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Review

Exploring the Impact of Alternate Wetting and Drying and the System of Rice Intensification on Greenhouse Gas Emissions: A Review of Rice Cultivation Practices

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Abstract: Rice provides ~20% of human dietary energy and, for many people, a similar share of their protein. Rice cultivation, however, produces significant greenhouse gas (GHG) emissions, comparable to those from the aviation sector. The main GHG from rice production is methane, mostly a result of conventional rice cultivation (CRC) keeping rice fields continuously flooded during the crop cycle. There is extensive evidence that alternate wetting and drying (AWD) of rice fields substantially reduces methane emissions. AWD is one component of the System of Rice Intensification (SRI), an agroecological approach to the management of plants, water, soil, and nutrients. This article reviews field studies measuring GHG emissions associated with the adoption of AWD and SRI. The review confirms that both AWD and SRI offer substantial reductions in methane emissions per hectare compared with CRC. These benefits are, however, partly offset by increases in emissions of nitrous oxide and carbon dioxide. The studies also show that SRI (but not AWD) improves yield and therefore further reduces GHG emissions per kg of rice. The review concludes that while both AWD and SRI substantially reduce emissions per hectare and per kilogram of rice, SRI can simultaneously contribute to food security while addressing the drivers of climate change. Further investigation of carbon emissions and sequestration under different rice cultivation methods is needed to strengthen the evidence base.

Keywords: climate change; food security; agricultural methane emissions; carbon sequestration; nationally determined contributions; climate-smart agriculture

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1. Introduction

Rice is one of the world's three main staple crops, providing more than a fifth of the calories consumed by people worldwide [1] and cultivated on ~195 million hectares, ~12% of the global cropped area [2]. Traditional lowland rice cultivation includes the continuous flooding of paddy fields. In India alone, ~65% of the ~44 million hectares under rice production in 2019 were irrigated [3]. Farmers mostly irrigate to suppress the growth of weeds and some plant pests but also because many believe rice is an aquatic plant that benefits from flooding. While rice plants can survive under flooded conditions, their root systems deteriorate under constant inundation due to hypoxia [4].

Continuous flooding also leads to methanogenesis, the biological process whereby the respiration of certain microbes (archaea) in anaerobic soil produces methane (CH_4) as a by-product of their metabolism [5]. Other factors such as temperature and soil type also affect this process [6]. The production of CH_4 from rice cultivation is particularly harmful because it is a potent GHG with a global warming potential (GWP) that is 27 times greater than that of carbon dioxide (CO_2) over 100 years and 80 times greater over 20 years [7].

As an alternative to the flooding of rice fields in traditional cultivation, the practice of alternate wetting and drying (AWD) involves allowing the surface water of rice fields to disappear, typically for between 1 and 10 days, before the field is irrigated again. The essence of AWD is maintaining intermittently aerobic soil conditions. This reduces the amount of water that is required for rice production and constrains the biotic process of methanogenesis in the soil, thereby reducing the amount of methane gas that is emitted into the atmosphere. As the more aerobic soil conditions created by AWD can increase the emission of nitrous oxide (N_2O), this must be taken into account when assessing the net change in GWP from the adoption of AWD and SRI.

Maintaining aerobic soil conditions is also one of the main elements of the System of Rice Intensification (SRI), and consequently, AWD is one of the essential practices in SRI. SRI also includes the principle of minimizing competition between plants so that each plant can fully express its potential. This typically involves transplanting individual seedlings in a grid pattern of approximately 25 × 25 cm. The pioneer of SRI, Henri de Laulanié, also specified the careful transplantation of young seedlings [8,9] although some farmers practice direct seeding instead of transplantation [10]. Finally, as an agroecological approach, SRI encourages farmers to build up soil health and to minimize or eliminate the use of synthetic nitrogen fertilizers (SNF) and other chemical inputs, although SRI is not necessarily an organic methodology [10]. AWD and the wider spacing of single plants are essential elements of SRI, although in all of the studies reviewed here, transplantation was practiced along with a variety of approaches to enhancing soil fertility.

2. Impacts of Rice Production Methods on Greenhouse Gas Emissions

Whether through AWD alone or through SRI, water management is critical to reducing the emissions associated with rice cultivation. There are, however, other important ways in which CH_4 and N_2O emissions can be reduced and soil organic carbon sequestration increased. These include nutrient management (e.g., reduced application of SNF); residue management (e.g., avoiding straw burning) [11]; and different tillage strategies [12].

The main benefit of water management is that it addresses methane emissions directly. Reducing the rate at which the atmospheric concentration of methane is increasing is crucial if we are to keep the average global temperature from rising to more than 1.5 °C above its pre-industrial level [13]. Reducing anthropogenic emissions of methane is one of the most urgent and cost-effective ways of limiting global heating and abating the worst degrees of environmental change [14]. In 2020, rice cultivation represented ~8% of global methane emissions [15], with a similar effect on global warming as the whole aviation sector [16]. While we use the GWP100 metric in this paper, a GWP20 metric would arguably present a more realistic picture of the benefits to be derived from reducing methane emissions.

Expanding low-emission rice cultivation methods rapidly could therefore contribute materially to the achievement of global climate-mitigation targets. Although rice cultivation contributes less to climate change than livestock, it has similar potential for mitigation [12]. Twenty-eight countries have rice (including thirteen that specify SRI) in their nationally determined contributions (NDCs) to climate change mitigation and/or adaptation, and many more could do the same [17,18].

Initial interest in, and research into, SRI focused on its yield increases and on other development advantages, e.g., lower costs of production, higher farmer income, better grain quality, and crop resistance to the hazards of climate change [19]. However, once reductions in GHG emissions began to be documented [20], interest grew in what SRI crop management could do to mitigate global warming. Various researchers have conducted field trials to compare the GHG emissions of SRI and AWD with those from conventional rice cultivation (CRC) practices, and some have modeled these effects.

This paper seeks to inform scholars, policymakers, and practitioners about these effects by identifying, analyzing, and comparing studies of GHG emission reductions and other benefits associated with AWD and SRI.

3. Identification of Studies for Analysis

To build a database for review, we used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 methodology [21], as set out below.

3.1. Definitions

There is no standard definition or set of practices for CRC, AWD, or SRI. Further, there are numerous variables involved that mean that any two farmers applying the same set of practices will not necessarily obtain the same results as each other, or from one year to the next. Consequently, while each individual study defines the practices that it is comparing, a review cannot be as specific.

For this research, CRC at the minimum includes the maintenance of anaerobic conditions in the fields through continuous flooding. As noted above, AWD is defined as the irrigation practice of allowing the surface water to disappear before rice fields are irrigated again. This is variously described in the literature as 'intermittent irrigation', 'intermittent flooding', 'cyclic wetting and drying', and 'pulsed irrigation'. The essence of AWD is maintaining intermittently aerobic soil conditions. Mid-season drainage, which can be part of CRC practices, does not ensure such conditions and thus does not qualify as AWD.

For SRI, the common and minimum practices are (a) AWD and (b) the wider spacing of plants. Both practices are designed to build larger and healthier root systems that increase the yield of each plant and of the field overall. All the studies included in the meta-analysis also involve the early transplantation of seedlings, although this was not a criterion for inclusion. The precise spacing of the plants, the age of transplanted seedlings, and other practices such as the use of organic manures or reduced synthetic fertilizers and pesticides vary between farmers and over time, so these were not made criteria for inclusion in the database.

3.2. Eligibility

The studies included in the database had to provide measured data of GHG emissions at the field level for CRC, AWD, and/or SRI practices, rather than data derived from modeling. Also, all the studies were in English.

3.3. Exclusion

The exclusion criteria were as follows:

(a) Research on life cycle emissions for conventional rice cultivation, AWD, or SRI were excluded unless they contained separated data for field-level emissions.
(b) Studies based only on models were excluded, although some studies include both modeled and observed data, in which case the latter were included.
(c) Studies were excluded if they did not include CH_4 and N_2O, i.e., they investigated only CH_4 or N_2O emissions.
(d) Studies comparing CRC and AWD were excluded if changes were made other than to water management, such as the fertilizer regime.
(e) Studies that included crop rotations were excluded if there was not segregated emissions data for the rice period.
(f) Studies were excluded if they used non-original data.

3.4. Searches

Searches were carried out across three sources, up to 20 December 2023.

(a) Science Direct [22] with the following search terms and no filters applied:

('System of Rice Intensification' or SRI) and (rice) and ('greenhouse gas emission' or 'GHG emission').

('Alternate wetting and drying' or AWD or 'intermittent irrigation' or 'intermittent flooding' or 'cyclic wetting and drying' or 'pulsed irrigation') and (rice) and ('greenhouse gas emission' or 'GHG emission')
Records identified: 2984.

(b) SRI-Rice Cornell Zotero database [23]. Papers were found using the tag 'Climate change and GHG'.

Records identified: 170.

(c) The journal Soil Science and Plant Nutrition Special Issue 'Frontline Research in Mitigating Greenhouse Gas Emissions from Paddy Fields' [24].

All articles included.
Records identified: 16.

(d) Citation searching identified 11 additional papers.

3.5. Identification of Studies

Applying the eligibility, inclusion, and exclusion criteria to the search results and citation searching identified 48 studies to be evaluated, as set out in Figure 1.

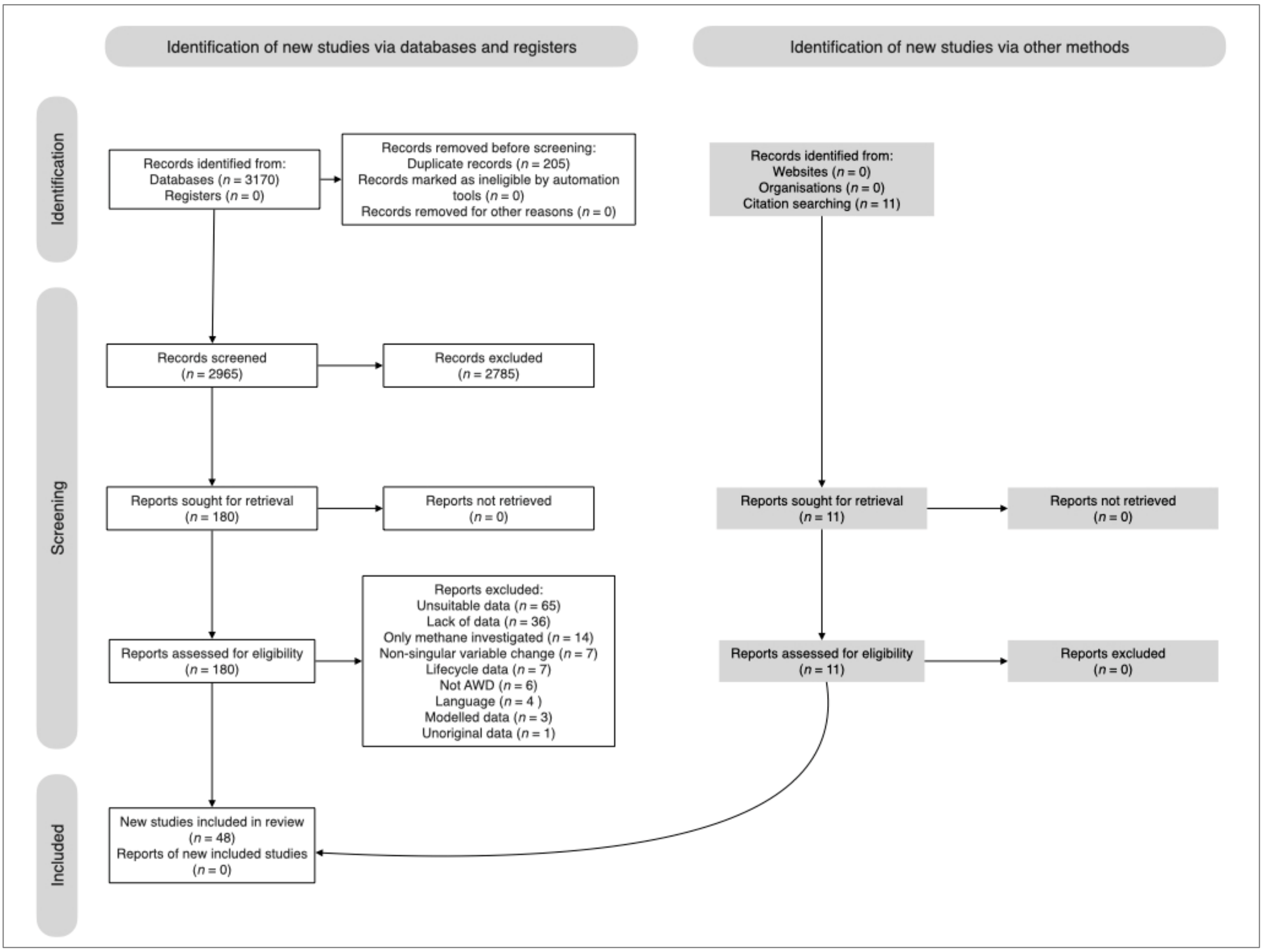

Figure 1. Identification of studies using PRISMA 2020 flow diagram.

4. Methodology

The absolute values of GHG emissions can vary significantly across locations due to climatic, soil, and other conditions. In addition, absolute values can be for emissions per day, per season, or per year. Consequently, the focus here was on the percentage changes in GHG emissions per hectare of rice cultivation. Where the studies reported yield data, changes in GHG emissions per kilogram of rice produced were calculated.

Emissions changes were recorded in terms of GWP over a 100-year period (GWP100), referred to as carbon dioxide equivalent (CO_2e) emissions. This figure provides a basis for aggregating and comparing the respective masses of absolute emissions per year or per growing season and multiplying the constituent gases (N_2O, CH_4) by their relevant multiplication factors to arrive at a summed GWP. Such a calculation enables the comparison between data sources. The GWP100 factors used are 27 for (non-fossil) CH_4 and 273 for N_2O [7]. Values for CO_2 emissions were reported in too few of the studies to be included in the GWP calculations.

The source data and calculations are available in the Supplementary Materials file.

5. Results

Table 1 presents the results of 41 studies in which GHG emissions from AWD were compared with those from CRC practices. These data are geographically diverse, coming from Asia, North and South America, and Europe. The studies are ordered in the table from those with the largest reduction in CO_2e emissions per hectare to those with the smallest (the final study in fact recorded an increase in emissions).

Table 1. Impact on GHG emissions and yield of changing of CRC to AWD (n = 41).

Study	Trial Location	Change in CO_2e ha^{-1}	Change in CO_2e Emissions kg^{-1} Rice	Change in Yield of Rice ha^{-1}
Martínez-Eixarch et al. 2021 [25]	Spain	−94%	−94%	−11%
Linquist et al. 2015 [26]	USA	−89%	−88%	−9%
LaHue et al. 2016 [27]	USA	−66%	−68%	9%
Pandey et al. 2014 [28]	Vietnam	−66%	−64%	−6%
Islam et al. 2020 [29]	Philippines	−65%	−67%	6%
Xu et al. 2015 [30]	China	−64%	−60%	−10%
Wang et al. 2018 [31]	China	−63%	−65%	8%
Win et al. 2020 [32]	Myanmar	−57%	−59%	5%
Loaiza et al. 2024 [33]	Colombia	−53%	−49%	−9%
Kim et al. 2014 [34]	Korea	−48%	−49%	1%
Sriphirom and Rossopa 2023 [35]	Thailand	−48%	−47%	−1%
Camargo et al. 2018 [36]	Brazil [a]	−42%	−47%	8%
Feng et al. 2021 [37]	China	−41%	−33%	−12%
Rajesh Krishnan et al. 2017 [38]	India	−39%	−45%	11%
Samoy-Pascual et al. 2019 [39]	Philippines	−39%	−37%	−4%
Zschornac et al. 2016 [40]	Brazil	−38%	−38%	−1%
Kumar et al. 2016 [6]	India	−37%	−19%	−22%
Islam et al. 2020 [41]	Bangladesh	−36%	−34%	−3%
Kudo et al. 2014 [42]	Japan	−36%	5%	−39%
Setyanto et al. 2018 [43]	Indonesia	−36%	−35%	−1%
Liao et al. 2023 [44]	China	−35%	−34%	−2%
Towprayoon et al. 2005 [45]	Thailand	−35%	−27%	−11%
Hou et al. 2016 [46]	China	−34%	−33%	−1%
Hoang et al. 2023 [47]	Vietnam	−33%	−36%	4%
Liang et al. 2022 [48]	China	−30%	n/a	n/a
Wang et al. 2017 [49]	China	−29%	−20%	−10%
Islam et al. 2022 [50]	Bangladesh	−27%	−26%	−1%
Tran et al. 2018 [51]	Vietnam	−26%	−31%	7%
Thu et al. 2016 [52]	Vietnam	−25%	−22%	−4%
Yang et al. 2012 [53]	China	−24%	−26%	3%
Begum et al. 2019 [54]	Bangladesh	−23%	−24%	1%
Li et al. 2024 [55]	China	−22%	−23%	2%
Gupta et al. 2016 [56]	India	−22%	−19%	−3%
Hoang et al. 2019 [57]	Vietnam	−21%	−26%	7%
Wang et al. 2020 [58]	China	−20%	−22%	3%

Table 1. *Cont.*

Study	Trial Location	Change in CO_2e ha^{-1}	Change in CO_2e Emissions kg^{-1} Rice	Change in Yield of Rice ha^{-1}
Tang et al. 2018 [59]	China	−17%	n/a	n/a
Tirol-Padre et al. 2018 [60]	SE Asia	−13%	−15%	3%
Mohapatra et al. 2023 [61]	India	−11%	−7%	−4%
Cowan et al. 2021 [62]	India	−8%	1%	−9%
Chidthaisong et al. 2018 [63]	Thailand	−4%	−1%	−4%
Sibayan et al. 2018 [64]	Philippines	6%	5%	2%
Average		−37%	−35%	−3%

[a] The study included Japan, but these data were excluded as the irrigation method was mid-season drainage and therefore not classified as AWD.

Table 2 presents the results of nine studies that compared GHG emissions from SRI and CRC practices. These studies were carried out in India, Nepal, and Cambodia. The order is the same as for Table 1, but for SRI, all the studies show a reduction in net emissions per hectare.

Table 2. Impact on GHG emissions and yield of changing from CRC to SRI (n = 9).

Study	Trial Location	Change in CO_2e ha^{-1}	Change in CO_2e Emissions kg^{-1} Rice	Change in Yield of Rice ha^{-1}
Karki 2010 [65]	Nepal	−74%	−88%	118%
Rajesh Krishnan et al. 2017 [38]	India	−42%	−62%	51%
Jain et al. 2014 [66]	India	−39%	−37%	−3%
Gangopadhyay et al. 2023 [67]	India	−27%	−71%	150%
Mohapatra et al. 2023 [61]	India	−26%	−47%	40%
Gangopadhyay et al. 2022 [68]	India	−25%	−67%	127%
Oo et al. 2018 [69]	India	−25%	−31%	8%
Ly et al. 2013 [70]	Cambodia	−15%	−15%	0%
Ramesh and Rathika 2020 [71]	India	−1%	−11%	11%
Average		−26%	−47%	40%

Table 3 presents the results from the two studies that compared SRI and AWD directly. Two studies cannot provide a basis for generalization, but they have some value when considered in the context provided by the two larger datasets in Tables 1 and 2.

Table 3. Impact on GHG emissions and yield of changing from AWD to SRI (n = 2).

Study	Trial Location	Change in CO_2e ha^{-1}	Change in CO_2e Emissions kg^{-1} Rice	Change in Yield of Rice ha^{-1}
Mohapatra et al. 2023 [61]	India	−6%	−20%	17%
Rajesh Krishnan et al. 2017 [38]	India	−5%	−30%	37%

The results of Tables 1–3 are summarized in Table 4, showing ranges in all the cases. The ranges are generally large and reflect the numerous factors that can influence both the absolute values and the relative performance of different cultivation practices. These include geography, soil type, rainfall, and other weather patterns during the trial, as well as the specific way in which each cultivation type was implemented. The median and mean values are shown for the comparisons between CRC and AWD and SRI, respectively, but not for the comparison between AWD and SRI, given the very small sample size. Regardless of sample size, averages must be treated with caution given the heterogeneous nature of each trial.

Table 4. Summary of changes in GHG emissions and yield between CRC, AWD, and SRI.

		Range	Median	Mean
Change in CO_2e emissions ha^{-1}	AWD compared to CRC	−94% to 6%	−35%	−37%
	SRI compared to CRC	−74% to −1%	−26%	−31%
	SRI compared to AWD	−6% to −5%		
Change in CO_2e emissions kg^{-1} rice	AWD compared to CRC	−94% to 5%	−33%	−35%
	SRI compared to CRC	−88% to −11%	−47%	−48%
	SRI compared to AWD	−30% to −20%		
Change in rice yield t ha^{-1}	CRC compared to AWD	−39% to 11%	−1%	−3%
	CRC compared to SRI	−3% to 150%	40%	56%
	AWD compared to SRI	17% to 37%		

Outliers at both ends of the range may be idiosyncratic, affected by soil or other conditions or by measurement problems. But the number of studies comparing AWD and CRC provides a substantial set of findings that AWD offers a significant reduction in GHG emissions per hectare, with median and mean reductions of 37% and 35%, respectively.

Although there is a smaller set of studies comparing SRI with CRC, the range is also smaller, and the median and mean reductions are 26% and 31%, respectively. One could infer from this that AWD outperforms SRI on this parameter. There are, however, two reasons why this inference may not be sound. First, these were not direct comparisons of AWD and SRI, and in each case, the CRC baseline was different. Second, AWD is a component of SRI. Consequently, we might expect that SRI would not offer a smaller improvement in per hectare emissions than AWD, unless other aspects of SRI tend to increase emissions. The limited evidence from the two studies that directly compared AWD and SRI suggests that this is not the case as both studies show that SRI has a slight advantage (of 5–6%) in per hectare emissions compared with AWD. Perhaps the most defensible conclusion is that AWD and SRI both offer a significant reduction in emissions per hectare.

Once yield is considered, the studies suggest that SRI has an advantage over AWD. Of the 41 studies comparing AWD with CRC, 39 included yield data. The mean change was a slight (3%) reduction in yield when moving from CRC to AWD. This is consistent with a meta-analysis of CRC and AWD yields by Carrijo et al. (2017). This analysis found AWD giving an average yield reduction of 5.4% compared to CRC across a large set of field trials [72]. These authors, noting that yields were affected by the severity of the drying, the pH of the soil, and its carbon content, concluded that under the right conditions and methods, AWD can be practiced without reducing yields.

The nine SRI studies show a considerable range in the gain in yield from the adoption of SRI, but only one study showed a lower yield (3%) while three studies showed yield more than doubling. The median and mean increases of 40% and 56%, and even the highest increases, are consistent with agronomic studies of yield improvements under SRI management [19]. Some of the variability may be explained by the fact that SRI, unlike AWD, is not a single practice or even a uniform set of practices. This is a point addressed in the Limitations and Recommendations section below. The two direct comparisons of AWD and SRI showed SRI achieving yields 17% and 37% higher than those from AWD.

When considering GHG emissions and yield together, the mean reduction in emissions per kilogram of rice produced was 35% for AWD and 48% for SRI. Figure 2 shows the results graphically.

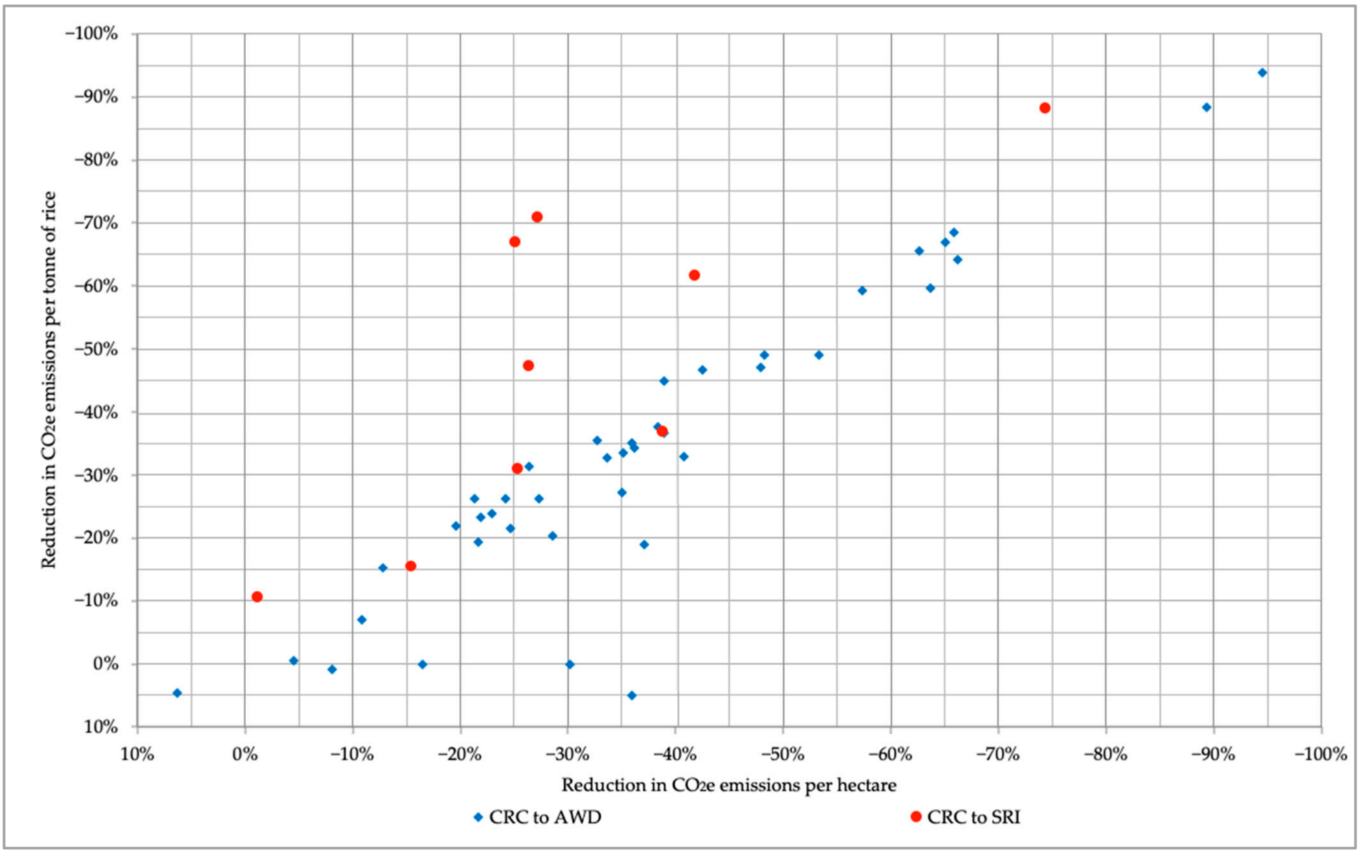

Figure 2. Reduction of CO_2e emissions per hectare and per tonne of rice produced. The scale on both axes is from the least reduction to the largest, with the most beneficial results being towards the top-right of the graph. Blue diamonds show the benefits of AWD compared with CRC (n = 39), and red dots show the benefits of SRI compared with AWD (n = 9). Two of the forty-one AWD studies in Table 1 were not included in the graph because they did not include yield data. The two excluded studies found reductions of CO_2e emissions per hectare of 30% and 17%, respectively.

6. Carbon Emissions and Sequestration

The majority of the studies analyzed above evaluated only CH_4 and N_2O. Seven of the AWD studies and the two studies that compared CRC, AWD, and SRI also included CO_2 emissions. These studies are all listed in the Supplementary Materials file. In addition, there is a separate study that considers carbon sequestration [68]. The dataset on CO_2 is not sufficiently large or consistent to draw robust conclusions, but it is important to include it since CO_2 must be taken into account in order to understand the real effects of AWD and SRI on emissions. Table 5 shows how the inclusion of CO_2 changes the numbers although not the direction.

Table 5. Reduction in CO_2e emissions from CRC to AWD, including and excluding CO_2 (n = 7).

Parameter	Mean Improvement		Change (%)
	$CH_4 + N_2O$	$CH_4 + N_2O + CO_2$	
CO_2e emissions ha^{-1}	−49%	−30%	−38%
CO_2e emissions kg^{-1} rice	−40%	−20%	−51%

The first point to note is that the seven studies in Table 5 showed reductions in GHG emissions for $CH_4 + N_2O$ that are above the averages for the larger dataset in Table 1: 49% vs. 37% per hectare; and 40% vs. 35% per kilogram of rice produced. These seven studies also showed AWD having a more negative effect on yields than across the larger dataset, i.e., a mean reduction of 13% compared with 3%. So, the baseline for these seven studies is not the same as for the larger dataset. The reductions of 30% and 20% per hectare and per kilogram when CO_2 is included compare with 37% and 35% for the larger dataset without CO_2. Consequently, these seven studies indicate that when CO_2 is included, the emissions benefits of AWD vs. CRC are substantially reduced, although they are still significantly beneficial.

The two studies that covered all three gases and CRC, AWD, and SRI have very different results. Rajesh Krishnan et al. (2017) found CO_2 emissions to be the lowest for CRC, higher for AWD, and highest for SRI [38]; while Mohapatra et al. (2023) found the opposite [61]. These results are set out in the Supplementary Materials file, but they do not support any conclusions on this point.

GHG emissions are not the only factor affecting climate change. Agricultural soils and vegetation are also an important carbon sink, and farming practices that increase soil organic carbon serve to reduce the atmospheric accumulation of carbon. Practices that disturb the soil have the opposite effect.

As seen above, AWD increases CO_2 emissions from rice fields, and it has also been found to reduce soil organic carbon [73], although this study included mid-season drainage as AWD, which we do not. Gangopadhyay et al. (2022) compared soil carbon sequestration under CRC, SRI, and no-till cultivation and found that sequestration in SRI-managed rice fields ranged from 27.5 to 96.2 t CO_2e per hectare per year, more than double that in CRC fields, and also more than under no-till [68]. SRI enhances the soil's potential for carbon sequestration because of the greater biomass of rice plants both above and below ground [68], without the trade-off in higher CH_4 emissions that can be caused by greater soil organic matter [74].

The role of carbon sequestration should not be underestimated. The potential increases in soil carbon sequestration as a result of SRI are an order of magnitude greater than the reductions in CO_2e emissions [68]. If substantiated by further research, the carbon sequestration potential of SRI will not only extend the climate change mitigation advantages that SRI has over CRC practices but may also put it ahead of AWD in terms of GHG benefits alone. Further research on this would be highly desirable.

7. Synergies between AWD and SRI in Farmer Transitions

While SRI offers a broader range of benefits than AWD, the latter offers some important benefits in its own right and, in some circumstances, it may be a good stepping-stone to SRI. Changing water management practices can be a challenging step for farmers in adopting SRI. Implementing AWD is thus a significant step towards SRI. Even if AWD does not offer improved yields, the savings in water and energy costs for pumping may be material. Water consumption can be lowered with AWD by as much as 25–30% without negatively affecting yield, although this is not the norm and requires the right conditions and careful management [73,75]. In many countries, farmers do not have to pay for water consumed (and maybe not even for electricity). However, increasing competition for scarce fresh water supplies may encourage or even necessitate the adoption of AWD in some areas. Farmers may also be incentivized to adopt AWD for its other, secondary benefits [76].

AWD may therefore be a step towards SRI, but water management is not the only barrier to the adoption of SRI. Given its many benefits, some explanation is required as to why SRI has not been adopted even more widely, even while millions of farmers have done so [77]. The main reason appears to be that it is relatively knowledge-intensive [78]. SRI involves adopting new practices that require greater precision in the management of the seeds, plants, fields, water, and other inputs. Time management increases the challenge that any form of agronomic change presents. SRI and AWD both require less water, but that water needs to be available at the right moment, which may concern farmers [79]. Further, transplanting is also time-sensitive. And any hired labor must be available with the right skills at the right time [80].

The second most cited barrier is that SRI is more labor-intensive. This is a question that requires further research since the evidence is conflicting [79–85]. Whether SRI requires more labor depends on whether the farmer is moving from practices that are labor-intensive or labor-extensive. SRI may be more labor-intensive for farmers as they learn new practices such as transplanting and weed management, but several studies show that once the new techniques have been mastered, the labor requirements are no greater than CRC. The extent of the adoption of SRI shows that none of these barriers are insurmountable. They can be addressed through a variety of approaches: knowledge-intensity and change management through peer-to-peer training, extension services, and demonstration farms [78]; labor-intensity through direct seeding, the provision of mechanical weeders, or the use of cover crops or mulch to prevent weeds growing on bare soil [10,86]; risk management through insurance; and finance through micro loans [87].

Once farmers have overcome these barriers, they can enjoy the numerous benefits of SRI. Aside from improved yield, input costs are reduced for seed, energy, and fertilizer, leading to higher returns for farmers [88,89]. SRI also produces rice seed and grains that are of higher quality than CRC rice and thus may command a higher market price [90], and the plants are more resistant to biotic and abiotic stresses [19] as well as being more resilient to cold temperatures, storm damage, and pests and diseases [91,92]. The latter effects become all the more important as a consequence of climate change.

8. Water Management and Yield

While yield is not the main subject of our review, the findings set out above raise an interesting question. If, as has been seen both in this review and in previous research, the adoption of AWD is associated with a lower yield, then the implication is that merely creating aerobic soil conditions does not, by itself, improve soil, root, and plant health, or if it does, then not to the extent of increasing yield. It follows, conversely, that any hypoxia caused by the continuous flooding of rice fields does not inhibit plant growth to the extent of reducing yields. This contradicts an idea as old as SRI itself, noted above and also in the discussion at 1.3.3 in Uphoff (2023) [10]. If cultivating rice under aerobic conditions improves plant growth, then AWD alone should improve yields. Of the 39 studies that reported yields for AWD vs. CRC, however, more than half (n = 23) showed a reduction in yield, and of the others, 7 showed only small gains of less than 3%. It appears, then, that SRI improves yield either through aspects other than water management (i.e., transplantation, spacing, and use of organic manures) or through the interaction of water management with one or more of those other practices. This illustrates the desirability of encouraging farmers to adopt the full suite of SRI practices to ensure the full range of benefits.

9. Limitations and Recommendations

This review has been limited by the relatively small number of studies of the climate change benefits of AWD and SRI that met our clear and, we think, reasonable criteria. In particular, the paucity of studies directly comparing AWD and SRI meant that we could only infer their relative benefits from the studies reported in Tables 1 and 2, although these inferences are supported by such research as is available.

In addition, our study is limited by the inherent heterogeneity of the factors bearing on the subject of this research. As noted above, soil type and health, climate, season, fertilization, and many other variables determine the absolute emissions and yields in any trial. An analysis of these factors and how they influence emissions would be valuable but is beyond the scope of this review of current knowledge.

Another material limitation when considering the climate benefits of different rice cultivation practices is the lack of data on CO_2 emissions and carbon sequestration. Studies that do not include the former may be overstating the benefits of AWD and SRI, while studies that exclude the latter may be understating them. Carbon sequestration has the potential to be a much more material contribution to both climate change mitigation and adaptation. Emission reductions are a necessary but insufficient part of tackling climate change—we also need to draw CO_2 down from the atmosphere and agricultural soils must play a significant part in this [93].

We would recommend that future studies consider the following design principles to address these limitations.

- Standardize the definitions of AWD, SRI, and CRC and make these explicit.
- Conduct baseline trials of CRC, AWD, and SRI alongside trials to test the effects of other practices (such as organic vs. inorganic fertilization).
- Include CH_4 and N_2O and CO_2 emissions together as the standard for evaluation.
- Include changes in soil organic carbon where possible to build the evidence base on carbon sequestration.
- State the GWPs explicitly as these have changed in the past and may change again.
- Apply GWP20 as well as GWP100 values as the time factor in emissions reductions becomes more pressing.
- Provide the raw data along with percentage changes.
- Include yields for each cultivation method so that emissions intensity can be calculated. This allows for a comparison between farmers with different seasonal practices with respect, for example, to crop rotations or multiple rice harvests.

We hope to see more geographic variability in future studies, notably in Africa as SRI is promoted there. Although we have noted carbon sequestration as an optional parameter, further investigations of the carbon sequestration potential of different rice cultivation practices would be invaluable.

10. Conclusions

This paper reviewed the published literature on GHG emissions associated with AWD and SRI rice crop management and compared these to the emissions from CRC practices. Our findings confirm that both SRI and AWD outperform CRC practices by significantly reducing per hectare GHG emissions. Reductions in CH_4 are the dominant effect, with increases in N_2O and CO_2 partly offsetting the benefits in some studies.

In line with previous research, the dataset indicates that SRI is associated with increased yields, and AWD with a slight reduction in yield. Consequently, SRI performs better than both CRC and AWD in terms of emissions per kg of rice produced. There is evidence, albeit limited, that SRI also increases soil organic carbon, and that AWD does not. The benefits of SRI may be further increased when carbon sequestration is taken into consideration. This warrants further research.

While GHG emissions can be reduced by AWD alone, SRI provides multiple benefits beyond AWD, even if it requires greater upfront effort by farmers and in agricultural extension. Where water management is a significant barrier to adoption, it may make tactical sense to help farmers adopt AWD first, and then transition to SRI for the additional benefits that it offers. In either case, AWD and SRI are not competing methods, since AWD is a component of SRI, as well as a logical stepping-stone towards it. SRI can also be combined with conservation agriculture practices such as no-tillage, cover cropping, and mulching [10,86].

Yields are not a matter of concern only to farmers. Food security is an increasingly critical and urgent issue for policymakers, and one that is arguably more important for them in the short run than climate change, albeit that food supply will be affected by climate change as well as policy responses, as has already been seen in the case of rice [94]. When food security is considered, SRI becomes an even more compelling policy option. In addition to national agricultural extension programs, international development efforts, climate financing, and loss and damage funds should be directed towards SRI as a matter of urgency.

Supplementary Materials: The source data and calculations can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14020378/s1.

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