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Effects of Alternate Wetting and Drying Irrigation on Methane and Nitrous Oxide Emissions From Rice Fields: A Meta-Analysis

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ABSTRACT

Reducing water input and promoting water productivity in rice field under alternate wetting and drying irrigation (AWD), instead of continuous flooding (CF), are vital due to increasing irrigation water scarcity. However, it is also important to understand how methane (CH_4) and nitrous oxide (N_2O) emissions and global warming potential ($GWP_{CH_4+N_2O}$ of CH_4 and N_2O) respond to AWD under the influence of various factors. Here, we conducted a meta-analysis to investigate the impact of AWD on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$, and its modification by climate conditions, soil properties, and management practices. Overall, compared to CF, AWD significantly reduced CH_4 emissions by 51.6% and $GWP_{CH_4+N_2O}$ by 46.9%, while increased N_2O emissions by 44.0%. The effect of AWD on CH_4 emissions was significantly modified by soil drying level, the number of drying events, mean annual precipitation (MAP), soil organic carbon content (SOC), growth cycle, and nitrogen fertilizer (N) application. Regarding N_2O emissions, mean annual temperature (MAT), elevation, soil texture, and soil pH had significant impacts on the AWD effect. Consequently, the $GWP_{CH_4+N_2O}$ under AWD was altered by soil drying level, soil pH, and growth cycle. Additionally, we found that MAP or MAT can be used to accurately assess the changes of global or national CH_4 and N_2O emissions under mild AWD. Moreover, increasing SOC, but not N application, is a potential strategy to further reduce CH_4 emissions under (mild) AWD, since no difference was found between application of 60–120 and > 120 kg N ha^{-1}. Furthermore, the soil pH can serve as an indicator to assess the reduction of $GWP_{CH_4+N_2O}$ under (mild) AWD as indicated by a significant linear correlation between them. These findings can provide valuable data support for accurate evaluation of non-CO_2 greenhouse gas emissions reduction in rice fields under large-scale promotion of AWD in the future.

1 | Introduction

Rice (*Oryza sativa*) is an important staple food, providing calories for more than half of the global population (Dong et al. 2011; Qiu et al. 2021). In 2022, the total planting area of rice worldwide was over 165 million ha (> 86% planted in Asia), accounting for > 29% of total area of other three main crops (i.e., 203, 219, and 134 million ha for maize (*Zea mays*), wheat (*Triticum aestivum*), and soybean (*Glycine max*), respectively) (FAO Statistics 2024). Paddy rice fields are typically continuously flooded (CF) until 7–14 days before harvest, except for some days in the late development stage to control tillering and facilitate a deeper root system (Qiu et al. 2022; Ye et al. 2013). This water management practice requires huge fresh water input (irrigation plus precipitation), typically ranging between 1300 and 1500 mm in Asia (IRRI 2024). As a result, irrigated rice consumes nearly 24%–30% of the global total fresh water resources (IRRI 2024). However, the scarcity of fresh irrigation water in agriculture continually increases due to population growth and competition with multiple nonagricultural sectors, especially in Asia (Kang et al. 2017; Rejesus et al. 2011). It is expected that by 2025, ~20% and ~ 29% of the total areas of irrigated rice may suffer from "physical water scarcity" (hydrologic constraints) and "economic water scarcity" (institutional and economic capacity constraints), respectively (Ishfaq et al. 2020; Rosa et al. 2020). In addition, occasional seasonal droughts strengthen the water shortage, threatening safe rice production. Hence, it is essential to seek water-saving technologies for rice production using less water to maintain reasonable yields, thereby increasing water productivity (crop yield/water use) to ensure the sustainability and stability for rice production and food security (Ye et al. 2013).

To date, varying water-saving technologies for rice production have been proposed, such as alternate wetting and drying irrigation (AWD), saturated soil culture cultivation, raised bed system, aerobic rice system, and nonflooded mulching cultivation, among others, as summarized elsewhere (Ishfaq et al. 2020). Among them, the AWD is the most promising water-saving irrigation technology that has been widely promoted worldwide (Carrijo, Lundy, and Linquist 2017). The AWD allows the water layer to drop to a certain depth below the soil surface (depending on soil drying level) after a few (typically 1–2) weeks, when rice plants have been established. Once the water level has dropped to the setting level below the soil surface, the rice fields are reflooded to a certain depth (typically 2–5 cm) above the surface, and this procedure is repeated until 1–2 weeks before harvest (IRRI 2024; Rejesus et al. 2011). It is noteworthy that the rice fields should remain flooded from 1 week before to 1 week after flowering since this stage is sensitive to water deficit stress (IRRI 2024). Therefore, the AWD can control the water supply to meet the physiological water requirements to save water and maintain acceptable rice yield. For instance, a meta-analysis showed that the AWD overall saves water by 25.7%, slightly decreases yield by 5.4%, and thereby increases water productivity by 24.2% (Carrijo, Lundy, and Linquist 2017). Especially, the adoption of mild or so-called "safe" AWD (reflood when field water level falls below 15 cm or soil water potential > −20 kPa) can achieve reduction of water use by 23.4% and increment of water productivity by 25.9% without rice yield loss (Carrijo, Lundy, and Linquist 2017). Additionally, the "safe" AWD is user-friendly for farmers, requiring only a few PVC water tubes to monitor the water depth (Lampayan et al. 2015). Moreover, AWD can reduce the accumulation of heavy metals in grain, such as mercury (H_g) (Rothenberg et al. 2016; Tanner et al. 2018) and arsenic (A_s) (Das et al. 2016; LaHue et al. 2016; Norton et al. 2017) by introducing aerobic cycles. This is because under anaerobic conditions, the reductive mobilization of A_s enhances its phytoavailability, while anaerobic microorganisms convert less toxic inorganic H_g into methylmercury, facilitating the accumulation of both A_s and H_g in rice grains (Linquist et al. 2015; Rothenberg et al. 2016).

Interestingly, although the AWD promotes nitrous oxide (N_2O) emissions, it can greatly reduce methane (CH_4) emissions (Carrijo, Lundy, and Linquist 2017; Wu et al. 2022), which are the most abundant non-CO_2 atmospheric greenhouse gas emissions in the atmosphere nowadays (Montzka, Dlugokencky, and Butler 2011; Shen et al. 2023). The paddy rice fields are a main contributor (0.8 ± 0.7 Gt CO_2 − eq year^{-1}) to CH_4 (Montzka, Dlugokencky, and Butler 2011) and N_2O emissions (260 Mt N_2O yr^{-1}) (Liao et al. 2021) in agriculture. The AWD have been reported to reduce global warming potential ($GWP_{CH_4+N_2O}$ of CH_4 and N_2O emissions) by 45%–90% with respect to CF (LaHue et al. 2016; Linquist et al. 2015). Therefore, in order to reduce greenhouse gas emissions, great efforts have been made worldwide to promote AWD. For instance, the American Carbon Registry allows farmers to adopt varying practices, including the AWD, in rice system to obtain carbon credits (allowing the owner to emit a certain amount of CO_2 or other greenhouse gases) (Carrijo, Lundy, and Linquist 2017). Therefore, the effects of AWD on CH_4 and N_2O emissions continue to draw research attention. Although numerous studies (listed in Table 1) have specifically reported the CH_4 and N_2O emissions in response to the AWD, most field experiments were conducted at a single site under a specified climate condition. However, the varying climates, soil properties, and management practices may modify the response of CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ to the AWD, which remains unclear. Therefore, in this study, we aimed at collecting the currently published studies concerning CH_4 and N_2O emissions under the AWD and adopting a meta-analytic approach to explore (1) the overall response of CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ to the AWD, and (2) the impacts of climate conditions, soil properties, and management practices on the AWD effect on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$.

2 | Materials and Methods

2.1 | Collection of Data

In this study, we collected peer-reviewed journal articles comparing growing season CH_4 and N_2O emissions between the AWD and CF by searching in the Web of Science, Google Scholar, and China National Knowledge Infrastructure (CNKI) using various keywords during the period 1990–2024. The keywords used for literature searching were (1) "greenhouse gas emissions" OR "GHG emissions" AND (2) "alternate wetting and drying irrigation" OR "AWD" OR "water management" OR "water saving." In addition, we also collected the relevant articles from the reference lists of the surveyed literature to avoid missing literature. Furthermore, the datasets included in this meta-analysis should meet the following criteria: (1) We selected only field studies; (2) The treatments of replicated CF and AWD must be carried out at the same experimental site for the same variety for each year to make sure that the climate, vegetation, and soil type were same among treatments; (3) When multiple studies reported dataset from the same experiments for the same year, we only collected the dataset one time. Finally, we collected 41 articles in total, which met the criteria (Table 1). The detailed spatial distribution of the locations of the analyzed studies is shown in Figure S1.

TABLE 1 | Summary of the literature used in this study.

Country	MAP (mm)	MAT (°C)	Elevation (m)	SOC ($g\,kg^{-1}$)	Soil texture	pH	AWD level	NDE (times)	BC rate ($t\,ha^{-1}$)	Growth cycle	N level ($kg\,ha^{-1}$)	Varity	CH_4	N_2O	Reference
USA	405	17[b]	30[a]	NA	Clay	5.3	M	2	NA	Middle	180	Inbred	•	•	LaHue et al. (2016)
USA	405	17[b]	30[a]	41.34	Clay	5.3	M&S	2	NA	Late	171	Inbred	•	•	Balaine et al. (2019)
Peru	1300	20	35	NA	Nonclay	7.64	M&S	NA	NA	Early	250	NA	•	NA	Echegaray-Cabrera et al. (2024)
USA	277[b]	−4[b]	60[a]	NA	Nonclay	5.6	NA	3	NA	Middle	144	NA	•	•	Linquist et al. (2015)
China	1118	16.7	3[a]	16.5	Nonclay	6.7	M	> 3	NA	Middle	96	Hybrid	•	•	Zhang et al. (2021)
China	750	15.5	133[a]	19.2	NA	6.41	M&S	> 3	NA	Middle	180	Hybrid	•	NA	Feng et al. (2021)
China	1923[b]	27	25[a]	NA	NA	NA	M&S	> 3	NA	Late	180	Inbred	•	NA	Liang et al. (2016)
China	837	15.5	156	NA	Nonclay	6.52	M	> 3	NA	Late	180	Hybrid	•	NA	Hao et al. (2022)
China	1458.2	23.7	76[a]	10.5	Clay	7.03	M	NA	NA	Late	135	Hybrid	•	NA	Wang, Li, and Dong (2020)
China	716	8	8.1[a]	23.17	Nonclay	6.71	M	> 3	NA	Middle	180	Inbred	•	•	Sha et al. (2022)
China	1236	15.2	30[a]	NA	Clay	6.2	NA	NA	NA	Late	90–270	Inbred	•	•	Wang et al. (2020)
China	1020	16.1	23[a]	23.5	Nonclay	6.9	M&S	NA	NA	Middle	225	Inbred	•	•	Li et al. (2023)
China	688	15	12[a]	NA	Nonclay	NA	M	NA	NA	Late	240	Hybrid	•	NA	Wang et al. (2018)
China	1458.2	23.7	76[a]	16.54	Clay	7.02	M	NA	NA	NA	135	Hybrid	•	NA	Ma, Wu, and Li (2022)
China	933	16.6	97[a]	NA	Nonclay	6.65	M	NA	NA	Late	0–180	NA	•	•	Liao et al. (2023)
China	341	12	197[a]	30.57	NA	5.27	M&S	NA	NA	NA	144	Inbred	•	•	Wu et al. (2022)
China	673	7.5	47[a]	40.18	Clay	6.94	M	NA	NA	Middle	210	Inbred	NA	•	Liu et al. (2022)
China	640	8	13[a]	NA	Nonclay	7.04	M	NA	0–20	Early	200	NA	NA	•	Chen et al. (2022)
China	716	8	13[a]	23.17	Nonclay	6.71	M	NA	NA	Middle	90	NA	NA	•	Zhao et al. (2023)
China	550	3	181[a]	35.4	NA	6.41	M	NA	NA	NA	110	Inbred	•	NA	Han et al. (2024)
China	1150	16.5	30[a]	11.14	Nonclay	7.7	M	NA	NA	Early	180	Hybrid	•	•	Li et al. (2024)
China	1458.2	23.7	76[a]	15.6	Clay	7	M	NA	NA	Late	90–120	Hybrid	•	•	Li, Li, and Li (2021)
China	640	8	8.1[a]	NA	Nonclay	NA	M	> 3	0–20	Middle	200	Inbred	•	•	Liu et al. (2023)
China	1587	17.5	137.5[a]	21.8	Clay	5.31	M	NA	NA	NA	150	NA	•	•	Cheng et al. (2018)

(Continues)

TABLE 1 | (Continued)

Country	MAP (mm)	MAT (°C)	Elevation (m)	SOC (g kg^{-1})	Soil texture	pH	AWD level	NDE (times)	BC rate (t ha^{-1})	Growth cycle	N level (kg ha^{-1})	Varity	CH_4	N_2O	Reference
China	550	2.9	200[a]	41.8	NA	6.4	M	NA	0–25	NA	110	Inbred	•	•	Zhang et al. (2022)
Philippines	900	23	116[a]	NA	Nonclay	6.7	M	NA	NA	NA	86.8	NA	•	NA	Win et al. (2022)
Philippines	1941	27.6	56[a]	14	Clay	7	M	> 3	NA	Early	90–120	Inbred	•	•	Sibayan et al. (2018)
Philippines	2115	27.4	21	NA	Clay	6.54	M	NA	NA	Early	160	Inbred	•	•	Islam et al. (2020)
Philippines	2013	27.2	19[a]	NA	Nonclay	7.3	M	NA	NA	NA	90–193	NA	•	•	Sander et al. (2020)
Bangladesh	540	24.3	106[a]	NA	NA	6.94	M	> 3	NA	Early	180	Inbred	•	NA	Habib et al. (2023)
Bangladesh	2123[b]	25[b]	11[a]	NA	Nonclay	6.13	M	> 3	NA	NA	90	Inbred	•	•	Islam et al. (2020)
Bangladesh	2679[b]	25[b]	11[a]	NA	Clay	7.2	M	3	NA	Middle	280	Inbred	•	•	Hossain and Islam (2022)
Bangladesh	2000	25	13[a]	NA	Nonclay	6.13	M	3	NA	Early	0–52	NA	•	NA	Islam et al. (2022)
Indonesia	1559	30	17[a]	NA	Clay	7.18	M	> 3	NA	Late	120	NA	•	NA	Ariani, Hanudin, and Haryono (2022)
Thailand	1200	27	2	NA	Clay	6	M	NA	NA	Middle	135	NA	•	•	Maneepitak et al. (2019)
Thailand	1395	28	176	NA	Clay	5.79	M&S	2	NA	Early	138	Inbred	•	NA	Sriphirom and Rossopa (2023)
Thailand	1249[b]	28[b]	114[a]	4.3	Nonclay	6.12	M	1	0–10	Late	0–90	NA	•	•	Sriphirom, Chidthaisong, and Towprayoon (2019); Sriphirom et al. (2020)
Thailand	1700	28	3	30	Clay	4.8	M	> 3	NA	Late	70	NA	•	•	Chidthaisong et al. (2018)
Vietnam	2500	25	5[a]	NA	Nonclay	4.18	M	3	NA	Early	92–119	Inbred	•	•	Tran et al. (2018)
Vietnam	1620	23.5	10[a]	7.8	Nonclay	4.76	M	NA	NA	Early	150	NA	•	•	Hung et al. (2022)
Vietnam	1415	27.4	3[a]	NA	Clay	5.2	M	> 3	NA	Early	90	Hybrid	•	•	Vo et al. (2024)

Note: The growth cycle is divided as early, middle, or late rice.
Abbreviations: AWD, alternate wetting and drying irrigation; BC, biochar application rate; MAP, mean annual precipitation; MAT, mean annual temperature. M and S represent mild and severe AWD, respectively; N, nitrogen fertilizer application rate; NA, not available; NDE, number of drying events; SOC, soil organic carbon content.
[a]The missing elevation data were filled from Satellite Online website (http://www.wxno.com/).
[b]The missing data of MAP and MAT were filled with the mean values during 1970–2000 with spatial resolution of ~1 km^2 from the WorldClim version 2.1 (https://www.worldclim.org/data/index.html).

The data were directly extracted from tables and the main text or indirectly from Figures of the original paper using the GetData Graph Digitizer software (version 2.26). In the literature, there are varied values of radiative forcing potential for N_2O and CH_4 with respect to CO_2 over a 100-year time expressed in CO_2 equivalents ($kg\ CO_2-eq\ ha^{-1}$), for instance, 298 and 25 $kg\ CO_2-eq\ ha^{-1}$ (IPCC 2007), or 265 and 28 $kg\ CO_2-eq\ ha^{-1}$ (IPCC 2014), or 273 and 27.2 $kg\ CO_2-eq\ ha^{-1}$ (Bo et al. 2022) for N_2O and CH_4. To avoid bias stemming from different calculations, we recalculated the $GWP_{CH_4+N_2O}$ using the following equation based on IPCC (2014) when both data of growing season total CH_4 ($kg\ CH_4\ ha^{-1}$) and N_2O ($kg\ N_2O\ ha^{-1}$) emissions in literature were available (IPCC 2014; Zhang et al. 2021), as

$$GWP_{CH_4+N_2O} = 28 \times CH_4 + 265 \times N_2O \tag{1}$$

In addition to CH_4 and N_2O emissions, we also recorded and classified the following regulatory variables for further analysis as sources of variance when reported, that is, AWD practice (drying level and the number of drying events), climate conditions (mean annual precipitation (MAP), mean annual temperature (MAT), and site elevation), soil properties (soil texture, soil pH, and soil organic carbon content (SOC)), and management practices (rice variety, rice growth cycle, nitrogen fertilizer (N) application rate, and biochar application rate), as shown in Table 1.

The AWD threshold was divided into two categories according to the field water level (FWL) or soil water potential (SWP) just before reflooding, that is, severe AWD ($SWP < -20$ kPa or $FWL < -15$ cm) and mild (or "safe") AWD ($SWP \geq -20$ kPa or $FWL \geq -15$ cm) (Carrijo, Lundy, and Linquist 2017). The number of drying events (≤ 3, > 3) was categorized based on the collected data. The MAP was classified into four categories, that is, < 200 mm (arid regions), 200–400 mm (semiarid regions), 400–800 mm (subhumid regions), and > 800 mm (humid regions) (Wu, Yang, and Zheng 2003). The rice plants can survive under air temperature ranging between 4.7°C and 42.9°C (Sánchez, Rasmussen, and Porter 2014), and therefore, can be planted in various MATs. In this study, we divided the MAT into < 20, 20–25, and > 25°C based on the collected dataset. The rice was planted in low altitudes regions (from 2 to 200 m) in all the collected studies. Here, we categorized site elevation as ≤ 20 and > 20 m.

The soil texture was classified as clay or nonclay soil using the USDA soil texture classes (Carrijo, Lundy, and Linquist 2017). The rice is planted in soils with pH ranging from strongly acidic to alkaline (Shen et al. 2023). Hence, we classified the soil pH into the categories of < 6.5 (acid), 6.5–7.3 (neutral), and > 7.3 (alkaline) based on the USDA recommendations (Zhou et al. 2017). The SOC, a key indicator of soil fertilization, is classified as < 12 (low), 12–18 (mid), and > 18 $g\ kg^{-1}$ (high) (Liu et al. 2019). The rice varietal type was divided into hybrid or inbred as adopted elsewhere (Carrijo, Lundy, and Linquist 2017). The growth cycle of rice was categorized as early, middle, and late rice, as reported in literature. The N application rates were divided into < 60, 60–120, and > 120 $kg\ N\ ha^{-1}$ (Linquist et al. 2013). The biochar application was grouped as ≤ 12, and > 12 $t\ ha^{-1}$ based on the collected data.

2.2 | Meta-Analysis

In the meta-analysis, the effect size of CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ was calculated using the natural logarithm of the response ratio (R), as

$$\ln R = \ln\left(X_e / X_c\right) \tag{2}$$

where X_e and X_c are the mean values of CH_4 emissions, N_2O emissions, and $GWP_{CH_4+N_2O}$ under the AWD and CF, respectively. The METAWIN software (version 2.1) was used to conduct a mixed effect meta-analysis, assuming a random variation in the effect size as a result of field observations (Feng et al. 2019). The comparison of random-effect and fixed-effect models is also shown in Figure S2. The mean response ratio ($\overline{\ln(R)}$) can be determined based on weight for the i-th observation, w_i (Adams, Gurevitch, and Rosenberg 1997; Kou-Giesbrecht and Menge 2021; Linquist et al. 2013), as

$$\overline{\ln(R)} = \frac{\sum w_i \ln\left(R_i\right)}{\sum w_i} \tag{3a}$$

$$w_i = \frac{n_{CF,i} n_{AWD,i}}{n_{CF,i} + n_{AWD,i}} \tag{3b}$$

where $n_{CF,j}$ and $n_{AWD,j}$ are the number of replications for the i-th observation of CF and AWD, respectively. Since many studies did not provide data of standard deviations, the variance of the effect size cannot be calculated when using weighted analysis (Mcgrath and Lobell 2013; Morgan, Ainsworth, and Long 2003). Therefore, we computed the sample variance of the effect size using resampling techniques (Morgan, Ainsworth, and Long 2003), as

$$\overline{B_k} = \frac{1}{n} \sum_{j=1}^{n} b_{kj} \tag{4}$$

where $B_k = \{b_{k1}, b_{k2}, \ldots, b_{kj}, \ldots, b_{kn}\}$ (for $k = 1, 2, \ldots, K$) is the k-th bootstrap samples by randomly drawing n observations with replacement from the original sample $X = \{x_1, x_2, x_3, \ldots, x_n\}$, $\overline{B_k}$ is the mean of k-th bootstrap samples. After generating all K bootstrap means (64,999 in this study), the variance of these bootstrap means ($Var(\overline{B})$) can be calculated as

$$Var\left(\overline{B}\right) = \frac{1}{K-1} \sum_{k=1}^{K} \left(\overline{B_k} - \overline{B}\right)^2 \tag{5}$$

$$\overline{B} = \frac{1}{K} \sum_{k=1}^{K} \overline{B_k} \tag{6}$$

where $\overline{B}$ is the mean of the bootstrap means. The confidence interval (CI) around the effect size can be then calculated using the bootstrap method (Mcgrath and Lobell 2013) after the maximum number of iterations (i.e., 64,999). If the 95% bootstrap CI does not overlap with zero, the treatment effect is significant. Examination of funnel plots indicates the absence of study bias (Figure S3).

To test the climate conditions, soil properties, and management practices on the AWD effect, we divided these data into various categories. The total heterogeneity was partitioned into between-group (Q_B) and within-group heterogeneities (Q_W). Differences among means of categories were significant when p values for Q_B were below 0.05. For the means of two different categories, there were significant differences when their 95% bootstrap CIs did not overlap.

To better represent the percentage change of the response (effect) relative to control, we inversed lnR and present $(R-1)\times100\%$ in the display elements with the results. A negative or positive percentage change indicates inhibitory or promoting effect of the AWD on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$.

3 | Results

The overall results showed that, compared to CF, although the AWD significantly increased N_2O by 44.0% (CI: 30.8% to 61.4%), it significantly decreased CH_4 emissions by 51.6% (CI: −55.1% to −48.4%), therefore reducing $GWP_{CH_4+N_2O}$ by 46.9% (CI: −51.4% to −42.8%) (Figure 1).

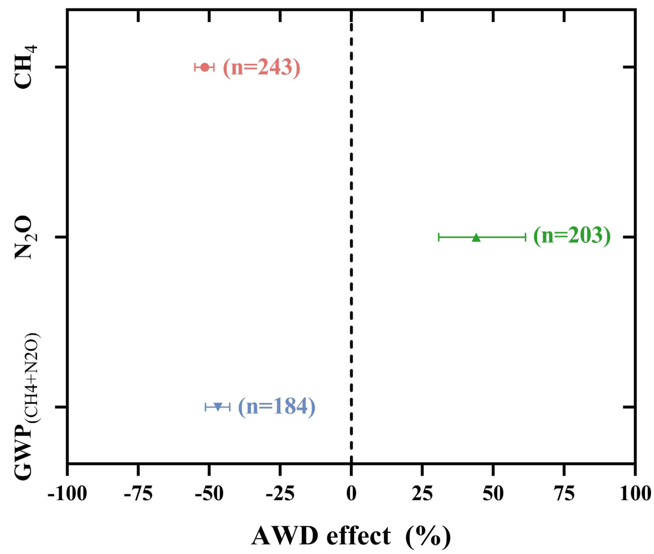

FIGURE 1 | The overall effect of the alternate wetting and drying irrigation (AWD) on CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$) compared to continuous flooding irrigation. Symbols are the mean effect sizes and the bars represent the 95% confidence intervals. Bars not overlapping with zero indicate significant difference between treatments. The numbers in parenthesis show the number of observations.

With regard to the AWD threshold, both mild and severe AWD significantly decreased CH_4 emissions and $GWP_{CH_4+N_2O}$ (Figure 2) while increasing N_2O emissions with respect to CF (Figure 2). However, the degree of soil drying markedly modified the AWD effect on CH_4 emissions and $GWP_{CH_4+N_2O}$ but not on N_2O emissions. An amplified reduction of CH_4 emissions and $GWP_{CH_4+N_2O}$ was observed under severe AWD (−65.2% and −56.3%, respectively) than under mild AWD (−49.4% and −45.2%, respectively). In addition, the number of drying events significantly altered the AWD effect on CH_4 emissions but not on N_2O emissions and $GWP_{CH_4+N_2O}$ (Figure 2). The AWD induced a greater reduction of CH_4 emissions when the number of drying events was >3 (−57.8%) than ≤ 3 (−40.6%).

Figure 3 shows the impact of climate conditions on the AWD effect for CH_4 and N_2O emissions as well as $GWP_{CH_4+N_2O}$. The AWD considerably reduced CH_4 emissions and $GWP_{CH_4+N_2O}$, while increasing N_2O emissions for all MAPs, MATs, and site elevations. However, MAP only impacted the effect of AWD on CH_4 emissions, with more reduction at 400–800 mm (−60.2%) than at >800 mm (−49.2%). In addition, the AWD effect on N_2O emissions, but not CH_4 emissions and $GWP_{CH_4+N_2O}$, was significantly altered by MAT (Figure 3). Specifically, the AWD led to a greater increment in N_2O emissions at <20°C (82.6%) than at >25°C (24.5%) (Figure 3). Regarding site elevation, it only altered the impact of AWD on N_2O emissions, with a greater increment at >20 m (80.0%) than at ≤20 m (25.5%).

Soil properties (soil texture, pH, and SOC) modulated the AWD effect on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$. Specifically, the AWD induced a smaller increment in N_2O in clay soils (20.2%) than in nonclay soils (88.6%), although soil texture did not markedly influence the effect of AWD on CH_4 emissions and $GWP_{CH_4+N_2O}$ (Figure 4). In addition, the AWD considerably reduced CH_4 emissions and $GWP_{CH_4+N_2O}$, while increasing N_2O emissions at all levels of soil pH, despite soil pH did not significantly alter the AWD effect on CH_4 emissions. Specifically, reduction of $GWP_{CH_4+N_2O}$ under AWD was greater at a soil pH of <6.5 (−54.2%) than at a pH of 6.5–7.3 (−36.7%), and it linearly decreased with increased soil pH (Figure 5c). More increment in N_2O emissions caused by the AWD was observed in soils with a pH of 6.5–7.3 (66.7%) than in soils with a pH <6.5 (19.3%) (Figure 4). Furthermore, SOC significantly altered the AWD effect on CH_4 emissions but not on N_2O emissions and $GWP_{CH_4+N_2O}$. The reduction of CH_4 emissions under AWD was significantly smaller when SOC was below 12 g kg^{-1} (−30.8%) compared to SOC above 18 g kg^{-1} (−56.9%). Additionally, a significant ($p<0.01$) positive linear relation was found between CH_4 reduction under the AWD and SOC (Figure 5a).

Regarding the rice variety and rice growth cycle, the AWD considerably reduced CH_4 emissions and $GWP_{CH_4+N_2O}$, while increasing N_2O emissions compared to CF for both hybrid and inbred rice, as well as for early, middle, and late rice (Figure 6). However, rice variety type did not markedly modify the effect of AWD on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$. More reduction of CH_4 emissions and $GWP_{CH_4+N_2O}$ under AWD was observed in early rice (−60.7% and −55.2%, respectively) than in late rice (−43.6% and −42.2%, respectively).

Reasonable N application is an important management practice to increase rice yield under AWD (Figure S4), which also greatly alters the AWD effect on CH_4 emissions. The reduction of CH_4 emissions under AWD was significantly greater in the presence of >60 kg N ha^{-1} (−56.5% ~ −52.6%) than <60 kg N ha^{-1} (−12.8%) (Figure 6; Figure S5), and it linearly increased as N application increased (Figure 5b). All N application levels led to a considerable reduction of $GWP_{CH_4+N_2O}$ under AWD, but N application did not modify the AWD effect on $GWP_{CH_4+N_2O}$, as well as N_2O emissions. Although the AWD significantly decreased

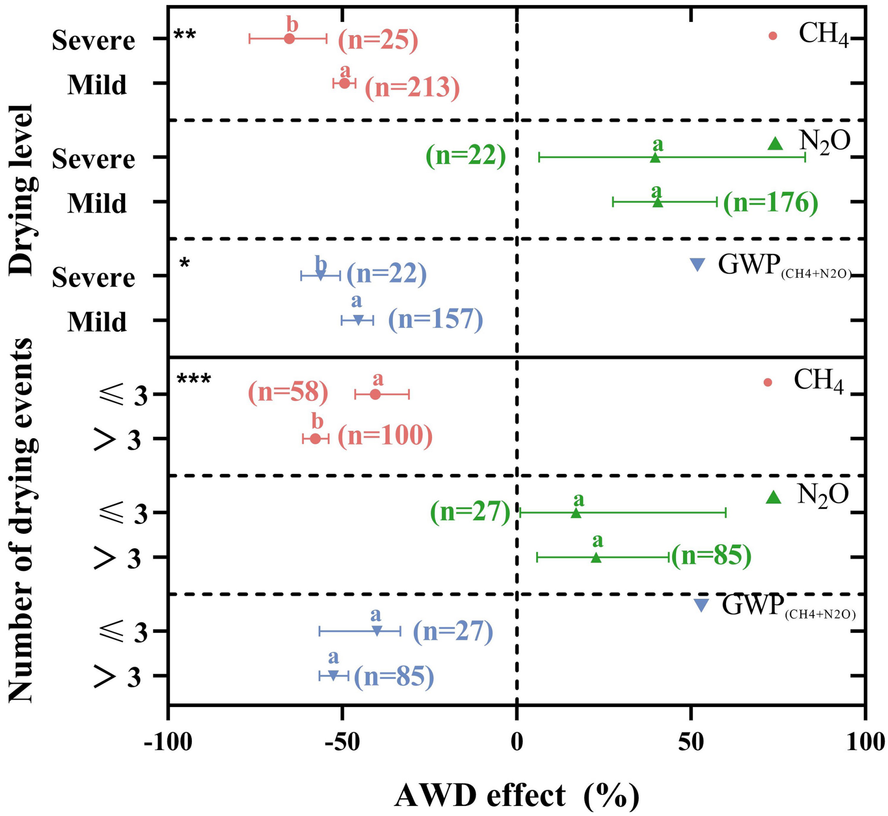

FIGURE 2 | The effects of the alternate wetting and drying irrigation (AWD) on CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$) subjected to varying degrees of soil drying (mild and severe AWD) and the number of drying events. Symbols are the mean effect sizes, and the bars represent the 95% confidence intervals. The numbers in parenthesis show the number of observations. Bars without overlapping with zero indicate significant difference between treatments. Different letters indicate significant differences among subgroups (i.e., 95% confidence intervals nonoverlap between categories). *, **, and *** indicate significant level at $p<0.05$, $p<0.01$, and $p<0.001$ for between-group heterogeneity (Q_B) of subgroups.

CH_4 emissions and $GWP_{CH_4+N_2O}$, while increasing N_2O emissions for both biochar categories compared to CF, biochar application did not alter the AWD impact on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$.

Since mild or "safe" AWD does not cause rice yield loss (Carrijo, Lundy, and Linquist 2017), it may be easier to be widely promoted. Hence, we further analyzed CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ under mild AWD as affected by various conditions, as shown in Table 2. Generally, the modification effect of climate conditions, soil properties, and management practices on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ in response to the AWD regardless of drying levels and mild AWD was similar, although the degree of modification effect was discrepant. The reduction of CH_4 emissions under mild AWD was more pronounced in areas with a MAP of 400–800 mm (59.5%) or a MAT > 25°C and < 20°C (−54.8% and −54.2%, respectively vs. −41.4% at 20°C–25°C). It was also amplified in the presence of SOC > 18 g kg^{-1} (−56.1% vs. −30.8% at < 12 g kg^{-1}), or for early rice (−58.6% vs. −39.6% for late rice), or when N application exceeded 60 kg N ha^{-1} (−52.7% ~ −53.5%). The increment in N_2O emissions under mild AWD was considerably promoted when MAP was 400–800 mm (93.6%), or MAT was below 20°C (79.1% vs. 21.9% at > 25°C), or site elevation was > 20 m (82.4%), or in nonclay soil (69.6%), or at pH ranged 6.5–7.3 (62.4% vs. 11.8% at pH < 6.5). Finally, greater reduction of $GWP_{CH_4+N_2O}$ under mild AWD was observed in soils with a pH < 6.5 (−52.8% vs. −36.6% at pH = 6.5–7.3), or for early rice (−54.5% vs. −40.0% for late rice).

Moreover, under mild AWD, more SOC or N application also linearly increased the reduction of CH_4 emissions (Figure 5 a,b), and greater pH linearly alleviated the reduction of $GWP_{CH_4+N_2O}$ (Figure 5c).

4 | Discussion

4.1 | Overall Effect of the AWD on CH_4 and N_2O Emissions and $GWP_{CH_4+N_2O}$

CH_4 is the final product of anaerobic degradation of organic matter (Conrad 2007), and soil microbial nitrification (aerobic)–denitrification (anaerobic) is the primary source of N_2O emissions (Kritee et al. 2018). Therefore, flooded rice fields (commonly anaerobic) are one of the major sources of CH_4 and N_2O emissions (Kritee et al. 2018; Liao et al. 2021; Montzka, Dlugokencky, and Butler 2011). Unsurprisingly, the AWD practice can increase soil redox potential, inhibiting CH_4 production activity and enhancing CH_4 oxidation activity, thereby

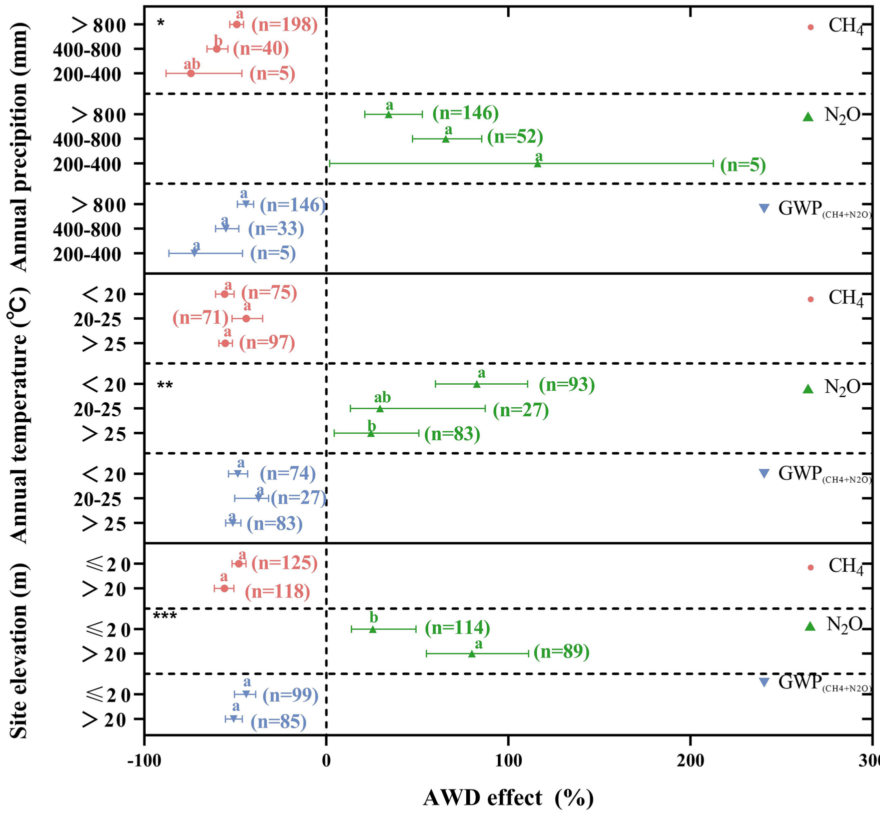

FIGURE 3 | The effects of mean annual precipitation (MAP), mean annual temperature (MAT), and site elevation on the alternate wetting and drying irrigation (AWD) effect on CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$). Explanation of the notations is the same as in Figure 2.

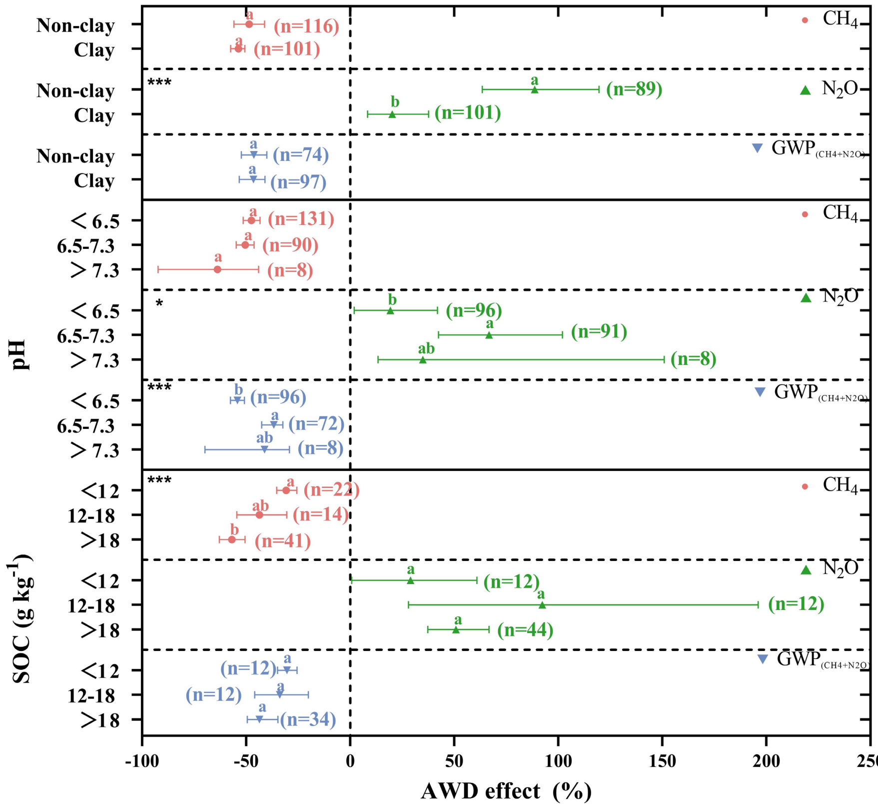

FIGURE 4 | Relative changes of CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$) under the alternate wetting and drying irrigation (AWD) as affected by varying soil types, pH, and soil organic carbon content (SOC). Explanation of the notations is the same as in Figure 2.

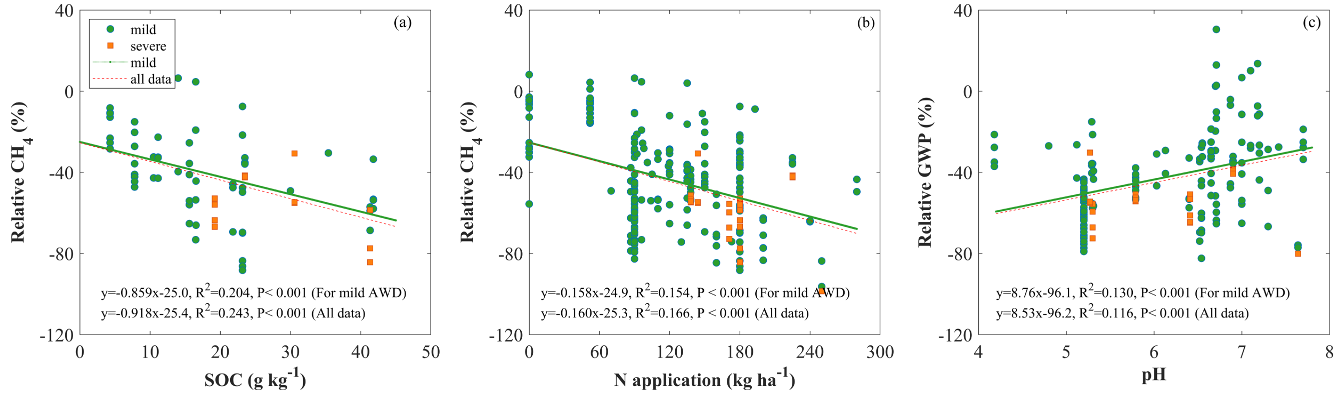

FIGURE 5 | Relationships between relative CH_4 and SOC (a) or N application (b), and relative $GWP_{CH_4+N_2O}$ and pH (c) under mild AWD or for all data. AWD is the alternate wetting and drying irrigation. SOC is the soil organic carbon content, and $GWP_{CH_4+N_2O}$ is the global warming potential. The relative value $(R-1)$ is based on is the response ratio (R) as shown in the Equation 2. A negative or positive percentage change shows inhibitory or promoting effect of the AWD on greenhouse gas emissions and $GWP_{CH_4+N_2O}$.

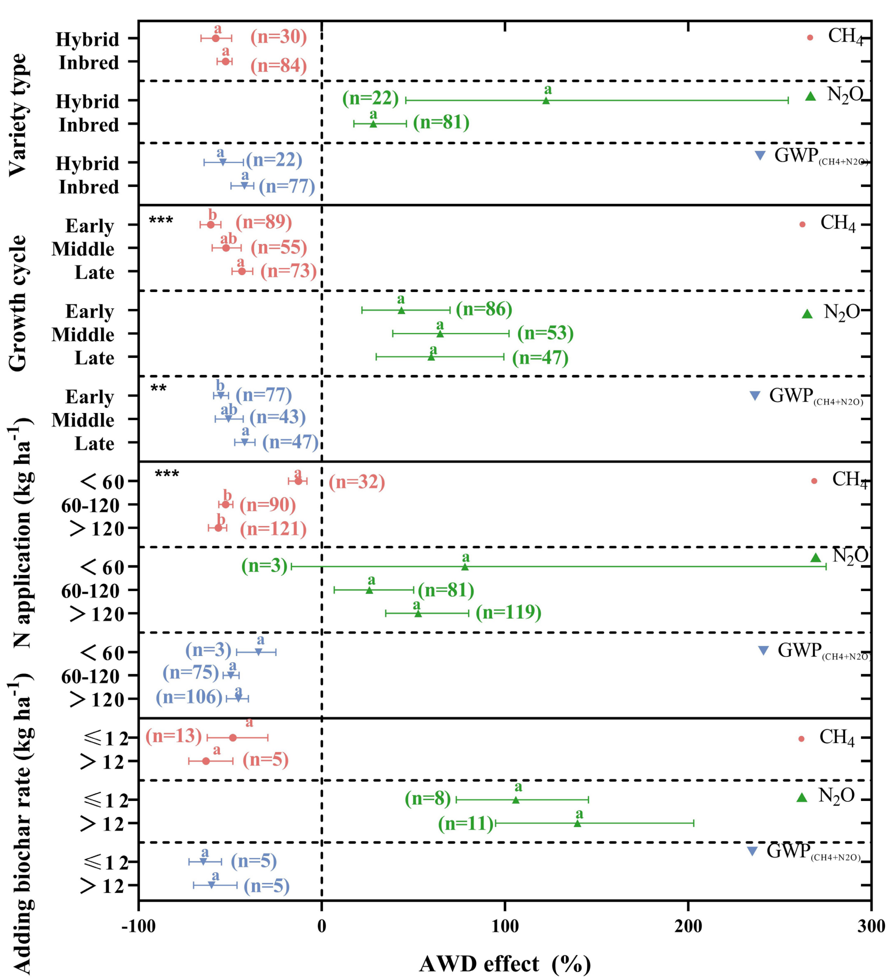

FIGURE 6 | The effects of the alternate wetting and drying irrigation (AWD) on CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$) depending on the type of rice variety, rice growth cycle, N application, and biochar application. Explanation of the notations is the same as in Figure 2.

decreasing CH_4 emissions (Li et al. 2023; Ma et al. 2010). We found an overall reduction (243 observations) of 51.6% in CH_4 emissions caused by the AWD (Figure 1). In contrast, multiple drying (aeration) events in the AWD result in greater O_2 availability and pulsed activity of microorganisms, thereby promoting nitrification–denitrification mineralization and redox cycles, enhancing N_2O emissions (Butterbach-Bahl et al. 2013; Kritee et al. 2018). In addition, most N in CF is lost as N_2 than N_2O (Linquist et al. 2015). As a result, the AWD increased N_2O emissions by an average of 44.0%, compared to

TABLE 2 | The effects of mild alternate wetting and drying irrigation (AWD) on CH_4 and N_2O emissions and global warming potential ($GWP_{CH_4+N_2O}$) relative to continuous flooding subjected to varying climate conditions, soil properties, and management practices.

		CH_4 emissions				N_2O emissions				$GWP_{CH_4+N_2O}$			
		Mean	95% CI			Mean	95% CI			Mean	95% CI		
Variable	**Category**	**effect (%)**	**Min**	**Max**	***p***	**effect (%)**	**Min**	**Max**	***p***	**effect (%)**	**Min**	**Max**	***p***
MAP (mm)	> 800	−47.7 a	−51.2	−44.3	**	32.1 b	18.9	50.9	*	−43.9 a	−49.0	−39.6	NS
	400–800	−59.5 b	−66.7	−51.5		93.6 a	66.4	130.5		−52.7 a	−60.4	−42.6	
MAT (°C)	< 20	−54.2 b	−60.1	−47.9	***	79.1 a	59.4	102.8	**	−44.9 a	−50.5	−38.6	NS
	20–25	−41.4 a	−47.4	−33.1		26.6 ab	11.7	81.5		−35.7 a	−47.1	−31.1	
	> 25	−54.8 b	−58.5	−50.7		21.9 b	4.3	44.3		−51.3 a	−55.5	−46.8	
Elevation (m)	≤ 20	−48.0 a	−51.9	−44.2	NS	25.5 b	13.7	42.8	***	−44.0 a	−50.5	−39.0	NS
	> 20	−51.8 a	−57.3	−46.4		82.4 a	57.8	112.8		−47.3 a	−52.4	−42.1	
Soil texture	Nonclay	−44.7 a	−51.1	−38.2	NS	69.6 a	50.0	92.3	**	−43.0 a	−48.5	−37.2	NS
	Clay	−53.6 a	−57.8	−50.4		23.2 b	10.2	43.7		−46.1 a	−53.5	−40.4	
Soil pH	< 6.5	−44.0 a	−48.1	−39.6	NS	11.8 b	−4.8	33.2	**	−52.8 b	−56.0	−49.4	***
	6.5–7.3	−50.8 a	−55.3	−46.4		62.4 a	39.4	96.9		−36.6 a	−42.8	−31.8	
	> 7.3	−54.6 a	−85.7	−39.7		26.9 ab	10.7	134.6		−37.0 ab	−65.0	−26.9	
Soil SOC ($g\,kg^{-1}$)	< 12	−30.8 a	−35.3	−25.8	**	28.9 a	0.72	60.6	NS	−30.4 a	−35.0	−25.5	NS
	12–18	−43.7 ab	−54.5	−30.5		92.3 a	28.0	196.1		−33.8 a	−45.9	−20.2	
	> 18	−56.1 b	−64.5	−46.9		40.2 a	30.5	50.7		−38.7 a	−47.5	−28.2	
Variety	Hybrid	−49.7 a	−56.3	−42.6	NS	70.2 a	20.3	138.5	NS	−45.3 a	−53.6	−36.3	NS
	Inbred	−52.3 a	−57.9	−48.1		28.6 a	17.6	50.1		−40.8 a	−49.6	−35.3	
Growth cycle	Early	−58.6 b	−63.2	−54.1	***	41.4 a	20.2	67.8	NS	−54.5 b	−58.3	−50.4	***
	Middle	−47.8 ab	−57.0	−37.6		38.1 a	24.4	52.3		−45.3 ab	−53.5	−35.7	
	Late	−39.6 a	−45.5	−33.3		80.3 a	43.0	130.8		−40.0 a	−45.9	−33.9	
N application ($kg\,ha^{-1}$)	< 60	−12.7 a	−18.2	−8.2	***	78.1 a	−16.7	275.3	NS	−34.5 a	−46.5	−25.1	NS
	60–120	−52.7 b	−56.4	−48.7		26.1 a	6.1	50.2		−50.0 a	−54.1	−45.5	
	> 120	−53.5 b	−58.9	−49.2		47.9 a	31.3	75.3		−41.9 a	−49.1	−33.7	
Biochar application ($t\,ha^{-1}$)	≤ 12	−48.4 a	−62.7	−26.9	NS	105.0 a	73.2	145.6	NS	−64.7 a	−72.5	−54.8	NS
	> 12	−63.2 a	−72.6	−48.6		139.5 a	94.7	202.6		−60.2 a	−70.0	−46.3	

Note: CI is the confidence interval. MAP and MAT are the mean annual precipitation and the mean annual temperature. SOC is the soil organic carbon content. Different letters for the same variable (95% CIs is nonoverlap) indicate significant differences between categories. *, **, and *** indicate significant level at $p < 0.05$, $p < 0.01$, and $p < 0.001$ for between-group heterogeneity (Q_B) of subgroups. NS is nonsignificant difference.

CF (Figure 1). Nevertheless, N_2O emissions generally account for a small proportion of the total greenhouse gas emissions (< 1 kg N_2O–C ha^{-1} $season^{-1}$ vs. 100 kg CH_4–C ha^{-1} $season^{-1}$) from rice systems, in which CH_4 emissions largely determine $GWP_{CH_4+N_2O}$, although there is a greater greenhouse warming potential (100 years) for N_2O than for CH_4 (Jiang et al. 2019; Linquist et al. 2012). The $GWP_{CH_4+N_2O}$ was overall reduced (184 observations) by 46.9% under AWD, compared to CF (Figure 1). Therefore, great efforts are needed to reduce CH_4 emissions to control $GWP_{CH_4+N_2O}$ in rice fields.

The degree of soil drying significantly altered the AWD effect on CH_4 emissions and $GWP_{CH_4+N_2O}$ but not on N_2O emissions. As expected, more reduction in CH_4 emissions and $GWP_{CH_4+N_2O}$ was observed under severe AWD (more drying days) than under mild AWD (Figure 2). However, mild or "safe" AWD may be much easier to be widely promoted as indicated by more studies focusing on mild AWD (Figure 2). This is because it can reduce water application by 23.4% and increase water productively by 25.9% without significant rice yield loss (Carrijo, Lundy, and Linquist 2017), thus it can be more easily accepted by farmers. This water management practice of mild or "safe" AWD has been a guideline in the office website of Rice Knowledge Bank of International Rice Research Institute (IRRI 2024). Hence, more efforts should be placed on mild AWD effect on decreasing greenhouse gas emissions and $GWP_{CH_4+N_2O}$, which also markedly reduced CH_4 emissions and $GWP_{CH_4+N_2O}$ by an average of 49.4% and 45.2%, respectively, despite overall increased N_2O emissions by 40.4% (Figure 2).

The number of drying events, affecting the total drying days, depends on the soil drying level, as well as the precipitation during the growth period of rice. Unsurprisingly, greater reduction of CH_4 emissions under AWD was observed with a greater number of drying events. Somewhat surprising that the number of drying events did not alter the AWD effect on $GWP_{CH_4+N_2O}$. This may be due to the wide variation in increased N_2O emissions reported in the literature, particularly for less than three drying events (CI: 1.0%–59.9%) (Figure 2).

4.2 | Climate Conditions, Soil Properties, and Management Practices Modify (Mild) AWD Effect

4.2.1 | MAP or MAT Can be Used to Accurately Assess the Changes of Global or National Non-CO_2 Greenhouse Gas Emissions Under Mild AWD

Rice is rarely planted in semiarid regions due to conflict between scarce water source and huge water input of rice, despite limited data have been reported in these regions (Figure 3). In subhumid regions (MAP of 400–800 mm), greater reduction in CH_4 emissions and increase in N_2O emissions under mild AWD were observed compared to humid regions (MAP of > 800 mm) (Table 2). This may be due to the higher number of drying events in subhumid regions (6.6 times) as a result of less precipitation in rice growth season when compared to humid regions (4.0 times).

Similarly, MAT also significantly altered the reduction of CH_4 emissions and increment of N_2O emissions under mild AWD. This is because temperature is a crucial factor influencing microbial activity for CH_4 and N_2O production (Figure 7), where optimal temperatures generally increase the rate of enzymatic

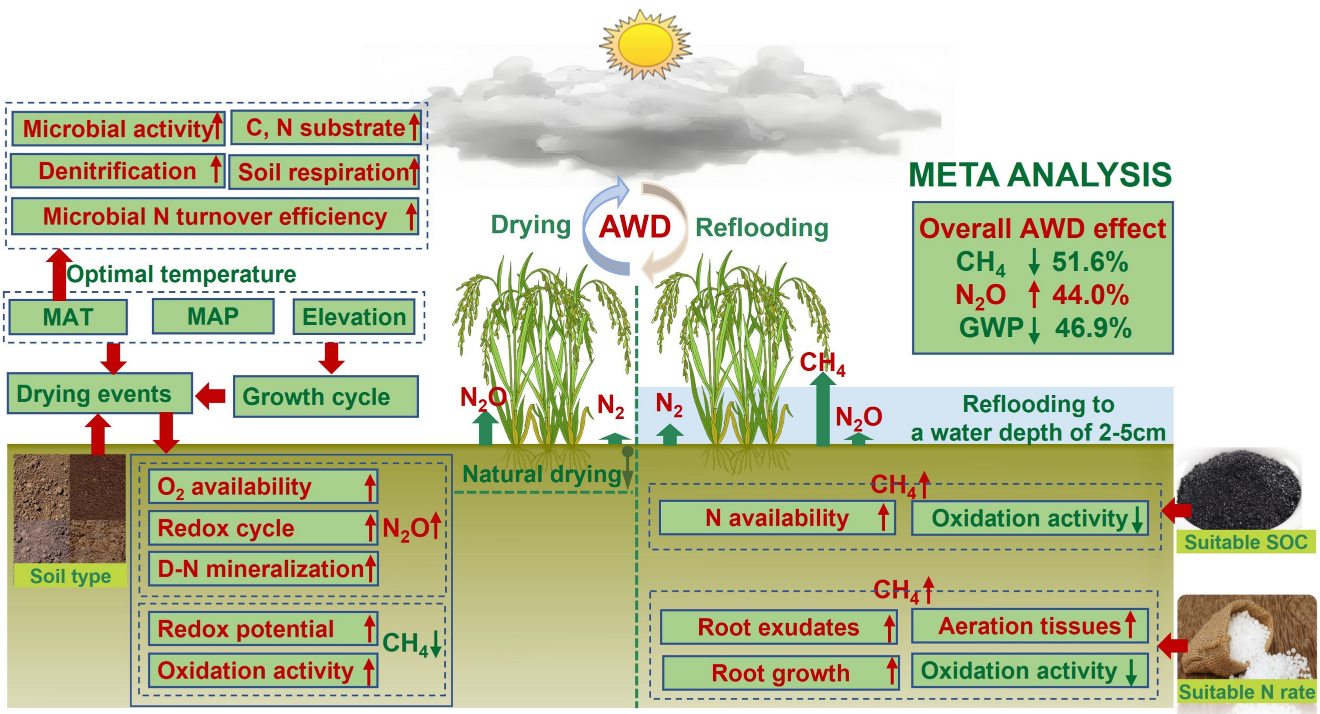

FIGURE 7 | Summary for effects of the alternate wetting and drying irrigation (AWD) on CH_4 and N_2O emissions as affected by climate conditions, soil properties, and management practices. SOC is the soil organic carbon content. MAP is the mean annual precipitation. MAT is the mean annual temperature. D–N is the nitrification–denitrification. Thin upper and lower arrows show increment and decline.

reactions, thereby enhancing microbial activity (Alster et al. 2020; Schipper et al. 2014). Additionally, denitrification is extremely sensitive to rising temperatures (Butterbach-Bahl et al. 2013; Yvon-Durocher et al. 2014). Moreover, temperature can affect microbial N turnover efficiency and availability of soil C and N substrate (Zhou et al. 2017). It also impacts microbial decomposition of organic matter and soil respiration, which affects soil oxygen concentrations (Butterbach-Bahl et al. 2013).

MAP and MAT are important indicators of regional climate conditions, easily accessible, and generally regarded as stable metrics for specific regions. Therefore, accurately assessing the changes of CH_4 and N_2O emissions under mild AWD on a global or national scale requires considering their impacts, which altered the response of mild AWD effect on both CH_4 and N_2O emissions.

4.2.2 | Impact of Soil Texture and pH on (Mild) AWD Effect

Soil texture plays a crucial role in regulating greenhouse gas emissions (Gu et al. 2013). This study also altered (mild) AWD effect on N_2O emissions, with less increment of N_2O emissions in clay soils than in nonclay soils (Figure 4 and Table 2). Fine-textured clay soil has a small soil size and soil pores, thereby tightly holding soil water. This may result in requiring more drying days to reach the critical soil drying level under AWD than in nonclay soils. While this extended drying period may favor the reduction of CH_4 emissions, somewhat surprising that soil texture did not impact the effect of AWD on CH_4 emissions in this study. Although this process may be also beneficial for emitting more N_2O under AWD, tight retention of soil water in the clay soils leads to low availability of soil O_2 (Zhou et al. 2017), thereby reducing N_2O emissions. In addition, a great cation exchange capacity in the clay soils can increase NH_4^+ adsorption through clay particles, therefore reducing soil NH_4^+ availability and inhibiting nitrification and denitrification, further decreasing N_2O emissions (Jarecki et al. 2008).

Regarding soil pH, an old meta-study (not accounting for AWD effect) showed maximum CH_4 emissions in soils with a pH of 5.0–5.5 than in soils with other pH levels (Yan et al. 2005). However, our meta-analysis shows that pH did not alter the impact of (mild) AWD on CH_4 emissions (Figure 4 and Table 2). Nevertheless, soil pH markedly modified the effect of (mild) AWD on N_2O and $GWP_{CH_4+N_2O}$, with more increment of N_2O and less reduction of $GWP_{CH_4+N_2O}$ in neutral pH (6.5–7.3) soil than in acidic (< 6.5) soil. Another study reported that N_2O emission under aerobic conditions was minimum between soil pH of 6.0 and 7.0 and rapidly reached its maximum (3.5 folds increase) at a soil pH of 8.0, where its rate is linearly related to the ammonium oxidation rate (Law, Lant, and Yuan 2011). Interestingly, a negative linear correlation was also found between the reduction of $GWP_{CH_4+N_2O}$ and pH (Figure 5c), which may serve as an indicator for assessing the impact of (mild) AWD effect on $GWP_{CH_4+N_2O}$. The more pronounced reduction of $GWP_{CH_4+N_2O}$ under (mild) AWD in acidic soils was mainly due to less increment of N_2O (Figure 4 and Table 2).

4.2.3 | Increasing SOC is a Potential Option to Further Reduce CH_4 Emissions Under (Mild) AWD

The SOC is a key indicator of soil fertilization (Liu et al. 2019), where there is also a positive correlation between the SOC and soil N mineralization of aerobic rice but not of anaerobic rice, showing that great N availability is likely in high SOC soils under AWD (Carrijo, Lundy, and Linquist 2017). While increases in SOC are likely to result in more N_2O emissions (Guenet et al. 2021; Lugato et al. 2018), we found that SOC did not significantly impact (mid) AWD effect on N_2O emissions in this study (Figure 4, Table 2), nor did it influence the effect of manure application on N_2O emissions relative to synthetic N application (Zhou et al. 2017). However, SOC is the substrate for CH_4 generation, and high SOC may be beneficial for reducing soil redox potential, therefore there exists a positive nonlinear relationship between CH_4 emissions and SOC (Yan et al. 2005). We also found that the reduction of CH_4 under AWD was greater when SOC was $> 18\,g\,kg^{-1}$ than $< 12\,g\,kg^{-1}$ (Figure 4, Table 2), and it was also linearly increased as SOC increased (Figure 5a). This provides an opportunity to further reduce CH_4 emissions under AWD by increasing the SOC because SOC is highly varied. For instance, SOC changed from 1.3 to $74.4\,g\,kg^{-1}$ (mean = 12.7) in the 0- to 20-cm soil layer of Chinese cropland in 2007–2008 (Yan et al. 2011), from 2.6 to $32.1\,g\,kg^{-1}$ (mean = 15.4, standard deviation = 5.1) in paddy rice soils of China (Tian et al. 2015), and from 0.34 to $31.2\,g\,kg^{-1}$ (mean < 10) in the 0- to 40-cm soil layer of paddy rice in most areas of northeast Thailand (Arunrat et al. 2020). Application of organic fertilizer, straw returning to field, mineral N, phosphorus, and potassium may be suitable strategies to increase SOC. A meta-analysis showed that the greatest increment in SOC in China occurred when mineral nitrogen, phosphorus, and potassium were applied in combination with manure ($0.401\,g\,kg^{-1}\,year^{-1}$), followed by the application of only manure ($0.36\,g\,kg^{-1}\,year^{-1}$), while the application of only mineral N caused the lowest increment ($0.046\,g\,kg^{-1}\,year^{-1}$) (Tian et al. 2015). All in all, increasing SOC should be a target for decreasing CH_4 emissions. Important to note is that increasing SOC can also offer multiple cobenefits such as in the adaptation of agroecosystems to air pollution and climate change (Agathokleous et al. 2023).

4.2.4 | Controlling N Application Level is Not a Strategy to Further Reduce Greenhouse Gas Emissions Under (Mild) AWD

Reasonable N application can increase the NH_4^+ concentrations in soil, restricting microbial CH_4 oxidation (Li et al. 2024). In addition, it promotes the growth of roots and aboveground biomass, promoting root exudates for methanogenesis and the development of aeration tissues of gas transport (Conrad 2007), thereby resulting in more CH_4 emissions (Figure 7). Therefore, the reduction of CH_4 emissions under (mild) AWD was significantly greater at $> 60\,kg\,N\,ha^{-1}$ than at $< 60\,kg\,N\,ha^{-1}$ (Figures 6 and S5), and it linearly increased as N application increased (Figure 5b). However, there was no significant difference in the reduction of CH_4 emissions under (mild) AWD between 60 and $120\,kg\,N\,ha^{-1}$ and $> 120\,kg\,N\,ha^{-1}$, neither was it for $GWP_{CH_4+N_2O}$ (Figure 6, and Table 2) (also for the relation between reduction of CH_4 emissions and application of $> 60\,kg\,N\,ha^{-1}$ (Figure S5)). These results indicate the inability to further reduce CH_4 emissions under (mild) AWD by controlling N application level, since N application normally exceeds $60\,kg\,N\,ha^{-1}$ in the agronomical practice.

Although some studies indicated that biochar application can reduce CH_4 and N_2O emissions, as well as $GWP_{CH_4+N_2O}$ (Liu et al. 2023; Sriphirom et al. 2020), our findings suggest that it does not further reduce CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ under (mild) AWD (Figure 6 and Table 2). It is important to note that, due to the limited number of observations, the impact of biochar application on CH_4 and N_2O emissions under (mild) AWD requires further investigation.

5 | Conclusions

In this study, a meta-analysis showed that compared to continuous flood irrigation, the AWD can lead to a great reduction in CH_4 emissions (−51.6%) as opposed to increment in N_2O emissions (44.0%), resulting in a 46.9% reduction of $GWP_{CH_4+N_2O}$. We also identified that the AWD effect on CH_4 and N_2O emissions and $GWP_{CH_4+N_2O}$ was altered by some climate conditions, soil properties, and management practices. The results lead to the conclusion that MAP or MAT can be used to accurately assess the changes of global or national CH_4 and N_2O emissions under mild AWD. Additionally, soil pH may be employed as an indicator for assessing the impact of (mild) AWD effect on $GWP_{CH_4+N_2O}$. Moreover, the results illuminate a novel conclusion, that increasing SOC, instead of controlling N application, is a potential option to further reduce CH_4 emissions under (mild) AWD. These findings can provide data support for the accurate assessment of non-CO_2 greenhouse gas emissions reduction in rice fields on a global or a national scale under large-scale promotion of AWD in the future.

Author Contributions

Chenxi Zhao: data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Rangjian Qiu:** conceptualization, formal analysis, funding acquisition, supervision, visualization, writing – original draft, writing – review and editing. **Tao Zhang:** formal analysis, writing – review and editing. **Yufeng Luo:** conceptualization, writing – review and editing. **Evgenios Agathokleous:** validation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.14010496.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.