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# Methane Emission Dynamics and Soil Redox Processes in Rice Paddy Systems Under Alternate Wetting and Drying Irrigation

Abdul Rehman[a]*, Iqra Anwar[b], Muhammad Dilshad[c], Tahira Tabassum[d], Ali Zohaib[e], Ameer Jan[f]

a. *Corresponding Author: Scientific Officer (Agriculture Engineering), Rice Research Station, Bahawalnagar, Pakistan (abdulrehmanbrw11@gmail.com)*
b. *Department of Botany, University of Agriculture, Faisalabad, Pakistan*
c. *Department of Agronomy, University of Agriculture, Faisalabad, Pakistan*
d. *Cereals and Pulses Section, Agronomic Research Institute, Faisalabad, Pakistan*
e. *Cereals and Pulses Section, Agronomic Research Institute, Faisalabad, Pakistan*
f. *University of Makran, Pakistan*

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**Abstract**

Rice paddies are a major anthropogenic source of atmospheric methane ($CH_4$), contributing 10–12% of global agricultural non-$CO_2$ greenhouse gas emissions. Conventional continuous flooding (CF) creates prolonged soil anoxia, driving methanogenesis and high $CH_4$ release. Alternate Wetting and Drying (AWD) has emerged as a climate-smart irrigation strategy that periodically drains paddies before re-flooding, reducing $CH_4$ emissions by 45–65% while saving 15–42% of irrigation water. This review synthesizes current knowledge on soil redox thermodynamics, microbial community responses, trace gas trade-offs, and agronomic thresholds governing AWD performance. Drainage reintroduces oxygen, raising redox potential and promoting ferric iron ($Fe^{3+}$) regeneration, which competitively suppresses methanogens. Molecular evidence shows AWD downregulates *mcrA* transcription while enhancing methanotrophic *pmoA* expression, lowering the *mcrA*/*pmoA* ratio and net $CH_4$ flux. However, periodic aeration stimulates nitrification and denitrification, increasing nitrous oxide ($N_2O$) emissions by 18.7–44.0%, with the magnitude dependent on nitrogen inputs. Net global warming potential nonetheless declines by 42.1–46.9% because $CH_4$ dominates paddy carbon footprints. Yield-scaled GWP falls by 35–36% under Safe AWD (soil water threshold ≤15 cm below surface), with no significant yield penalty. Severe AWD beyond this threshold risks 31–85% yield losses. Synergistic practices controlled-release fertilizers, biochar, and deep nitrogen placement can further mitigate $N_2O$ spikes. This review provides an integrated framework for optimizing AWD to balance climate mitigation, water conservation, and food security across diverse soil textures and climatic zones.

**Keywords**: Alternate Wetting and Drying (AWD); methane ($CH_4$); nitrous oxide ($N_2O$); soil redox potential; methanogens; methanotrophs; *mcrA*/*pmoA* ratio; global warming potential; water productivity; rice paddy

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## 1. Introduction

Paddy rice (*Oryza sativa* L.) fields represent one of the principal anthropogenic sources of atmospheric methane ($CH_4$), accounting for approximately 10% to 12% of global agricultural non-$CO_2$ greenhouse gas (GHG) emissions. Conventional rice cultivation relies on continuous flooding (CF) throughout the vegetative and reproductive growth stages (Zhao et al., 2024). While continuous submergence suppresses weed growth and ensures stable moisture availability, it severely restricts atmospheric oxygen ($O_2$) diffusion into the soil. This prolonged anoxia induces highly reducing soil conditions, triggering the anaerobic decomposition of soil organic carbon (SOC) and root exudates by methanogenic archaea (Xiao et al., 2025).

Concurrently, global rice production faces severe challenges from escalating freshwater scarcity in major agricultural river basins, alongside growing pressure to mitigate agro-climatic impacts. In response, climate-smart water management techniques most notably Alternate Wetting and Drying (AWD) have been developed and widely disseminated. AWD alters the continuous hydraulic head of traditional paddies by allowing the field to drain naturally to a specified soil depth or redox potential before re-flooding (Bwire et al., 2024). Allowing field drainage introduces atmospheric $O_2$ into the porous soil matrix, shifting the soil thermodynamic landscape and disrupting the obligate anaerobic conditions necessary for methanogenesis. Comprehensive field evaluations and meta-analyses demonstrate that AWD can reduce seasonal $CH_4$ emissions by 30% to over 70% while yielding irrigation water savings of 15% to 42% without sacrificing grain yield (Shu et al., 2026).

However, the biogeochemical transitions driven by periodic drying and re-wetting cycles introduce complex biogeochemical trade-offs. Re-oxygenation of previously anoxic soil rapidly increases oxidation-reduction potential ($E_h$), altering terminal electron acceptor hierarchies and promoting the oxidation of reduced mineral species such as ferrous iron ($Fe^{2+}$) (Sriphirom et al., 2026). Although these redox shifts inhibit methanogenesis, they simultaneously stimulate microbial nitrification during dry periods ($NH_4^+ \rightarrow NO_3^-$) and subsequent denitrification during re-flooding ($NO_3^- \rightarrow N_2O \rightarrow N_2$). Consequently, AWD often increases emissions of nitrous oxide ($N_2O$), a potent greenhouse gas with a global warming potential 273 times greater than $CO_2$ on a 100-year timescale (Li et al., 2026).

Understanding the thermodynamic, microbiological, and agronomic controls governing these trace gas dynamics is essential for refining AWD management to maximize net climate change mitigation while maintaining grain yields. This review synthesizes current knowledge regarding soil redox thermodynamics, methanogenic and methanotrophic community responses, trace gas exchange trade-offs, and agronomic management boundaries under AWD systems across diverse soil textures and climate zones (Wang et al., 2025).

## 2. Biogeochemical Mechanisms and Soil Redox Thermodynamics

### *2.1. Sequential Electron Reduction Cascade*

The biogeochemical response of paddy soils to water management is governed by classical thermodynamic principles. When a dry soil is submerged, atmospheric $O_2$ ingress is restricted because the diffusion coefficient of $O_2$ in water is approximately $10^4$ times slower than in air. Facultative and obligate anaerobic microorganisms rapidly consume dissolved oxygen, lowering concentrations to hypoxic or anoxic levels ($< 0.5$ mg $L^{-1}$) (Liu et al., 2025). Microorganisms then sequentially utilize alternative inorganic electron acceptors for respiration according to their thermodynamic energy yield, which is reflected in their standard reduction potentials ($E_h$) at pH 7.0 (Sprenger, 2011).

This thermodynamic cascade proceeds systematically from high-potential electron acceptors to low-potential ones:

- Oxygen Reduction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ ($E_h = +300$ to $+400$ mV)
- Nitrate Reduction (Denitrification): $2NO_3^- + 12H^+ + 10e^- \rightarrow N_2 + 6H_2O$ ($E_h = +200$ to $+300$ mV)
- Manganese(IV) Reduction: $MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$ ($E_h = +100$ to $+200$ mV)
- Iron(III) Reduction: $Fe(OH)_3 + 3H^+ + e^- \rightarrow Fe^{2+} + 3H_2O$ ($E_h = -100$ to $+100$ mV)
- Sulfate Reduction: $SO_4^{2-} + 10H^+ + 8e^- \rightarrow H_2S + 4H_2O$ ($E_h = -150$ to $-100$ mV)

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- 6. Carbon Dioxide Reduction (Methanogenesis): $CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$ ( $E_h = -200$ to $-300$ mV)

Methanogenesis represents the terminal step in anaerobic organic matter mineralization and requires extremely reducing conditions ( $E_h < -150$ to $-200$ mV ). Under continuous flooding, soil $E_h$ declines into this methanogenic window, promoting high rates of $CH_4$ generation (Pangala, 2014).

Table 1 details the thermodynamic sequence, redox potential ranges, key microbial mediators, and dominant trace gas or dissolved byproducts associated with each terminal electron accepting process in paddy soils (Akay, 2025).

**Table 1. Thermodynamic Sequence of Soil Electron Acceptors, Redox Potentials, and Microbially Mediated Reactions in Paddy Soils**

| Process Stage | Primary Electron Acceptor | Redox Potential (Eh , mV at pH 7.0) | Key Microbial Genera / Groups | Associated Trace Gas / Byproducts |
|---|---|---|---|---|
| Aerobic Respiration | $O_2$ | $+400$ to $+600$ | *Pseudomonas*, *Bacillus*, Aerobic Heterotrophs | $CO_2$ |
| Nitrate Reduction | $NO_3^-$ | $+200$ to $+400$ | *Paracoccus*, *Pseudomonas*, *Azoarcus* | $N_2O$, $N_2$ |
| Manganese Reduction | $Mn^{4+}$ | $+100$ to $+300$ | *Geobacter*, *Shewanella* species | Soluble $Mn^{2+}$ |
| Iron Reduction | $Fe^{3+}$ | $-100$ to $+100$ | *Geobacter*, *Anaeromyxobacter* | Soluble $Fe^{2+}$ |
| Sulfate Reduction | $SO_4^{2-}$ | $-150$ to $-100$ | *Desulfovibrio*, *Desulfobacter* | $H_2S$, Metal Sulfides |
| Methanogenesis | $CO_2$ / Acetate | $-300$ to $-150$ | *Methanosarcina*, *Methanosaeta*, *Methanobacterium* | $CH_4$ |

*2.2. Re-oxygenation Kinetics and Fe(III) Regeneration*

Implementing AWD interrupts the continuous reduction of soil $E_h$. Draining irrigation water allows air to enter macropores, increasing soil $E_h$ back into positive ranges ( $+200$ to $+400$ mV ). This rapid change in thermodynamic conditions directly inhibits obligate anaerobic methanogens, whose enzyme systems specifically methyl-coenzyme M reductase are deactivated by molecular $O_2$ (Huang et al., 2026).

A major indirect mechanism of methanogenesis suppression during soil drying involves the oxidative regeneration of ferric iron oxides ($Fe^{3+}$). During flooded phases, microbial iron reduction converts insoluble $Fe^{3+}$ minerals (e.g., ferrihydrite and goethite) into soluble ferrous iron ($Fe^{2+}$), accounting for 68% to 94% of total anaerobic electron consumption in paddy soils (Yuan et al., 2019). When AWD re-aerates the soil, $Fe^{2+}$ oxidizes back into poorly crystalline $Fe^{3+}$ oxyhydroxides:

$$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H^+$$

Upon subsequent re-flooding, iron-reducing bacteria utilize these regenerated $Fe^{3+}$ minerals as terminal electron acceptors. Because $Fe^{3+}$ reduction is thermodynamically favored over $CO_2$ reduction ($E_h = -100$ to $+100$ mV versus $-200$ to $-300$ mV), iron reducers outcompete methanogens for substrate electron donors such as acetate and molecular hydrogen ($H_2$). This competitive suppression creates a temporal delay in $CH_4$ production following re-submergence, suppressing methane emissions beyond the active drainage window (Gao et al., 2025).

Furthermore, the oxidation of $Fe^{2+}$ by $O_2$ during drainage cycles yields reactive oxygen species (ROS), including superoxide radicals ($O_2^{\bullet-}$) and hydroxyl radicals ($\bullet OH$), via Fenton-like pathways. These reactive species can induce oxidative stress in methanogenic populations and alter complex soil organic carbon fractions, further suppressing methanogenic activity (Danielsson et al., 2018).

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## 3. Microbial Ecology of Methane Cycling Under AWD

### *3.1. Methanogenic Community Shifts and mcrA Gene Expression*

Methane generation in paddy soils is mediated by methanogenic archaea belonging to the phylum *Euryarchaeota*. These organisms produce methane via two primary metabolic pathways: the acetoclastic pathway, which cleaves acetate into $CH_4$ and $CO_2$, and the hydrogenotrophic pathway, which reduces $CO_2$ using $H_2$. The diagnostic biomarker for these communities is the *mcrA* gene, which encodes the alpha subunit of methyl-coenzyme M reductase, the enzyme catalyzing the final step of methanogenesis (Li et al., 2026).

The dominant methanogenic taxa in rice paddies belong to the orders *Methanosarcinales* (including the acetoclastic and facultative genera *Methanosarcina* and *Methanosaeta*), *Methanobacteriales* (*Methanobacterium*), *Methanocellales* (*Methanocella*), and *Methanomicrobiales*. Under continuous flooding, *Methanosaeta* and *Methanosarcina* dominate due to high acetate availability from anaerobic fermentation (Paul et al., 2026).

Under continuous flooding, deep anoxia ( $E_h < -200$ mV ) drives both acetoclastic and hydrogenotrophic pathways, resulting in elevated *mcrA* gene expression and high $CH_4$ transport through plant aerenchyma to the atmosphere. When AWD drainage introduces oxygen, soil aeration and $Fe^{3+}$ regeneration suppress *mcrA* transcription while disrupting syntrophic microbial networks (Shu et al., 2026). Although total genomic DNA abundances of methanogens often remain stable due to desiccation resistance, active transcription (*mcrA* mRNA) drops substantially. Aeration reduces positive interactions among syntrophic acetogens and methanogens, disrupting inter-species hydrogen transfer and suppressing net methane production (Qi et al., 2025).

### *3.2. Methanotrophic Dynamics and pmoA Functional Shifts*

Biological methane oxidation in paddy systems is carried out by aerobic methanotrophic bacteria (methanotrophs) located at oxic-anoxic interfaces, such as the upper soil layer and the rhizosphere. These bacteria utilize particulate methane monooxygenase (*pmoA* gene marker) to oxidize $CH_4$ to methanol ( $CH_3OH$ ), which is subsequently converted to $CO_2$ or incorporated into biomass (Ho et al., 2011).

Paddy soil methanotrophs are categorized into two primary physiological lineages:

- Type I Methanotrophs (Gammaproteobacteria): Include genera such as *Methylomonas*, *Methylosarcina*, and unclassified *Methylomonadaceae*. These organisms utilize the ribulose monophosphate (RuMP) pathway for carbon assimilation, exhibit rapid metabolic responses to shifting $CH_4$ and $O_2$ availability, and thrive at dynamic oxic-anoxic boundaries created during wetting-drying cycles (Obregon Alvarez et al., 2023).
- Type II Methanotrophs (Alphaproteobacteria): Include genera such as *Methylocystis* and *Methylocella*. These organisms utilize the serine pathway for carbon assimilation, generally exhibit higher substrate affinity, and maintain stable populations under low methane or oligotrophic conditions (Robroek et al., 2015).
- Periodic soil aeration under AWD enhances *pmoA* gene transcription and stimulates Type I methanotrophic activity compared to continuous flooding. Oxygen penetration deeper into the soil matrix during drainage broadens the aerobic niche for methanotrophs, increasing the fraction of generated $CH_4$ oxidized before escaping to the atmosphere (Ho et al., 2016).

### *3.3. Network Connectivity and the mcrA/pmoA Transcriptional Ratio*

Net $CH_4$ flux from paddy soils represents the balance between methanogenic production (*mcrA*) and methanotrophic consumption (*pmoA*). Under continuous flooding, high *mcrA* transcription relative to *pmoA* produces an elevated *mcrA*/*pmoA* transcript ratio ($> 1.0$), favoring high net methane release (Li et al., 2026).

AWD significantly lowers the *mcrA*/*pmoA* transcript ratio by simultaneously repressing *mcrA* expression and upregulating *pmoA* transcription. Co-occurrence network analyses reveal that dry cultivation reduces positive ecological connections among methanogenic archaea while increasing modular connectivity between methanotrophs and aerobic heterotrophs. This structural realigning of the microbial network suppresses net $CH_4$ emissions (Alvarez et al., 2022).

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## 4. Methane and Nitrous Oxide Emission Dynamics and Trade-Offs

### *4.1. Methane Mitigation Efficacy Across Soil and Climatic Gradients*

AWD consistently achieves marked reductions in seasonal $CH_4$ emissions compared to continuous flooding, though the precise mitigation efficacy varies with regional climate, soil texture, and organic inputs. Synthesized findings across global meta-analyses demonstrate average seasonal $CH_4$ reductions ranging from 45% to 64.5% under standard AWD regimes (Chittapur et al., 2026).

Climate zone plays a major role in governing AWD mitigation efficiency. Tropical rice systems exhibit greater absolute and relative $CH_4$ reductions (68.2%) under AWD compared to temperate systems (58.9%). Tropical soils feature higher ambient temperatures that drive rapid soil drying, high microbial metabolic rates, and quick depletion of available dissolved oxygen during flooded phases, amplifying the contrast between flooded and drained phases (Zhang et al., 2025).

Soil texture also influences water drainage rates and oxygen penetration. Fine-textured clay soils experience greater relative $CH_4$ reductions under AWD (up to 71.3%) than coarse-textured sandy or loamy soils. In clay soils, continuous flooding generates strong anaerobic conditions and high baseline $CH_4$ emissions; drainage induces shrinkage cracking that allows oxygen to penetrate deep into the subsoil matrix, interrupting methanogenesis throughout the soil profile (Ume et al., 2025).

### *4.2. Nitrous Oxide Trade-Offs and Coupled Nitrification-Denitrification*

While AWD suppresses $CH_4$ emissions, the periodic reintroduction of oxygen promotes conditions favorable for nitrous oxide ($N_2O$) generation. Nitrous oxide is generated as an intermediate byproduct during two main microbial processes:

- Aerobic Nitrification: During dry phases, soil oxygenation allows ammonia-oxidizing bacteria and archaea to oxidize ammonium ($NH_4^+$) from fertilizers or SOC mineralization into nitrite ($NO_2^-$) and nitrate ($NO_3^-$), releasing $N_2O$ as a byproduct (Zhu et al., 2025).
- Anaerobic Denitrification: Upon re-flooding, facultative anaerobes utilize the generated $NO_3^-$ as an electron acceptor. As soil $E_h$ declines, denitrification proceeds sequentially ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$). Rapid re-flooding can temporarily inhibit nitrous oxide reductase (NosZ), causing transient spikes in $N_2O$ emissions (Wang et al., 2025).

Meta-analyses report average increases in seasonal $N_2O$ emissions under AWD ranging from 18.7% to 44.0% relative to continuous flooding. The magnitude of this increase depends strongly on synthetic nitrogen fertilizer application rates. High N inputs ($> 180$ kg N $ha^{-1}$) exacerbate AWD-induced $N_2O$ emissions, resulting in a 28.4% increase, whereas lower N inputs ($< 120$ kg N $ha^{-1}$) produce a more modest 11.8% increase (Canisares et al., 2026).

### *4.3. Net Global Warming Potential and Yield-Scaled Emissions*

Evaluating the overall climate impact of AWD requires integrating $CH_4$ and $N_2O$ dynamics into net Global Warming Potential (GWP), expressed in mass equivalents of carbon dioxide ($CO_2$eq) over a 100-year timescale:

$$\mathrm{GWP} = (\mathrm{Flux}_{CH_4} \times 27) + (\mathrm{Flux}_{N_2O} \times 273)$$

Because $CH_4$ accounts for 90% to 97% of net non-$CO_2$ GWP in continuously flooded paddies, substantial absolute reductions in $CH_4$ under AWD generally outweigh concurrent increases in $N_2O$. Global meta-analyses demonstrate net seasonal GWP reductions of 42.1% to 46.9% under AWD relative to continuous flooding (Gong et al., 2021).

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Yield-scaled GWP ($GWP_{yield}$), defined as total GWP per unit of harvested grain yield (Mg $CO_2$eq $Mg^{-1}$grain), decreases by 35% to 36% under safe AWD practices, demonstrating that water-saving irrigation can decouple rice production from greenhouse gas intensity.

Table 2 synthesizes meta-analytic data comparing $CH_4$, $N_2O$, and net GWP responses to AWD across climate zones, soil textures, and nitrogen application levels (Guardia et al., 2016).

**Table 2. Comparative Meta-Analysis of Methane, Nitrous Oxide, and Net Global Warming Potential Responses to AWD Across Environmental and Management Regimes**

| Variable Category | Sub-category / Treatment Level | CH4 Emission Change (%) | N2 O Emission Change (%) | Net GWP Change (%) |
|---|---|---|---|---|
| **Overall Global Impact** | Global Meta-Analysis Average | −51.6 to −64.5 | +18.7 to +44.0 | −42.1 to −46.9 |
| **Climate Zone** | Tropical Regions | −68.2 ± 10.4 | +15.6 ± 8.2 | −46.7 ± 8.5 |
| | Subtropical / Temperate Regions | −58.9 ± 11.2 | +23.4 ± 9.1 | −35.2 ± 9.0 |
| **Soil Texture** | Fine / Clay Soils | −71.3 ± 9.8 | +23.1 ± 10.2 | −48.5 ± 7.9 |
| | Coarse / Loamy Soils | −52.4 ± 12.1 | +12.4 ± 7.5 | −38.1 ± 10.1 |
| **N Fertilizer Input** | Low Input (< 120 kg N $ha^{-1}$) | −61.2 ± 11.5 | +11.8 ± 8.9 | −48.2 ± 8.1 |
| | Moderate Input (120–180 kg N $ha^{-1}$) | −64.1 ± 10.8 | +16.3 ± 11.7 | −43.5 ± 9.2 |
| | High Input (> 180 kg N $ha^{-1}$) | −66.5 ± 12.0 | +28.4 ± 15.2 | −36.1 ± 11.0 |

## 5. Agronomic Feasibility, Yield Dynamics, and Management Thresholds

### *5.1. Safe AWD vs. Severe AWD Operational Limits*

The agronomic viability of AWD depends on maintaining soil moisture within safe hydrological limits. The International Rice Research Institute (IRRI) defines "Safe AWD" as allowing field water levels to recede naturally to a maximum threshold of 15 cm below the soil surface before re-flooding to a depth of approximately 5 cm. Field implementation relies on a simple perforated plastic field water tube (pani pipe) inserted 15 cm into the soil (Vitali, 2024).

Under Safe AWD, capillary action maintains hydration within the root zone despite the absence of surface standing water. Consequently, plant water status, stomatal conductance, photosynthetic activity, and grain yield remain equivalent to continuously flooded crops (Gilardi et al., 2023).

Conversely, "Severe AWD" occurs when field water levels drop deeper than 15 cm below the surface, or when soil matric potential drops below −20 kPa. Under severe moisture stress, plants experience root dehydration, leaf rolling, stomatal closure, impaired panicle initiation, and spikelet sterility (Phoeurn, 2024). Yield penalties under Severe AWD range from 31% to 64% during moderate water deficits, and up to 85% under extreme stress. Maintaining surface flooding during flowering and panicle initiation is essential, as rice crops are particularly vulnerable to moisture deficits during these reproductive stages (Gilardi, 2025).

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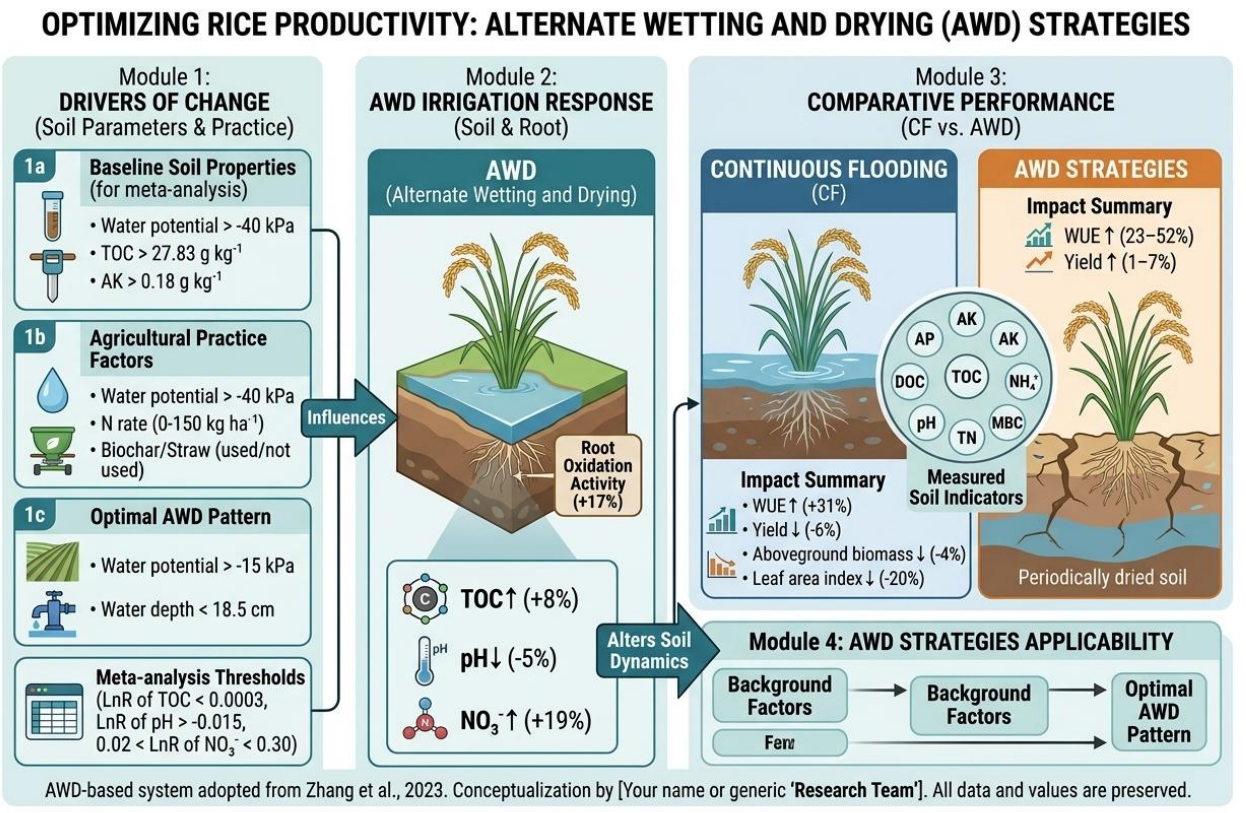


Figure 1 Alternate wetting and drying irrigation (AWD) (Adopted from Zhang et al., 2023).

**Figure 1.** Conceptual diagram of Alternate Wetting and Drying (AWD) modules illustrating baseline driver thresholds, soil-root dynamics, comparative performance relative to continuous flooding (CF), and applicability frameworks.

*5.2. Water Productivity and Yield Maintenance*

When implemented within safe thresholds, AWD increases farm-level water productivity (WP), defined as grain yield produced per unit of total water input (irrigation plus rainfall, expressed in $\mathrm{kg\ grain\ m^{-3}water}$). Safe AWD reduces total seasonal irrigation water applied by 15% to 42% relative to continuous flooding (Ali & Talukder, 2008).

Because rice grain yields under Safe AWD do not significantly differ from continuously flooded controls, reduced water input translates to a 20% to 46% increase in water productivity. This improvement reduces pumping energy costs, conserves regional groundwater reserves, and increases farming system resilience to seasonal dry spells (Singh et al., 2010).

*5.3. Synergistic Management: Fertilization, Organic Amendments, and Biochar*

Integrated agronomic practices can address the $N_2O$ trade-off and optimize methane suppression under AWD:

- Controlled-Release Nitrogen Fertilizers: Formulations such as polymer-coated urea slow the release of mineral nitrogen, preventing high concentrations of ammonium ($NH_4^+$) and nitrate ($NO_3^-$) during dry-wet transitions and mitigating $N_2O$ spikes (Fischer & Glaser, 2012).
- Biochar Amendments: Incorporating pyrolyzed organic biomass (biochar) increases soil porosity, improves soil aeration, buffers pH, and adsorbs dissolved organic carbon (DOC). Biochar enhances methane oxidation by expanding methanotrophic habitats while reducing substrate availability for methanogenesis, further

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lowering the *mcrA*/*pmoA* transcript ratio (Yang et al., 2025).

- Deep Placement of Nitrogen Fertilizer: Placing urea briquettes into the anaerobic subsoil ( *7-- 10* cm depth) isolates ammonium from aerobic surface layers during drainage phases, reducing nitrification during dry periods and subsequent denitrification upon re-flooding.

Table 3 compares agronomic metrics, water use efficiency, trace gas fluxes, and yield impacts across continuous flooding, safe AWD, and severe AWD systems (Sánchez-Monedero et al., 2019).

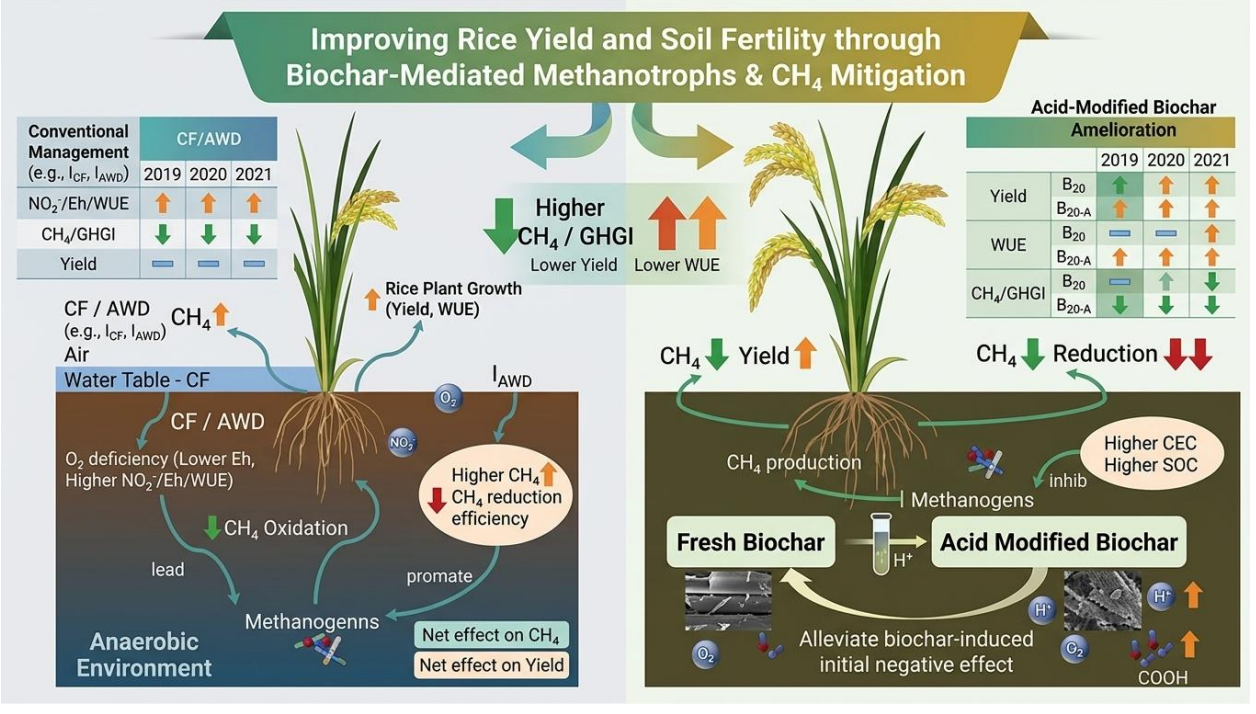


**Figure 2.** Biogeochemical pathways and trade-offs of methane ($CH_4$) emissions in paddy soils under conventional management versus acid-modified biochar amelioration.

**Table 3. Agronomic Performance, Water Productivity, and Yield Impacts Under Continuous Flooding, Safe AWD, and Severe AWD Systems**

| Performance Parameter | Continuous Flooding (CF) | Safe AWD (Threshold ≤−15 cm) | Severe AWD (Threshold >−15 cm) |
|---|---|---|---|
| **Seasonal Water Applied** ($m^3\ ha^{-1}$) | *9,260* to *16,559* | *6,200* to *11,000* (15–42% reduction) | *4,500* to *7,500* (45–60% reduction) |
| **Grain Yield** ($Mg\ ha^{-1}$) | *5.2* to *8.2* (Baseline) | *5.1* to *8.3* (No significant penalty) | *2.1* to *4.5* (31–65% yield penalty) |
| **Water Productivity** ($kg\ m^{-3}$) | Baseline (*0.45--0.65*) | *+20%* to *+ 46%* increase | Variable / Reduced by yield loss |
| **Seasonal $CH_4$ Flux** ($kg\ ha^{-1}$) | High (*150--450*) | Reduced by *45%* to *65%* | Reduced by *70%* to *90%* |
| **Seasonal $N_2O$ Flux** ($kg\ ha^{-1}$) | Low (*0.1--0.8*) | Increased by *18%* to *44%* | Increased by *> 100%* |
| **Net GWP** ($Mg\ CO_2eq\ ha^{-1}$) | High (Baseline) | Reduced by *42%* to *47%* | Reduced by *50%* to *70%* |
| **Yield-Scaled GWP** | High (Baseline) | Reduced by *35%* to *36%* | Elevated due to low grain yields |

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## 6. Conclusion

Alternate Wetting and Drying represents a robust, scalable strategy for reconciling rice production with climate mitigation and water scarcity challenges. This review demonstrates that AWD suppresses $CH_4$ emissions through interconnected biogeochemical and microbial mechanisms: re-oxygenation elevates soil redox potential, regenerates $Fe^{3+}$ electron acceptors that outcompete methanogens, deactivates oxygen-sensitive methanogenic enzymes, and shifts the *mcrA*/*pmoA* transcriptional balance toward methane oxidation. These processes yield seasonal $CH_4$ reductions of 45–65% and net GWP reductions of 42–47%, with tropical and fine-textured clay soils exhibiting the greatest mitigation efficacy. However, the $N_2O$ trade-off increasing by 18.7–44.0% under AWD necessitates integrated nutrient management, particularly at high nitrogen application rates (>180 kg N $ha^{-1}$). Critically, agronomic feasibility hinges on adhering to Safe AWD thresholds (≤15 cm water table decline), which maintain yields while increasing water productivity by 20–46%. Severe AWD beyond this boundary incurs unacceptable yield penalties (31–85%). Future research should prioritize long-term field validation across underrepresented agroecosystems, mechanistic modeling of coupled carbon-nitrogen-redox dynamics, and site-specific optimization of synergistic amendments (biochar, controlled-release fertilizers, deep nitrogen placement) to minimize $N_2O$ emissions without compromising $CH_4$ suppression. Collectively, the evidence supports Safe AWD as a core component of climate-smart rice cultivation, capable of decoupling grain production from greenhouse gas intensity while enhancing resilience to hydrological uncertainty.

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