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Effect of water-saving technologies on nitrogen losses in rice fields: A meta-analysis

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ABSTRACT

Nitrogen losses from intensified agricultural lands such as rice fields have posed severe water pollution. Thus, several water-saving technologies (WST) such as alternate wet and dry (AWD), controlled irrigation (CI), and shallow intermittent irrigation (SII) have been adopted to reduce nitrogen loss from rice fields. Research on WST effects has shown varied impacts on nitrogen losses, with limited consensus on the most efficient WST type or the most affected nitrogen component. This study synthesizes the current knowledge of the impact of WST on nitrogen loss in rice fields using meta-analysis. A total of 182 observations from 38 peer-reviewed studies were analyzed using meta-analytic and meta-CART models, with WST as treatment, and continuous flooding (CF) irrigation as control. The results revealed that nitrogen losses were significantly lower under WST compared to CF irrigation ($p < 0.001$), with reductions of 35 %, 28.2 %, and 25.2 % in ammonia (NH_4^+-N), nitrate (NO_3^--N) and total nitrogen (TN) leaching, respectively. However, ammonia (NH_3) volatilization showed no significant difference between WST and CF irrigation, with response ratios close to zero. In contrast, nitrous oxide (N_2O) emissions were significantly higher under WST, particularly under AWD (RR = 0.37). NO_3^--N leaching was reduced 2.2 times more effectively with the application of controlled release fertilizer (CRF) under WST compared to urea (46 %N) (53.2 % vs. 24.3 %). Applying biochar combined with urea reduced nitrogen leaching by 42.7 %, outperforming urea alone but remaining less effective than CRF. Urea application increased N_2O emissions by 3.0 %, while CRF reduced them by 3.1 % under WST compared to CF irrigation. At higher nitrogen application rates (>225 kg N ha^{-1}), WST led to greater reductions in nitrogen leaching (1.9 times for NO_3^--N and 1.6 times for TN) compared to CF irrigation. Additionally, NO_3^--N leaching was 2.19 times effectively reduced in rice fields with higher seedling density (26–45 plants m^{-2}) compared to lower density (10–25 plants m^{-2}) under WST. The meta-analysis further showed no significant effect of WST on rice grain yield compared to CF irrigation. This study provides a quantitative synthesis of the effects of WST on nitrogen losses in rice fields, highlighting their variable effectiveness depending on WST type, nitrogen source, application rate, and seedling density. Future research should address the availability of CRF, explore alternatives for developing countries, and examine the relationship between water management, rice seedling density, and nitrogen losses.

1. Introduction

Rice is a fundamental staple and one of most important crops, supporting food security and national economic development (Huy et al., 2024; Muthayya et al., 2014; Sievers et al., 2024; Wang et al., 2024). Rice is cultivated in environments with high water potential, such as lowlands, wetlands, and various soil types, including saline, alkaline, and acid-sulphur soils (Bouman et al., 2007; Liu et al., 2018; Qiu et al., 2024). With the rapid growth of the world population, large wetland and lowland areas in Asia and Africa are being used for rice production to meet rising food demand (Balasubramanian et al., 2007; Muthayya et al., 2014; Yuan et al., 2024). This intensification of rice production poses significant environmental challenges despite its importance for food security (Silva et al., 2022).

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Farmers apply nitrogen fertilizers in paddy fields to increase yields (Albornoz, 2016; Wang et al., 2024; Zhang et al., 2018; Zhong et al., 2023). Nitrogen is an essential nutrient for plant growth and achieving higher yields (Zhang et al., 2015; Zhong et al., 2023). It is introduced into the soil through synthetic fertilizers, biological nitrogen fixation, and manure (Zhang et al., 2015). However, the most used form of nitrogen by farmers is synthetic nitrogen (Wang et al., 2024). Once applied in the farm, nitrogen undergoes transformation processes such as nitrification, which produces ammonium (NH_4^+-N) and nitrate (NO_3^--N) readily assimilable by plants, and denitrification, which transforms nitrate into nitrous oxide (N_2O) (Jansson and Persson, 1982). Despite its importance for plant growth, inappropriate nitrogen management, such as quantities exceeding crop needs or failing to synchronize application with plant demand, often leads to significant nitrogen losses (Ju et al., 2009; Zhao et al., 2012). Excess nitrogen that cannot be absorbed by plants or fixed in the soil tends to migrate into ground water or emitted into the atmosphere causing pollution and other detrimental environmental impacts (Akter et al., 2018; Xiao et al., 2019). Nitrogen is susceptible to losses through leaching, runoff, volatilization, and denitrification, which contribute to environmental pollution (Das et al., 2024; Fageria and Baligar, 2005; Prasad et al., 2024). The nitrogen pathways such as leaching and runoff involve nitrogen forms likeNO_3^--N, NH_4^+-N, and total nitrogen (TN) (Abid et al., 2024; Fan et al., 2018; Garnier et al., 2023). Volatilization and denitrification result in gaseous losses, notably as ammonia (NH_3) and nitrous oxide (N_2O) (Garnier et al., 2023; Shen et al., 2022; Zumft and Körner, 1997). These two processes are among the primary contributors to agricultural nitrogen losses to the atmosphere (Das et al., 2024; Thompson et al., 2019). Nitrogen losses via water pathways (e.g., leaching and runoff) or gaseous emissions are strongly influenced by the availability of water and nutrients (Akter et al., 2018; Belder et al., 2004; Gao et al., 2018; Xiao et al., 2014). Therefore, integrated water and nitrogen management are critical factors in mitigating nitrogen losses in rice fields (Araki et al., 2012; Chen et al., 2019; Li et al., 2016; Wang et al., 2014).

Water management significantly affects nitrogen losses in rice fields (Abid et al., 2022; Liu et al., 2018). Continuous flooding (CF), a conventional irrigation practice, maintains water levels between 50 and 100 mm above the field surface throughout the growing season (Liang et al., 2013). While CF irrigation is effective for weed control and sustaining productivity, it requires substantial water inputs due to considerable water losses through percolation and runoff (Belder et al., 2004; Gao et al., 2018; Liang et al., 2013; Sakurai, 2006; Seck et al., 2012; Tan et al., 2012). In fact, 25–85 % of the applied water in CF irrigation is lost depending on soil texture and crop management practices (Bouman et al., 2007). Moreover, CF irrigation could potentially increase the risk of water pollution, as agrochemicals are transported to surface and groundwater (Zhang et al., 2011; Zhao et al., 2012). Under these flooded conditions, only 10–35 % of the applied nitrogen is retained in the soil for plant uptake. The remainder is lost to the environment through water or gaseous pathways (Asif et al., 2024; Liang et al., 2007). These nitrogen losses not only reduce nitrogen use efficiency but also contribute to diffuse pollution and eutrophication in aquatic ecosystems (Akter et al., 2018). Therefore, optimizing the water and nitrogen fertilizers uses is essential to improve sustainable rice productivity (Yao et al., 2024).

In recent years, water-saving technologies (WST) such as alternate wetting and drying (AWD), controlled irrigation (CI), and shallow intermittent irrigation (SII) have been developed to enhance water use efficiency and potentially reduce environmental impacts in rice cultivation (Gao et al., 2018; Hao et al., 2022; Tan et al., 2012; Wu et al., 2022; Xiao et al., 2019; Yang et al., 2013; Zhuang et al., 2019). These practices alternate between flooded and non-flooded conditions to minimize water losses and potentially mitigate nitrogen losses (Carrijo et al., 2017; Zhuang et al., 2019). AWD involves initial flooding (5–70 mm) and reflooding when the soil surface becomes dry (Ishfaq et al., 2020; Liang et al., 2013). The threshold for reflooding can be based on soil water potential (SWP), field water level below the soil (FWL), visible soil cracking, or plant water stress indicators (Chu et al., 2014; Li and Barker, 2004; Peng and Bouman, 2007). AWD is classified into safe or mild-AWD (SWP≥-20 KPa or FWL≤150 mm) and severe-AWD (SWP<-20KPa) (Carrijo et al., 2017). CI manages flooded and non-flooded conditions based on the soil's saturated water content (θs) and the rice growth stage. A thin water layer of 5–25 mm is maintained during the re-greening stage. Irrigation is applied at soil water content thresholds of 0.65θs during tillering, 0.75θs at jointing and booting, 0.8θs at heading and flowering, and 0.7θs at the milk stage (Chen et al., 2019; Wang and Huang, 2021; Yu et al., 2021). SII maintains the soil water content close to saturation state. At re-greening stage, water levels are kept at 40–50 mm for 10 days (Won et al., 2015). Once the water disappears, irrigation is reapplied to a depth of 40 mm, with a midseason drainage period of 10 days during maximum tillering (Chen et al., 2021; Wang and Huang, 2021; Won et al., 2015). Several studies suggested that WST can reduce water use by 16–53 % (Chu et al., 2014; Yao et al., 2012; Ye et al., 2013) and nitrogen leaching by limiting water percolation (Cui et al., 2004; Peng et al., 2014; S.-Z. Peng et al., 2011; Zhuang et al., 2019).

Although WST improves water use efficiency in rice fields, their effectiveness in reducing nitrogen losses remains unclear (Adhya et al., 2014; Chu et al., 2014; Liu et al., 2018). These technologies affect soil key processes, including aeration, microbial activity, nitrogen transformation and root growth, compared to CF irrigation (Akter et al., 2018; Tan et al., 2015; Yoshinaga et al., 2004). The variation in WST is often attributed to regional heterogeneities in climatic conditions, cultivation practices, and cropping systems which contribute to significant spatial and temporal differences in nitrogen losses (Fu et al., 2021; Hou et al., 2016). For instance, some studies highlighted the potential of WST as a promising strategy to address the interlinked challenges for sustained rice production while limiting nitrogen losses (Shihong et al., 2012; Xu et al., 2012). Conversely, other studies reported higher NH_3 volatilization and N_2O emissions under WST compared to CF (Cheng et al., 2022; Echegaray-Cabrera et al., 2024; Zhao et al., 2010). Additionally, studies showed conflicting results regarding nitrogen concentration in drained water. While TN and NH_4^+-N concentrations are often higher in WST fields during most of the rice growth stages (Gordon et al., 2008; Cheng-xin Zheng et al., 2019; Chengxin Zheng et al., 2019), other studies reported reductions in nitrogen losses under WST (Dong et al., 2012; S.-Z. Peng et al., 2011; Qi et al., 2020). Moreover, there are conflicts on the most affected nitrogen form by WST (S.-Z. Peng et al., 2011; Tan et al., 2012; Chengxin Zheng et al., 2019). Some studies identified NH_4^+-N as the predominant form in percolation water (Gao et al., 2016; S. Peng et al., 2011), whereas others reported NO_3^--N as the main form (Zhao et al., 2009). These disparities support the need for a comprehensive quantitative evaluation to synthesize the actual knowledge on the effects of WST on nitrogen losses. Poor water management practices not only lead to economic losses for farmers but also conduct to significant environmental issues. Despite numerous site-specific experimental studies, there is a lack of quantitative syntheses assessing the overall effect of WST in mitigating nitrogen losses.

The present study uses meta-analysis to synthesize the effects of WST on nitrogen losses and rice grain yield. It first (i) evaluates the effect of WST on nitrogen leaching (NO_3^--N, NH_4^+-N, and TN); then (ii) assesses the potential of WST in reducing nitrogen gaseous losses (NH_3 and N_2O); (iii) analyzes the effect of WST on rice grain yield; and (iv) examines the influence of fertilization, rice seedling density, soil properties, and climatic conditions on the effect of WST on nitrogen losses. The findings will provide insights on the optimizing of water and nutrient management strategies in rice systems, promoting sustainable practices that can balance productivity and protect the environment.

2. Materials and methods

2.1. Selection of studies

The articles were searched in Scopus™ and Web of knowledge™ databases without restrictions on the years of publication or geographic location. Meta-analysis articles were excluded from the search results. Specific keywords were used across four search fields: (1) (nitrogen OR nitrate OR ammonia OR (nitrous AND oxide)) AND (loss* OR leach* OR runoff OR seep* OR emission OR volatilization); (2) (water AND management) OR (water AND saving); (3) (paddy AND field) OR (lowland) OR (wetland) OR (inland valley) OR (valley*); and (4) (rice). Initially, 921 articles were identified. After screening titles, abstracts, and full texts, 38 articles containing 182 observations met the inclusion criteria. The screening criteria required studies conducted in rice fields that addressed the loss of at least one nitrogen component (NO_3^--N, NH_4^+-N, TN, NH_3, or N_2O). The studies also had to involve at least one WST such as AWD, CI, or SII, with CF irrigation as a comparison treatment.

2.2. Variables and data extraction

The response variables in this meta-analysis included NO_3^--N, NH_4^+-N, TN leaching, NH_3 volatilization, N_2O emission, and rice grain yield. The principal explanatory variable was WST as treatments, with CF irrigation as control. Additional moderator variables potentially influencing the effects of WST on nitrogen losses were also considered. These included fertilization practices, such as the nitrogen fertilizer source, amount, frequency of application, and method of application, along with rice seedling density, soil properties, and the Standardized Precipitation Evapotranspiration Index (SPEI). Some of these variables were grouped into classes of values based on percentiles to facilitate analysis. Soil type and texture data were obtained directly from articles where available or extracted from the USDA Soil Texture Classification Database at a depth of 10 cm with a resolution of 250 m (Hengl, 2018). SPEI data were directly extracted from the generic Spanish National Research Council (CSIC) database, which bases SPEI on the FAO-56 Penman-Monteith estimation of potential evapotranspiration.

Numerical data were extracted from the methodology and results sections, as well as from tables and figures within the articles, using Engauge WebPlotDigitizer Version 4.6. The outcomes of the meta-analysis could be significantly influenced by the selected statistical values used to compute effect size metrics. Key values include the mean, standard deviation, or variance, and the number of replications (Lajeunesse, 2011; Viechtbauer, 2010). In cases where standard deviations and variances were not explicitly provided in the study, an imputation approach was employed to estimate these values following formula (1). This method estimates missing standard deviations using the mean and standard deviations from all other studies with complete information (Lajeunesse, 2013; Lipsey and Wilson, 2001; Spooner et al., 2002; Wiebe et al., 2006).

$$\widetilde{SD_j} = \overline{X}_j \left(\frac{\sum_i^k SD_i}{\sum_i^k \overline{X}_i} \right) \tag{1}$$

where: SD_j represents the missing standard deviation of a given study; X_j the observed mean of the study with the missing standard deviation; SD_i and X_i respectively stand for the standard deviations and mean values derived from all studies with complete information.

2.3. Statistical models

2.3.1. Effect size and variance

The effect size of NO_3^--N, NH_4^+-N, TN leaching, NH_3 volatilization, N_2O emission, and rice grain yield was estimated using the log response ratio (RR). RR represents the log ratio of the given response variable in the WST treatment over to the control CF irrigation. This approach to effect size is supported by previous studies (Friedrich et al., 2008; Hedges et al., 1999; Lajeunesse, 2011) and facilitates the comparison of treatment effects across different studies included in the meta-analysis.

The RR was calculated using formula (2):

$$RR = \log\left(\frac{\overline{X}_t}{\overline{X}_c}\right) \tag{2}$$

where X_t and X_c are the means of a given response variable in WST and CF, respectively. A null effect size (RR = 0) suggests that the average outcome of nitrogen losses or rice grain yield is similar between the WST and CF irrigation. A negative effect size (RR < 0) indicates a reduction in nitrogen losses or rice grain yield due to the application of WST, whereas a positive effect size (RR > 0) indicates an increase in nitrogen losses or rice grain yield due to the application of WST.

The sampling variance σ^2 (*RR*) was calculated using the standard deviations, the number of replicates, and the means of each group, as described Benítez-López et al. (2017) and Cooper et al. (2009), following formula (3):

$$\sigma^2(ES) = \frac{SD_t^2}{N_t \overline{X}_t^{\,2}} + \frac{SD_c^2}{N_c \overline{X}_c^{\,2}} \tag{3}$$

where SD_t and SD_c denote the standard deviations of the means X_t and X_c, respectively; N_t and N_c represent the number of replicates for treatments and control, respectively.

2.3.2. Random effects meta-analysis and forest plots

This study uses random effects meta-analysis to combine effect sizes from numerous studies and estimate the pooled effect size and variance (Riley et al., 2011) of nitrogen losses and grain yield, under WST, integrating fertilization practices, rice seedling density, soil properties, and SPEI. A random effects model was chosen because the variance between studies was statistically significant. Heterogeneity was quantified using the p-value from the heterogeneity test (Q) and the statistical index I^2. A p-value less than α (α = 0.05) indicated significant heterogeneity among studies or groups. The I^2 value estimates the proportion of total variability in observed effect sizes attributable to heterogeneity among the true effects. A low I^2 value indicates minimal heterogeneity, while a value exceeding 50 suggests significant heterogeneity (López-López et al., 2013; Raudenbush, 2009; Viechtbauer, 2010).

To synthesize the outcomes of the pooled studies, forest plots were constructed. Forest plots of sub-meta-analysis were also constructed for each level of explanatory variables (WST technique, fertilization practice, rice seedling density, etc.). The plots illustrated each effect size with a diamond, where the center represented the estimate, and the bounds indicated the confidence interval. the size of the diamonds was determined by the square root of the model weights, ensuring their width was proportional to the weights and reflected the precision (i.e., inverse standard errors) of the estimate. Therefore, more precise estimates appeared more prominently in the plot (Viechtbauer, 2010). The vertical line (at zero) represents the line of no-effect, where the effect size of WST applied treatments equals that of the CF treatments.

2.3.3. Meta-CART analysis

Meta-CART analysis was used to explain the substantial heterogeneity across studies. Numerous factors and their interactions, such as fertilization practices, rice seedling density, soil properties, and SPEI, can influence the effects of WST on nitrogen losses and rice grain yield. Meta-CART analysis explored these combinations and provided a nuanced understanding of the heterogeneity in effect sizes under WST. This approach produced a tree model where terminal nodes represented distinct subgroups, and the splitting variables acted as influential factors (Bull et al., 2018; O'Brien et al., 2015; van Genugten et al., 2016). The model's graphical representation included solid lines showing the range of effect sizes for all included studies. Diamonds between these lines depicted the 95 % confidence intervals of the summary effect sizes (Li et al., 2020). The random-effects (RE) meta-CART was computed using the "metacart" package in R. This analytical approach identified and characterized subgroups, providing estimates of summary effect sizes and their corresponding confidence intervals within these subgroups.

2.4. Quality assessment

The dataset of this meta-analysis was obtained from articles published in scientific journals on agronomy, agriculture, and environmental science in Scopus™ and Web of Knowledge™ databases (view supplementary data). Publication bias was analyzed using funnel plots and Egger's asymmetry test (Mavridis and Salanti, 2014; Ouedraogo et al., 2020). The results of this asymmetry test for each response variable are presented in Table 1, and were found to be non-significant, suggesting the absence of bias. Finally, a sensitivity analysis was performed using the leave-one-out method for each response variable model.

3. Results

3.1. Response of nitrogen losses to water-saving technologies

Nitrogen losses including NO_3^--N, NH_4^+-N, TN leaching, NH_3 volatilization and N_2O emission were evaluated under three WST (AWD, CI and SII) as treatments, with continuous flooding (CF) irrigation as control. For all nitrogen losses components, the Q-statistic indicated substantial heterogeneity between data points from the collected articles (Q > 0, p-values < 0.0001, $I^2 > 75$ %), supporting the use of the random effects model (Table 1). NO_3^--N, NH_4^+-N, and TN leaching were lower under WST compared to CF, with estimated summary effect sizes of −0.33, −0.43 and −0.29 (p-values<0.0001), respectively. In contrast, NH_3 volatilization (RR = −0.02, p-value=0.01) was similar under WST compared to CF, while the N_2O emission (RR=0.17, p-value=0.001) was higher under WST applied treatments compared to CF irrigation (Fig. 1).

NO_3-N leaching decreased by 27.7 %, 30.3 %, and 20.6 % under AWD, CI, and SII, respectively, compared to CF irrigation (Fig. 1A). For NH_4^+-N leaching, AWD, and CI reduced losses by 49.3 % and 45.7 %, respectively, compared to CF, while SII reduced NH_4^+-N leaching by 11.3 % (Fig. 1B). However, AWD significantly increased N_2O emissions by 44.8 % (RR = 0.37, p-value < 0.0001) compared to CF, while CI and SII had no significant effect on this emission compared to CF (Fig. 1E).

3.2. Response of rice grain yield to water-saving technologies

A total of 137 observations on rice grain yield were collected from 38 studies. The heterogeneity test showed significant variation between the outcomes of the collected articles (Q > 0, p-value < 0.0001, I^2 = 78.72 %). The estimated summary effect size was 0.003 (p-value < 0.0001), indicating that rice grain yield was not affected under WST compared to CF irrigation (Fig. 1F).

Table 1
Result of Egger's asymmetry test and Q-statistic test.

Response variables	Egger's asymmetry test			Heterogeneity test (Q-statistic)		
	df	Z-value	p-value	Q value	p-value	I^2 (%)
NO_3^--N leaching	64	0.19	0.85	> 0	< 0.0001	85.48
NH_4^+-N leaching	53	−0.51	0.6	> 0	< 0.0001	91.97
TN leaching	59	−0.57	0.49	> 0	< 0.0001	95.36
NH_3 volatilization	69	0.13	0.89	> 0	< 0.0001	78.72
N_2O emission	37	1.2	0.08	> 0	< 0.0001	80.52
Rice Grain Yield	137	1.14	0.25	> 0	< 0.0001	75.23

To better understand the strong heterogeneity and assess the impact of moderating variables on the effectiveness of water-saving irrigation technologies in reducing nitrogen losses in rice fields. The random-effects model was applied to analyze the influence of various moderators on the response ratio.

3.3. Influence of fertilization practices, rice seedling density, soil characteristics and SPEI on nitrogen losses under WST

3.3.1. Influence of fertilizer application practices on nitrogen losses

The sources of nitrogen fertilizers were categorized as follows: Urea 46 % N (hereafter, Urea alone), Urea combined with compound fertilizers (N: P2O5:K2O) (hereafter, Urea + CF), Urea combined with zeolite (hereafter, Urea + Zeolite), Urea combined with biochar (hereafter, Urea + Biochar), Controlled Release Fertilizer (CRF), and no application of nitrogen fertilizer (hereafter, no N fert). These nitrogen fertilizer sources were used to estimate the summary effect sizes and to make forest plots (Fig. 2). NO_3^--N, NH_4^+-N, and TN leaching under WST were significantly lower with CRF (RR = −0.73; −0.51, and −0.39; p-value < 0.05), Urea + Biochar (RR = −0.56; −0.35, and −0.22; p-value < 0.05), and Urea + CF (RR = −0.37; −0.67, and −0.38) compared to CF irrigation. Conversely, nitrogen leaching showed only a slight decrease with Urea alone (RR = −0.28; −0.032, and −0.24; p-value < 0.05), particularly for NH_4^+-N under WST compared to CF irrigation. In contrast, NO_3^--N leaching increased with Urea + Zeolite (RR = 0.13; p-value = 0.001) under WST compared to CF irrigation. For nitrogen losses through gaseous, N_2O emissions were significantly higher with the application of Urea + CF (RR = 0.89; p-value = 0.009) and Urea + Zeolite (RR = 0.44; p-value < 0.0001) under WST compared to CF irrigation. In contrast, N_2O emissions were slightly lower with CRF (RR = −0.03; p-value = 0.04) under WST compared to CF irrigation. For NH_3 volatilization, no significant difference was observed between WST and CF irrigation.

Nitrogen was applied at rates of [0, 135],]135, 225], and]225, 500] kg N ha^{-1} . Nitrogen leaching decreased by 30.3 % and 18.2 % for NO_3^--N (RR = −0.36; p-value = 0.001) and TN (RR = −0.20; p-value = 0.0001), respectively, under WST compared to CF irrigation at the [0, 135] kg N ha^{-1} rate. This reduction was more substantial at 47.8 % and 32.2 % for NO_3^--N (RR = −0.65; p-value < 0.0001) and TN (RR = −0.39; p-value = 0.0001), respectively, under WST compared to CF irrigation when the nitrogen rate was]225, 500] kg N ha^{-1} . However, N_2O emissions showed no significant effect at the [0, 135] kg N ha^{-1} rate under WST compared to CF irrigation but exhibited significantly higher emissions at the]135, 225] kg N ha^{-1} rate (Fig. 3 C).

Two fertilizer application methods were collected from studies: broadcasting and site-specific or deep placement. NO_3^--N leaching (RR = −0.48, p-value < 0.0001) and N_2O emission (RR = −0.12; p-value = 0.01) were lower with site-specific placement under WST compared to CF irrigation. However, with the broadcast method, N_2O emissions were significantly higher (RR = 0.29; p-value < 0.0001) under WST compared to CF irrigation (Fig. 3). Generally, fertilizers were split-applied one, two and three times. For the one-time application, NO_3^--N (RR = −0.65; p-value=0.008) and TN (RR= −0.38; p-value=0.014) were significantly lower under WST compared to CF irrigation. Similarly, for the two-time application NO_3^--N (RR = −0.48; p-value=0.007) and TN (RR = −0.48; p-value<0.0001) leaching were significantly lower under WST compared to CF irrigation. However, for the three-time application, NO_3^--N and TN leaching were not significantly different between WST and CF irrigation (Fig. 3A,B).

3.3.2. Influence of rice seedling density on nitrogen losses

Rice seedling density was categorized into two classes: [10,25] plants m^{-2} and]25, 45] plants m^{-2}. NO_3^--N leaching was reduced by 35 % (RR = −0.43; p-value < 0.001) under WST in rice fields with high seedling density (]25,45] plants m^{-2}) compared to CF irrigation. In contrast, in fields with lower seedling density ([10,25] plants m^{-2}), NO_3^--

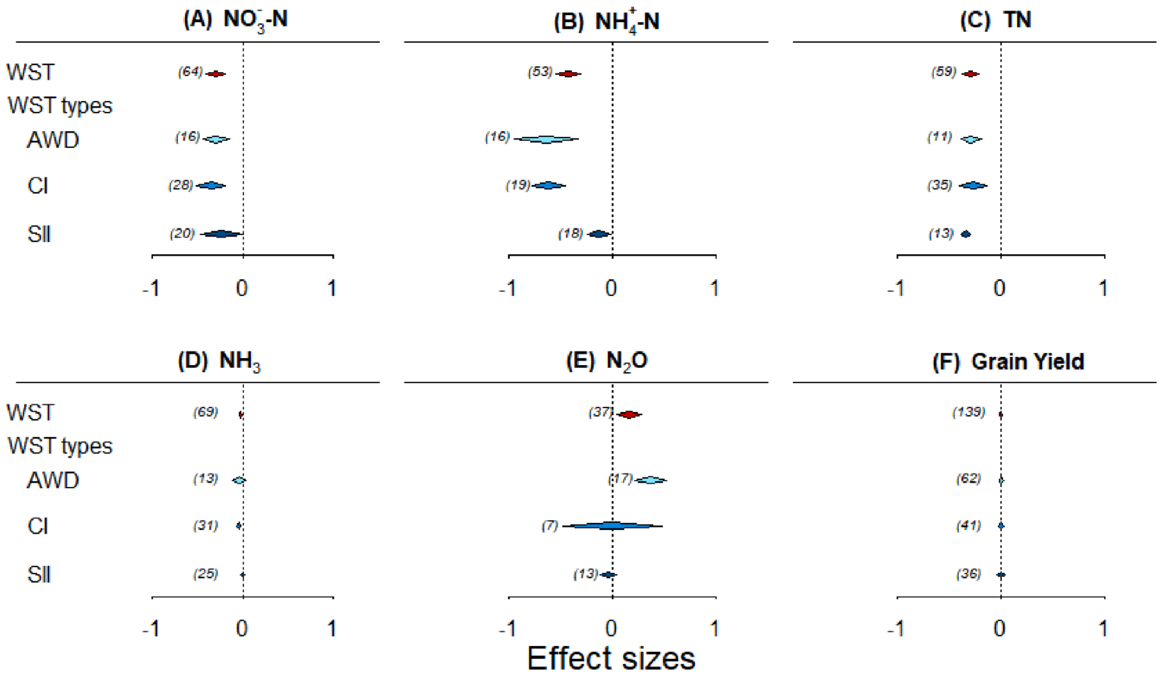

Fig. 1. Effect sizes of NO_3^--N, NH_4^+-N, TN leaching, NH_3 volatilization, N_2O emission and rice grain yield under WST (AWD, CI, SII) compared to CF irrigation in rice field. The number in parentheses () denotes the number of observations.

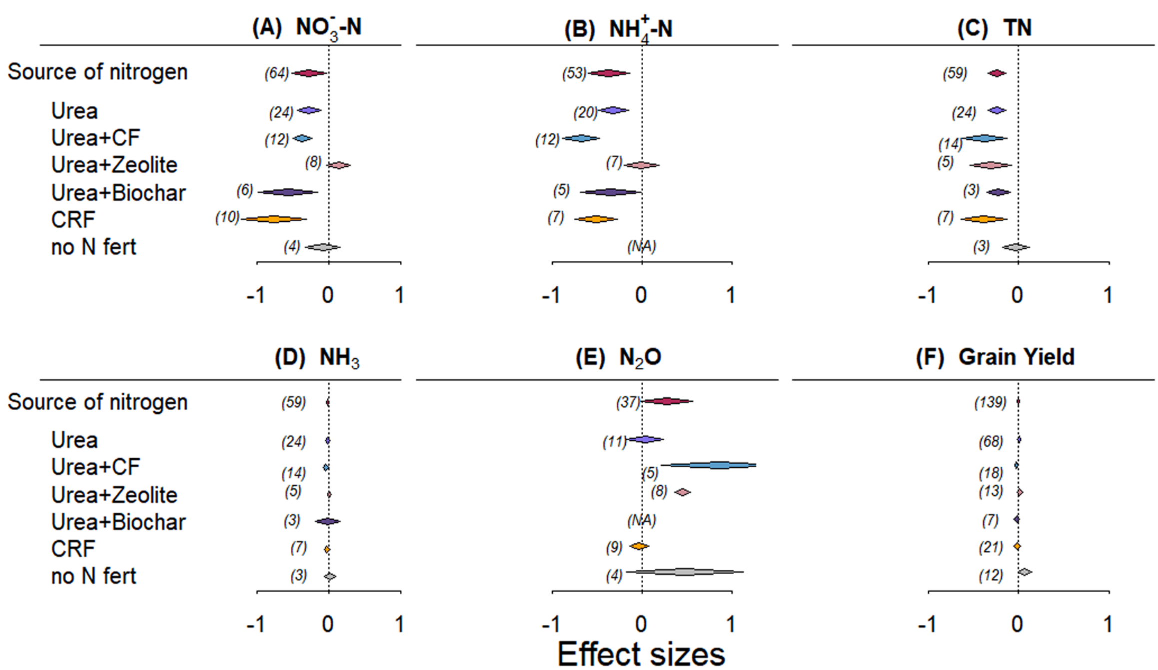

Fig. 2. Effect sizes of NO_3-N, NH_4-N, TN leaching, NH_3 volatilization, N_2O emission and rice grain yield under WST (AWD, CI, SII) influenced by source of nitrogen fertilizers.The number in parentheses () denotes the number of observations.

N leaching was reduced by 16.0 % (RR = −0.17; p-value = 0.03) under WST compared to CF irrigation (Fig. 3A, B). Consequently, WST was 2.19 times more effective in reducing NO_3^--N leaching in rice fields with high seedling density than in those with lower seedling density. Conversely, N_2O emissions were 52 % higher (RR = 0.42; p-value = 0.015) under WST in fields with high rice seedling density (]25,45] plants m^{-2}) compared to CF irrigation. In rice fields lower seedling density ([10,25] plants m^{-2}), N_2O emissions were still higher under WST, but by a smaller margin, being 21 % higher compared to CF irrigation (RR = 0.19; p-value=0.003) (Fig. 3C).

The random-effects meta-tree analysis, with 50 observations, examined the impact of various factors, including nitrogen fertilization source, nitrogen input, fertilizer splitting, rice seedling density, and soil texture, on TN leaching under WST compared to CF irrigation. Rice seedling density was identified as the key moderator influencing TN leaching (Fig. 4). The heterogeneity between-subgroups was significant (QB = 24.45, df = 1, p-value < 0.0001), with a low residual heterogeneity (τ^2 = 0.054). Two subgroups were identified: rice fields with high

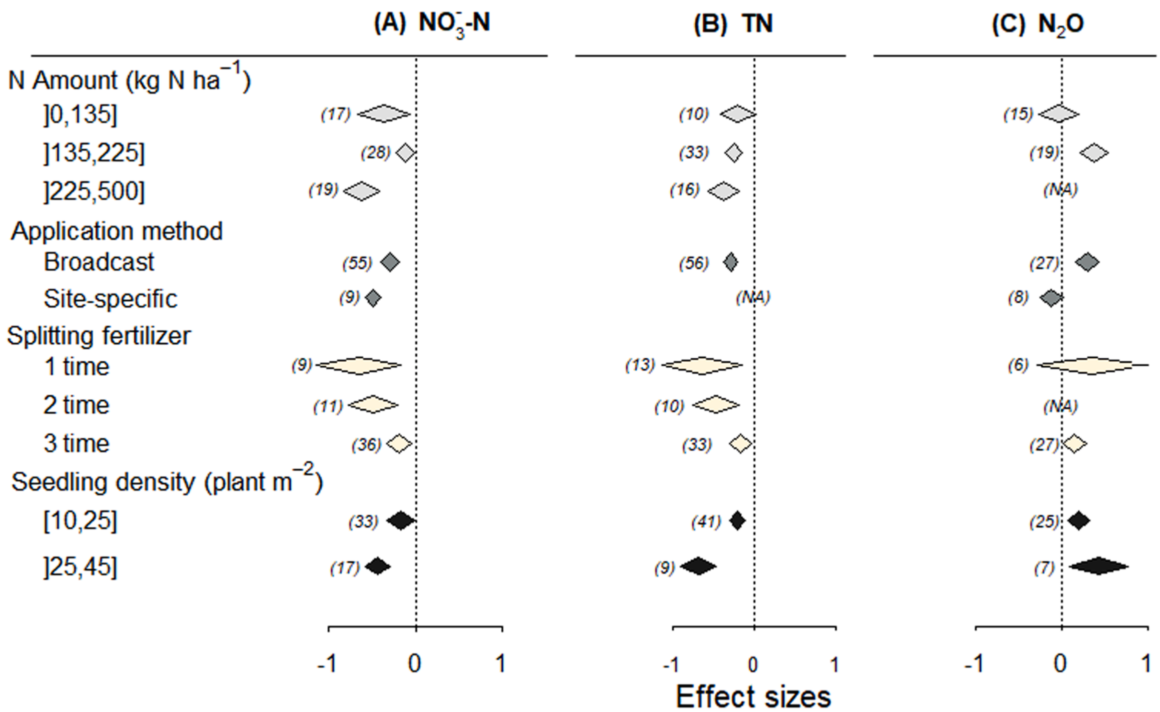

Fig. 3. Effect sizes of NO_3-N, TN leaching and N_2O emission under WST influenced by the among of nitrogen applied, method of application, number of split and rice seedling density. The number in parentheses () denotes the number of observations.

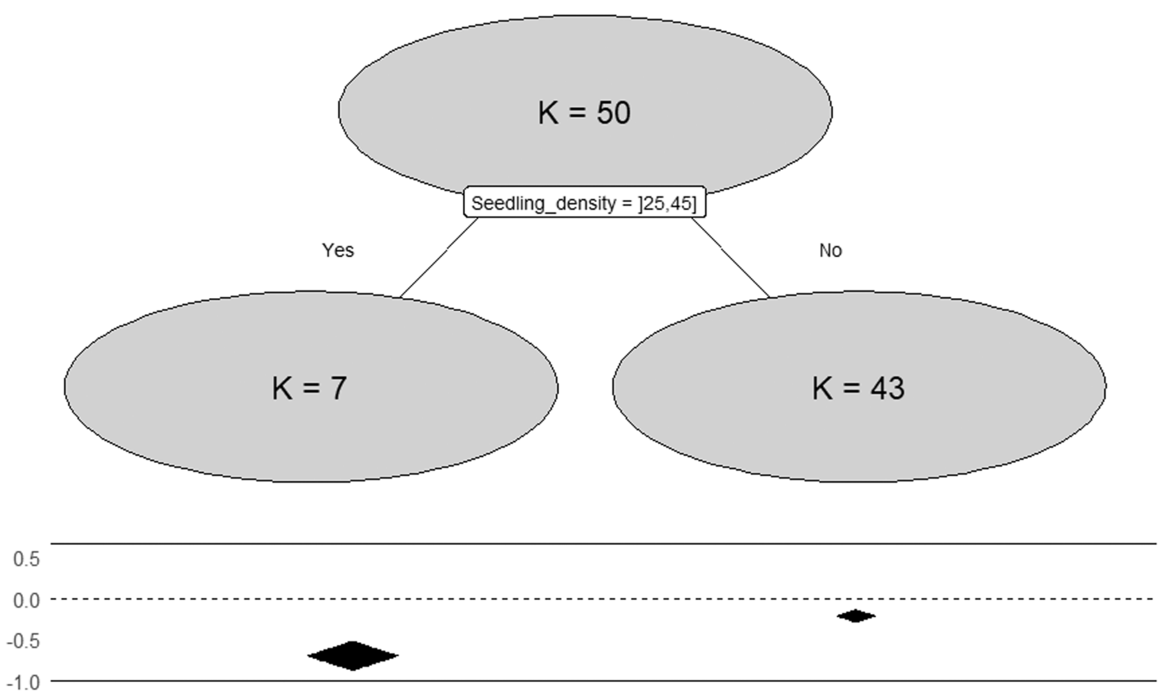

Fig. 4. Meta-CART analysis of the influence of moderator's variables on TN loss under WST compared to CF irrigation.Solid lines represent the range of effect sizes for all observations, while diamonds between the solid lines indicate the 95 % confidence intervals of the summary response ratios.

seedling density (]25, 45] plants m^{-2}) exhibited a stronger negative effect on TN leaching ($g = -0.70$; $p < 0.0001$), while fields with low seedling density ([10,25] plants m^{-2}) showed a moderate negative effect ($g = -0.21$; $p < 0.0001$). Both subgroups indicated significant reductions in TN leaching under WST compared to CF, with more pronounced effects observed at higher seedling densities (Fig. 4).

3.3.3. Influence of soil type, soil texture, and SPEI on nitrogen losses in rice fields

Four soil types (mollisols, inceptisols, alfisols, and entisols) and five soil textures (loam, clay, clay loam, sandy loam, and silty clay loam) were used to estimate the summary effect sizes and construct the forest plot (Fig. 5). TN leaching was significantly lower in WST compared to CF irrigation across all soil types, soil textures, and SPEI classes (p-value < 0.001; Fig. 5 A). However, the response ratio of TN loss varied

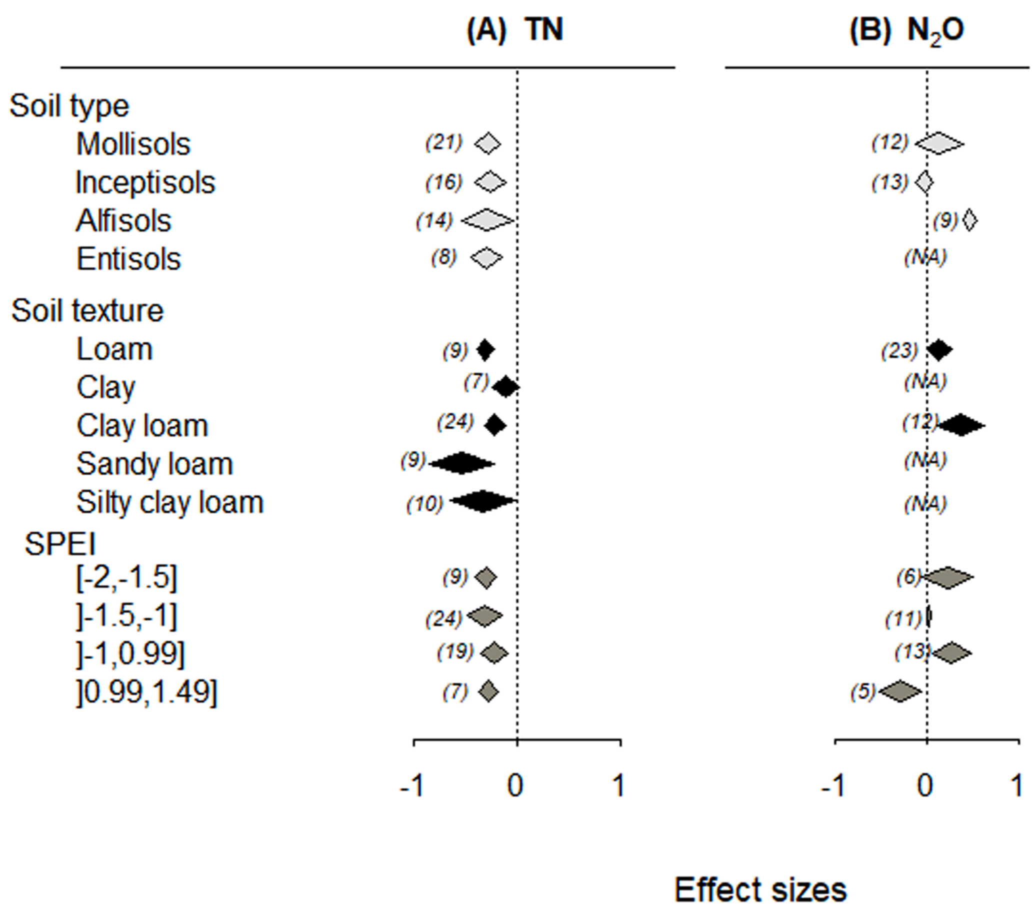

Fig. 5. Effect sizes of TN leaching and N_2O emission under WST influenced by soil types, soil textures and SPEI. The number in parentheses () denotes the number of observations.

significantly among different soil textures. In sandy loam soils, TN leaching was reduced by approximately 41.7 % (RR = −0.54; p-value = 0.0007) under WST compared to CF irrigation, while in clay soils, TN leaching was only reduced by 11.3 % (RR = −0.12; p-value = 0.04) under WST compared to CF irrigation (Fig. 5A). Conversely, N_2O emissions were significantly higher in alfisols (RR = 0.46; p-value = 0.03) under WST compared to CF irrigation, while mollisols and inceptisols showed no significant difference in N_2O emissions between WST and CF irrigation (Fig. 5B).

Five SPEI classes were used to estimate summary effect sizes: severe dry ([−2, −1.5]), moderate dry (]−1.5, −1]), normal (]−1, 0.99]), and moderate wet (]0.99, 1.49]) (Fig. 5). TN leaching was significantly lower under WST compared to CF irrigation across all SPEI classes (Fig. 5A). However, N_2O emissions were significantly lower (RR = −0.29; p-value = 0.014) under moderate wet conditions (SPEI:]0.99, 1.49]) with WST compared to CF irrigation. In contrast, N_2O emissions tended to be higher (RR > 0; p-value < 0.05) under normal to severe dry conditions (SPEI ≤ 0.99) in WST compared to CF irrigation (Fig. 5B).

4. Discussion

4.1. Nitrogen losses through leaching under water-saving technologies

Previous studies consistently highlight the link between nitrogen leaching and water management practices. A key factor in mitigating nitrogen leaching under Water-Saving Technology (WST) is the overall reduction in water input (Liang et al., 2023; Yang et al., 2013). The reduction of irrigation frequency and the application drainage management minimize the volume of leached water, leading to decreased NO_3^--N leaching into groundwater under WST (Liang et al., 2017; Qi et al., 2020; Qiao et al., 2011; Shao et al., 2015; Si et al., 2018). The results of this meta-analysis reveal reductions of 35 %, 28.2 %, and 25.2 % in NH_4^+-N, NO_3^--N and TN leaching, respectively, under WST compared to conventional flooding (CF) irrigation. Hao et al. (2022) reported a 43.23 % reduction in nitrogen leaching with WST practices, while our study provides more precise estimates for each nitrogen component. Specifically, NH_4^+-N leaching decreased by 35 %, followed by NO_3^--N (28.2 %) and TN leaching (25.2 %). These findings align with Peng et al. (2011), who observed lower concentrations of TN, NH_4^+-N, and NO_3^--N under WST compared to CF irrigation, with reductions of 12.1 %, 20.3 %, and 13.5 %, respectively. The difference in reduction rate can be attributed to the aerobic conditions in WST, which enhance the activity of nitrosomonas and nitrobacter, promoting the conversion of NH_4^+-N into NO_3^--N. This result in a decrease of available NH_4^+-N in the soil. In contrast, anaerobic CF irrigation typically shows higher NH_4^+-N concentrations due to reduced nitrification, as this process is influenced by the continuous water layer that limits soil oxygen availability (Bock and Wagner, 2006; Buresh et al., 2008; Fan et al., 2018; Kassam and Uphoff, 2011; Krupa et al., 2011).

The present meta-analysis demonstrates that WST reduces nitrogen leaching, resolving the conflicting findings of previous studies (Cui et al., 2004; Ye et al., 2015; Yu et al., 2021), which suggested that WST might marginally increase nitrogen losses compared to CF irrigation. Our results indicate that the extent of nitrogen leaching reduction depends on the types of WST. NH_4^+-N and NO_3^--N leaching were approximately 1.5 and 4 time lower, respectively, in AWD and CI practices compared to SII practice. The ability of AWD to lower irrigation thresholds and increase ponded water depth relative to SII, leads to a significant reduction in drained water volume (7.2–42.5 %) (Liang et al., 20; S.-Z. Peng et al., 2011; Qi et al., 2020), which further mitigates nitrogen losses through leaching.

4.2. Nitrogen losses through gaseous under water-saving technologies

NH_3 volatilization is influenced by soil water content and the availability of NH_4^+-N in the soil. Win et al. (2009) and Dong et al. (2012) reported higher NH_3 volatilization under WST compared to CF irrigation; and Cui et al. (2004) found 22.9 % increase in NH_3 volatilization under WST. In contrast, Yang et al. (2012) and Xiao et al. (2019) documented reductions in NH_3 volatilization peaks, and Yang et al. (2013) reported reductions of 23–24 % under WST compared to CF irrigation. These contrasting results highlight the complexity of NH_3 volatilization dynamics under WST. Our meta-analysis reveals no significant difference in NH_3 volatilization between WST and CF irrigation. These findings align with studies by Liang et al. (2017) and Shizhang et al. (2009), which observed minimal impact of irrigation regimes on NH_3 volatilization. Similarly, Xu et al. (2015) and Liang et al. (2023) reported no reduction in NH_3 volatilization under WST when continuous water layers were maintained prior to fertilization. These results suggest that factors such as soil type, fertilizer application methods, and environmental conditions significantly influence NH_3 volatilization rates, contrarily to the irrigation regime alone.

The emission of N_2O was significantly higher under WST compared to CF irrigation (Fig. 1E). Among the WST types, N_2O emissions were highest in AWD, followed by CI, and then SII. This increase in N_2O emissions under WST is attributed to enhanced denitrification driven by frequent nitrification-denitrification cycles caused by the drying and reflooding processes (Buresh et al., 2008; LaHue et al., 2016). Such cycles lead to substantial N_2O emissions, as observed by Peng et al. (2011) and Xu et al. (2012), (2013). Consistent with these findings, Sha et al. (2022) reported a 14–35 % increase in N_2O emissions under AWD compared to CF irrigation. Our meta-analysis showed that overall N_2O emissions were 12.7 % higher under WST, with AWD specifically leading to a 44.8 % increase. These results support the need for careful management of WST practices to balance water conservation benefits with the potential environmental impact of increased greenhouse gas emissions. The increase in N_2O emissions is linked to factors such as enhanced soil organic matter decomposition, improved soil redox potential, and accelerated N_2O production (Bateman and Baggs, 2005; Liao et al., 2020; Pandey et al., 2021; Zhou et al., 2020). These findings suggest that while WST effectively reduces water use and nitrogen losses, the application of WST particularly in AWD requires suitable strategies to mitigate greenhouse gas emissions.

4.3. Potential factors affecting nitrogen losses

4.3.1. Fertilizer management

Nitrogen losses are influenced by the source, quantity, and method of fertilizer application (Fig. 2 and Fig. 3). These factors differently affect nitrogen losses between WST and CF irrigation, as well as among various nitrogen components. The use of controlled release fertilizer (CRF) as a nitrogen source leads to lower NO_3^--N, NH_4^+-N, and TN leaching (S.-Z. Peng et al., 2011; Yang et al., 2013, 2020; Ye et al., 2013). Specifically, our results demonstrated that CRF was more effective in reducing NO_3^--N leaching under WST, achieving 2.2 time greater reduction in leaching (53.2 % vs. 24.3 %) compared to urea (46 %N). Additionally, biochar combined with urea significantly reduced NO_3^--N leaching by 42.7 %, outperforming urea alone but being less effective than CRF. Similar trends were observed for NH_4^+-N and TN leaching. These findings indicate that CRF and biochar enhance the effectiveness of WST in reducing nitrogen leaching. Biochar improves soil moisture (Chen et al., 2021) and is recognized for its ability to enhance soil physicochemical properties, nutrient availability, and ecological sustainability (Qi et al., 2021; Soltys et al., 2020). Furthermore, biochar enhances nutrient use efficiency (Islam et al., 2024; Ye et al., 2019), which may explain its contribution to reducing nitrogen losses under WST.

The results of this meta-analysis also revealed that mixing urea with compound fertilizers (Urea + CF) or with zeolite (Urea + Zeolite) significantly increased N_2O emissions by 143.7 % (RR=0.89) and 55.3 % (RR=0.44), respectively, under WST compared to CF irrigation (Fig. 2). When urea (46 % N) is applied alone, N_2O emissions increased by 3.0 %, while the use of CRF resulted in a 3.1 % reduction in N_2O emissions under WST compared to CF irrigation. According to Qi Liu et al. (2018), zeolite facilitates the denitrification process in soils, leading to higher N_2O emissions. Under WST, CRF slows and controls the release of nitrifiable nitrogen, limiting denitrification (Kumar et al., 2007; Wang and Li, 2019). This controlled release prevents an excess of nitrogen in the soil from being converted into gaseous nitrogen (Ding et al., 2022; Wang and Li, 2019), reducing emissions that would otherwise occur under WST. The results from the meta-CART analysis support these findings, emphasizing the effectiveness of combining meta-analysis with meta-CART analysis to investigate the impacts of WST alongside various moderator variables.

Nitrogen losses also varied depending on the quantity of nitrogen fertilizer applied in the rice fields. When nitrogen fertilizers were applied at rates exceeding 225 kg N ha^{-1} , NO_3^--N and TN leaching were reduced by 47.8 % and 32.2 %, respectively, under WST compared to CF irrigation. In contrast, with application rate less than 200 kg N ha^{-1} , NO_3^--N and TN leaching were reduced by 25.1 % and 20.6 %, respectively, under WST compared to CF irrigation. This indicates that reductions in NO_3^--N and TN leaching were 1.9 times and 1.6 times greater, respectively, at higher nitrogen application rates compared to lower rates. These findings suggest that at higher nitrogen application rates, WST significantly reduces nitrogen leaching compared to CF irrigation. Supporting this observation, Wang and Huang (2021) found that WST reduces nitrogen losses by 48.9 % compared to CF irrigation when nitrogen fertilizer rates exceed 240 kg N ha^{-1} . Further studies have noted that nitrogen remains concentrated in the surface water of rice fields for up to seven days following fertilization (Han et al., 2021; Hua et al., 2019; Wang et al., 2016). Consequently, high rates of nitrogen fertilization lead to increased nitrogen concentrations in the leachate (Zhong et al., 2016), emphasizing the effectiveness of WST in mitigating nitrogen leaching compared to CF irrigation. These results highlight the importance of optimizing nitrogen fertilizer rates in conjunction with WST practices to achieve the best outcomes for reducing nitrogen losses in rice fields. When smaller amounts of nitrogen are applied, WST optimizes nitrogen use for plant uptake, leading to reduced nitrogen leaching and gaseous emissions. This finding aligns with studies by Yao et al. (2012) and Zhong et al. (2016), which demonstrate a strong association between N_2O emissions and nitrogen fertilizer application rates. However, Zucong et al. (1997) observed no significant difference in N_2O emission rates between treatments with 0 kg N ha^{-1} and 100 kg N ha^{-1} , though these studies did not specifically compare WST to CF irrigation.

The results of our meta-analysis further indicated that the method of fertilization significantly influences N_2O emissions. When fertilizers were applied by broadcasting, N_2O emissions increased by 33.6 % (RR=0.29) under WST compared to CF irrigation. Conversely, deep placement of fertilizers reduced N_2O emissions by 11.3 % (RR=-0.12) under WST compared to CF irrigation (Fig. 3C). Ding et al. (2022) also found that deep placement significantly reduces N_2O emissions by 52–82 % under AWD, underscoring its effectiveness as a mitigation strategy for N_2O emissions associated with WST (Pardha-Saradhi et al., 2016; Yao et al., 2018). In contrast, broadcasting leads to the accumulation of ammoniacal nitrogen in water, which increases NH_3 volatilization and N_2O emissions. These results underscore the critical role of fertilizer application method in managing N_2O emissions under different irrigation practices, with deep placement emerging as a more sustainable option under WST.

4.3.2. Rice seedling density and soil texture

In this meta-analysis, NO_3^--N leaching was reduced 2.19 times more effectively in rice fields with high seedling density (]25, 45] plants m^{-2}) compared to those with lower seedling density ([10,25] plants m^{-2}) when WST was used instead of CF irrigation (Fig. 3C). This greater reduction is primarily due to the higher number of plants per unit area, which increases the total nitrogen uptake by the rice plants. Higher planting densities promote dense root systems, which absorb more nutrients from the soil and transport them to the plant's aerial parts (Guan et al., 2022; Shi et al., 2016). This high nutrient uptake improves nitrogen use efficiency, resulting in less nitrogen remaining in the soil to be leached away. Similarly, Zhu et al. (2015) observed lower concentrations of $NH4^+$-N and $NO3^-$-N in rice soils as seedling density increased. Under WST, the reduced water movement through the soil further limits NO_3^--N leaching. This interaction between water management and planting density underscores the importance of optimizing seedling density to maximize nitrogen uptake and minimize nitrogen losses.

Our analysis revealed that TN leaching was reduced 3.97 times more effectively in sandy loam soils compared to clay soils under WST relative to CF irrigation (Fig. 5A). This significant difference can be attributed to the inherent characteristics of these soil types and their interactions with water management practices (Xiong et al., 2010). Sandy loam soils, characterized by their coarse texture and lower water retention capacity, experience faster drainage and reduced water holding compared to clay soils. Consequently, WST limits the water available to transport nitrogen away from the root zone, leading to a greater reduction in nitrogen leaching. In contrast, clay soils retain more water and remain saturated for longer periods. This prolonged saturation can make WST less effective in reducing nitrogen losses. Therefore, sandy loam soils better fit with WST, resulting in more substantial reductions in TN leaching compared to clay soils.

The limited availability of comparative studies examining the effects of rice seedling density on nitrogen losses under different water management practices presents a significant research gap. Addressing this gap is crucial for understanding the complex relationship between seedling density, water management and nitrogen losses. Further research could offer valuable insights into optimizing seedling density as part of an integrated approach to enhance the efficacy of WST while minimizing potential environmental impacts.

4.4. Effect of water-saving technologies on rice grain yield

Rice grain yield is the primary goal for farmers, as achieving high yields ensures economic benefits. For this reason, many farmers prefer CF irrigation (Liang et al., 2013). Nonetheless, studies have reported no significant difference in nitrogen uptake, aboveground biomass, or grain yield between WST and CF irrigation (Belder et al., 2004; Dong et al., 2012; Gao et al., 2018; Wang et al., 2023). These findings are consistent with our meta-analysis, which similarly indicate that WST does not significantly affect rice grain yields compared to CF irrigation. However, few studies present contrasting results. For instance, Hang et al. (2022), observed increased rice grain yield under WST compared to CF irrigation, while Hao et al. (2022) reported a 7.31 % increase in rice grain yields under WST. Conversely, other research have suggested that WST might lead to lower rice grain yield than CF irrigation (Lagomarsino et al., 2016; Li et al., 2011; Peng et al., 2006). It is crucial to acknowledge that rice grain yield is influenced by a combination of factors, including crop management practices, climatic conditions, soil characteristics, soil hydraulic parameters, and crop genetic traits. Our meta-analysis suggests that WST can be implemented without compromising expected yields. Recent advances in the development of water stress-tolerant rice varieties may also explain the observed lack of significant difference in yields between WST and CF systems (Abbasi and Sepaskhah, 2011; Yao et al., 2012). These findings indicate that WST offers a promising alternative for rice cultivation, enabling water savings without reducing productivity. Further research should investigate the long-term effects of WST on different rice varieties and under diverse environmental conditions to optimize its adoption and effectiveness.

4.5. Number of studies and data quality in the meta-analysis

The number of studies is an essential criterion for assessing the quality of the results in a meta-analysis (Higgins and Green, 2008; Murad et al., 2014; Thorlund et al., 2010). In this review, the initial search in databases yielded 921 articles. However, the final dataset retained 38 articles containing 182 observations due to screening based on the inclusion criteria i.e. studies that contain at least one of our main response's variables, explanatory variables, quantitative statistical data, or clear plots on nitrogen losses. These criteria are essential for reliability of the meta-analysis findings while ensuring consistency across studies. The low number of included studies also reflects the lack of high-quality and quantitative data research on the effects of water management practices (WST and CF irrigation) on nitrogen losses in rice fields. In fact, the number of studies is not always a determinant that undermines the results of meta-analysis (Herbison et al., 2011); but especially, it is the number of couple data points (degree of freedom) that supports the model choice and the statistical power of the results (Herbison et al., 2011). We performed the data quality check to avoid potential limitations related to the small number of studies (publication bias) using statistical tests such as funnel plots, Egger's asymmetry test, and heterogeneity tests (Q-statistic). Publication bias, defined as a systematic error in meta-analysis caused by incomplete representation of available evidence, is a critical factor to address in meta-analysis (Carlson et al., 2023; Mavridis and Salanti, 2014). The results from this review showed no significant publication bias (Table 1), suggesting a reliability of our results.

5. Conclusion

Water-saving technologies have been used to reduce nitrogen losses in rice fields, offering a sustainable alternative to continuous flooding irrigation, particularly in high nitrogen fertilizer application rates and high seedling densities systems. The combination of water-saving practices with nutrient management strategies, such as controlled-release fertilizers and site-specific applications, can help to mitigate high nitrous oxide emissions and enhance their effectiveness in reducing nitrogen leaching. Importantly, water-saving does not significantly affect rice grain yield, ensuring both environmental and agricultural sustainability. Future research should focus on optimizing practices such as seedling density, alternative nitrogen fertilizers, and their combinations with water-saving technologies. Moreover, cost-benefit analyses are important to validate the economic feasibility of these technologies across diverse local conditions and agricultural systems.

CRediT authorship contribution statement

Tovihoudji Pierre G.: Writing – review & editing, Visualization, Validation, Methodology, Conceptualization. **Gbedourorou Sabi Kidirou:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Zakari Sissou:** Writing – review & editing, Visualization, Validation. **Akponikpè P. B. Irénikatché:** Writing – review & editing, Validation, Supervision, Conceptualization. **Vanclooster Marnik:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109400.

Data availability

Data will be made available on request.

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