is required to achieve optimum yield (Minamikawa, 2025), although yield advantages over CF may be limited (Minamikawa, 2025).

As described above, aeration during the grain filling stage supports root activity and assimilate supply, contributing to yield formation. Thus, MiDi-based water management should be tuned to both growth stage and soil redox conditions, rather than applying a uniform drainage intensity throughout the season.

## 6. Future directions for research and dissemination

Although multiple aeration practices, including MiDi and AWD, are gradually expanding in the Asia–Monsoon region, adoption remains limited for fully realizing the benefits they can offer—such as improving rice yield, saving irrigation water, and reducing CH<sub>4</sub> emissions. This final chapter outlines future directions for research and field implementation. In particular, for wider adoption, it is essential to motivate farmers, not only through visible agronomic gains but also by offering a diverse set of incentives. Farm-level perspectives from Bangladesh and Vietnam (Column I and Column II) illustrate how incentives and implementation constraints shape adoption in practice.

### 6.1. Priority research areas

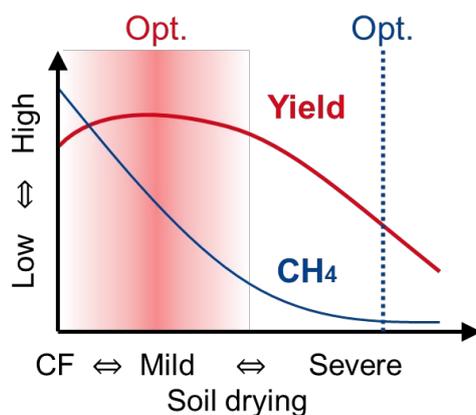
What specific characteristics of multiple aeration practices contribute to enhanced rice yield? Rice yield is influenced by multiple factors, such as soil fertility, weather conditions, rice variety, nutrient management, and pest pressure. Therefore, it is unlikely that a single mechanism triggered by multiple aeration practices can fully explain the observed yield improvements. Multiple aeration practices simultaneously influence multiple aspects of rice physiology depending on the timing (i.e., growth stage) and intensity of drainage events. In this context, a better understanding of the underlying physiological mechanisms at finer temporal and spatial scales is needed. Varietal effects are not treated as a primary driver in the Guidelines, because the multi-site field trials synthesized here employed different locally preferred cultivars across sites, yet consistent patterns in yield and CH<sub>4</sub> responses to drainage intensity were observed. Nevertheless, cultivar traits related to tolerance to intermittent drying and stable performance under variable soil moisture may further reduce yield risk and enhance the robustness of MiDi/AWD outcomes, and thus merit targeted investigation. Key research questions arise from this perspective:

- Which features of multiple aeration most strongly contribute to yield gains under specific combinations of growth stage and drainage intensity?
- How do physiological processes respond at finer temporal and spatial scales within the plant–soil system?
- Where (in terms of soil redox conditions, climate, and cropping system) are yield gains likely—or limited?

Given that MiDi and its predecessor, midseason drainage, are common in East Asia but have seen limited application beyond the region, there is a clear need to demonstrate and adapt this practice in underutilized areas, particularly within the Asia–Monsoon region. Although multi-country field trials have been conducted, actual adoption of MiDi remains limited outside East Asia. Such efforts will support the optimization and region-specific tailoring of MiDi-based practice, including the establishment of operationally safe ranges of drainage intensity suitable for different cultivation environments. Evidence from AWD studies suggests that “safe” management can be described not only by practical field water-level indicators (e.g.,

a 15-cm drawdown) but also by complementary information on root-zone water status (e.g., soil water potential), because the same drawdown depth can correspond to different root-zone water availability depending on soil and hydrologic conditions (Carrijo et al., 2017). Future work should therefore develop and validate operational safe ranges that link practical water-level indicators with complementary soil water potential information across soils and rooting conditions.

In this context, optimizing appropriate drainage intensity should take precedence over CH<sub>4</sub>-focused drainage strategies, particularly those that may unintentionally lead to excessive drying (see the conceptual map of outcome-specific optima in Figure 7). While soil conditions are important, they are only one of several factors influencing the yield optimum; in practice, the optimal drainage intensity emerges from multiple interacting conditions, including climate, soil properties, cropping system, irrigation infrastructure and control capacity, and farmers' management capacity (labor, knowledge, and risk tolerance). Because of these interacting effects, the optimal drainage intensity is not fixed but varies with both the management objective and field conditions: while moderate soil drying generally supports yield improvement under non-chronically reductive conditions, chronically reductive soils may benefit from a temporary phase of severe drying during midseason drainage to restore root activity (Figure 7). In contrast, sustained or repeated severe drying is more effective for reducing CH<sub>4</sub> emissions. Therefore, the most appropriate drainage intensity should be determined based on site-specific conditions, with carbon credit pricing considered as an additional factor where relevant.



**Figure 7. Conceptual responses of rice yield and CH<sub>4</sub> emissions to drainage intensity. The optimal drainage intensity for yield (red gradient) varies across cultivation environments**

In addition, it would be highly valuable to identify areas where yield gains are likely, as well as environmental conditions that are more conducive to yield improvement. Conversely, identifying regions or conditions where yield benefits are limited would also help inform targeted dissemination strategies. As described in Chapter 5, areas with chronically reductive soils, as well as their contrasting counterparts, may serve as important clues in this regard.

Integrated management approaches also hold great potential for enhancing both agronomic and environmental outcomes. Future research should explore combinations of multiple aeration practices with organic amendments, improved rice varieties, and soil-quality-enhancing technologies such as biochar (Qian et al., 2023; Lou et al., 2024). These integrated approaches may generate synergies—but also trade-offs—involving soil redox dynamics, GHG emissions, soil carbon sequestration, and heavy metal uptake.

## 6.2. Dual approach to disseminate multiple aeration practices

The Guidelines emphasize MiDi and AWD primarily for their potential to improve rice yield. Evidence summarized in the country case studies (Columns I and II) illustrates why incentives differ by context: visible gains (e.g., yield improvement and pump-fuel savings) can drive uptake, whereas transaction costs (e.g., routine water-level monitoring) and uncertain yield responses may require external support. Because substantial yield increases are not guaranteed under MiDi or AWD, wider adoption will likely require a portfolio of incentives, including farm-level cost savings, results-based payments such as carbon credits where feasible (discussed below), and broader benefits such as reduced irrigation water use that supports regional water conservation.

In this context, the Guidelines promote a dual approach, as presented in Table 3. These two approaches are conceptually independent yet fully compatible, as practices that spread naturally through visible yield gains may lack additionality requirements, whereas those that require external incentives, such as carbon credits, satisfy it. As a practical illustration, Japan’s compliance carbon credit scheme—the Joint Crediting Mechanism (JCM)—is briefly introduced below to demonstrate how this strategy can facilitate credible and scalable implementation. Together, these approaches offer a complementary pathway to promote the wider adoption of climate-smart practices.

**Table 3. Dual approach to disseminate multiple aeration practices**

Approach	Core idea
Yield-based	Farmers are most likely to adopt new practices when they see clear and immediate benefit—such as higher productivity.
Credit-based	Yield improvement from multiple aeration practices is not always evident. However, GHG emission reductions can serve as a basis for providing alternative incentives to farmers through carbon credit schemes.

Modified from Minamikawa et al. (2019).

The yield-based approach is the most acceptable to farmers, as it directly aligns with their own incentives (Table 3). This can be seen as a non-market, bottom-up strategy. For example, Yamaguchi et al. (2017) reported that rice yield improvement due to reduced lodging was a strong incentive to adopt AWD in the Mekong Delta in Vietnam. However, irrigated rice areas where yield gains can be realized are limited,

and there must be an upper boundary to CH<sub>4</sub> mitigation that can be achieved through voluntary efforts alone.

The credit-based approach leverages the climate benefit—particularly CH<sub>4</sub> emission reductions—as a basis for carbon credit schemes (Table 3). This pathway is closely relevant for policymakers and institutions, providing incentives at a broader scale. As noted above, this approach can be applied in cases where there is no evident yield increase sufficient to promote spontaneous adoption.

In recent years, several methodologies for monitoring, reporting, and verification (MRV) related to paddy water management have been developed under both voluntary and compliance carbon credit schemes. The JCM, as one of the compliance schemes, satisfies the requirements of Article 6 of the Paris Agreement and enables Japan and its partner countries to jointly implement projects. Issued credits are distributed based on prior agreements, with a portion allocated to farmers. Under the JCM methodology approved in February 2025 for the Philippines (PH\_AM004; JCM, 2025), credits are issued based on proper implementation and documentation of multiple aeration practices by project participants and collaborating farmers. Notably, the JCM methodology follows a results-based payment system, placing strong emphasis on verified outcomes to enhance both credibility and accountability.

Depending on the institutional and market context, an intermediate pathway may also exist between the yield-based and credit-based approaches, including ESG-related initiatives and public sector support, such as environmental certification schemes, government-backed technology adoption programs, and partnerships with ESG-conscious companies. From the farmer's perspective, the choice of approach often depends on the perceived benefits and ease of access. In this context, intermediaries play a critical role—much like in credit-based schemes—by facilitating implementation and reducing transaction costs.

Accordingly, a portfolio of dissemination approaches should be considered to account for the diversity of regional conditions in the Asia-Monsoon region. As scientific understanding evolves, the requirements imposed on farmers to qualify for incentives will likely increase. Therefore, continuous support from researchers and policymakers will remain essential to ensure that climate mitigation strategies respect and support farmers' livelihoods.

## Author contributions statement

K.M., S.K., and A.L. conceived the study, led the first large-scale international evaluation of MiDi and its generalization across diverse rice systems, compiled the data, and wrote the original draft manuscript. K.U., T.T., and Y.T. supported the data analysis and contributed to the review and editing of the manuscript.

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