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Review

The Impact on Greenhouse Gas Emissions of Rice Crop Management under the System of Rice Intensification: A Review

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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 substantively 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 practiced by millions of farmers in both lowland irrigated rice and upland rainfed cultivation. Thirteen countries have included SRI in their Nationally Determined Contributions to GHG reduction or climate change mitigation. This article reviews 16 field studies of the net reduction in GHG emissions from the adoption of AWD, nine from the adoption of SRI, and two that compared SRI and AWD. Where available, the review includes data on yield and therefore on carbon dioxide-equivalent GHG emissions per kilogram of rice produced. The evidence indicates that AWD and SRI offer a similar and substantial reduction (~35–41%) in GHG emissions per hectare compared with conventional rice cultivation. However, SRI offers ~66% greater yield than CRC, and therefore greater reduction in emissions per kilogram of rice, ~54% more than AWD. The limited data directly comparing SRI and AWD support this finding. SRI also appears to have greater potential to sequester carbon in the soil. SRI lowers rice farmers' costs of production, adds to their income and can make climate-friendly methods more attractive. Both AWD and SRI are greatly preferable to current conventional practices, but SRI offers opportunities to contribute to food security while directly addressing the drivers of climate change.

Keywords: System of Rice Intensification; alternate wetting and drying; greenhouse gas emissions; agricultural methane emissions; food security; 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, ~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. In fact, while rice can survive under flooded conditions, its root systems deteriorate under constant inundation due to hypoxia [4].

Continuous flooding also leads to methanogenesis, the biological process whereby the anaerobic respiration of certain microbes (archaea) in the soil produces methane (CH_4) as a by-product of their metabolism [5]. Other factors also affect this process [6]. The production of methane from rice cultivation is particularly harmful because methane is a potent GHG with a global warming potential

(GWP) that is 27 times greater than carbon dioxide (CO_2) over 100 years and 80 times greater over 20 years [7].

Reducing the rate at which the atmospheric concentration of methane is increasing is critical if we are to keep the average global temperature from rising to more than 1.5°C above its pre-industrial level [8]. Reducing anthropogenic emissions of methane is one of the most urgent and cost-effective ways for staying below the 1.5°C threshold and limiting the worst degrees of environmental change [9]. Rice cultivation represented ~8% of global methane emissions in 2020 [10], with a similar GHG effect as the whole aviation sector [11]. Expanding low-emission rice cultivation methods rapidly could therefore contribute materially to the achievement of global climate-mitigation targets. While we use the GWP100 metric in this paper, as discussed below, a GWP20 metric would arguably present a more realistic picture of the benefits from achieving these reductions in GHG emission.

2. Impacts of Rice Production Methods on Greenhouse Gas Emissions

SRI is a methodology for improving rice cultivation that includes keeping paddy soils moist but mostly aerobic, i.e., not inundated [12]. Irrigation water is provided to rice fields intermittently, usually through what is referred to as alternate wetting and drying (AWD) with no continuous flooding. 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 gets emitted into the atmosphere. As the more aerobic soil conditions created by AWD can increase the emission of N_2O, this must be taken into account when assessing the *net* GHG emissions changes from AWD and SRI.

Initial interest in and research into SRI focused on its yield increases and on some other development advantages, e.g., lower costs of production, higher farmer income, better grain quality, and crop resistance to the hazards of climate change [13]. However, once reductions in GHG emissions began to be documented [14], interest grew in what SRI crop management could do to mitigate global warming. This paper seeks to help scholars, policymakers, and practitioners by identifying and synthesizing studies of the GHG emissions benefits associated with SRI and AWD.

3. Materials and Methods

Researchers have conducted field trials in several countries to compare the GHG emissions of SRI and AWD with those from conventional rice cultivation (CRC) practices. We compiled the published results from field trials that made direct, field-level measurements of GHG emissions, rather than estimates of emissions through modeling based on factors such as flooding days. While this criterion limited the number of studies that were included, it provides a firmer empirical basis.

The absolute values of GHG emissions can vary significantly across locations due to climatic, soil and other conditions, so the focus here is on the percentage changes in emissions per hectare of rice cultivation. Where the studies reported yield data, these are also considered. With yield data, we could also calculate changes in GHG emissions per kilogram of rice produced.

Emissions changes (**Δ**) have been 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, CO_2) by their relevant multiplication factors to arrive at a summed GWP. Such a calculation enables comparison between data sources. The GWP100 factors used are 27 for (non-fossil) CH_4 and 273 for N_2O [7].

We converted values for emissions reduction into per-hectare values where necessary and calculated changes in emissions per kilogram of rice produced where yield data were available.

Although values for CO_2 reduction were reported in some studies, we did not include them in the calculation of GHG/GWP percentage changes. The main factor here is energy savings from reduced irrigation which can be material but vary depending on the type of irrigation system [15]. Where AWD is applied alone, reduced electricity costs and water savings will be the principal benefit for the farmer, although other secondary benefits have been identified [16].

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Data sources were identified from the Cornell University SRI-Rice Zotero database [17] by selecting for articles on GHG emissions. This was cross-checked and expanded upon with a search of the Google Scholar database using search terms including 'system of rice intensification greenhouse gas' and 'alternate wetting and drying greenhouse gas.' Finally, some additional studies were identified through a literature review. One study [14] was excluded as it did not provide numbers, although it showed an unspecified reduction in methane and an unspecified increase in nitrous oxide emissions. Another, significant study [15] was excluded because it did not provide the actual data, although its results are noted in the Discussion.

It is possible that one or more studies have not been captured in this review, but the resulting data set gives a reasonable representation of the variation and direction of the research results in this field. All the source data and calculations are available in the Supplementary Data file.

4. Results

Table 1 presents the results of 9 studies that compared GHG emissions from SRI and CRC practices. All these studies were carried out in India or Nepal, and most investigated emissions of both methane and nitrous oxide. One study measured carbon sequestration and observed a 115% increase in carbon sequestration in rice soils that used SRI compared to CRC practices [18]. However, we could not pursue the important subject of carbon sequestration because so little research has been done and reported on this.

Table 2 presents the results of 16 studies in which GHG emissions from AWD were compared with those from CRC practices. These data are more geographically diverse, coming from Asia, and North and South America.

Table 3 presents the results from the two studies that compared SRI and AWD directly. Just two studies do not provide the basis for generalizing, but they have some value when considered in the context provided by the other data sets.

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Table 1. Field trials comparing GHG emissions and yield of SRI and CRC practices.

Study	SRI Δ from CRC in Net Emissions t CO_2e ha^{-1}	SRI Δ from CRC in Net Emissions kg CO_2e kg^{-1} rice	SRI Δ from CRC in Yield t ha^{-1}
Nepal (2011) [19]	-74%	-88%	+118%
India (2012) [20]	-38%	-44%	+11%
India (2013) [21]	-31%	n/a	n/a
India (2014) [22]	-39%	-37%	-3%
India (2017) [23]	-42%	-62%	+51%
India (2020) [24]	-1%	-11%	+11%
India (2022) [18]	-25%	-67%	+127%
India (2023) [25]	-27%	-71%	+150%

Table 2. Field trials comparing GHG emissions and yield of AWD and CRC practices.

Study	AWD Δ from CRC in Net Emissions t CO_2e ha^{-1}	AWD Δ from CRC in Net Emissions kg CO_2e kg^{-1} rice	AWD Δ from CRC in Yield t ha^{-1}
China (2012) [26]	-24%	-26%	+3%
Korea (2014) [27]	-48%	-49%	+1%
USA (2015) [28]	-89%	-88%	-9%
China (2015) [29]	-64%	-60%	-10%
Brazil (2016) [30]	-38%	n/a	n/a
USA (2016) [31]	-66%	-68%	+9%
China (2016) [32]	-59%	-60%	+2%
India (2017) [23]	-39%	-45%	+11%
Brazil, Japan (2018) [33]	-59%	-62%	+9%
Philippines (2018) [34]	+6%	5%	+2%
Vietnam (2018) [35]	-26%	-31%	+7%
SE Asia (2018) [36]	-13%	-15%	+3%
Indonesia (2018) [37]	-36%	-35%	-1%
Thailand (2018) [38]	-4%	-1%	-4%
India (2018) [39]	-25%	-31%	+8%
Philippines (2020) [40]	-65%	-67%	+6%

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Table 3. Field trials comparing GHG emissions of AWD and SRI.

Study	SRI **Δ** from AWD in Net Emissions t CO_2e ha^{-1}	SRI **Δ** from AWD in Net Emissions kg CO_2e kg^{-1} rice	SRI **Δ** from AWD in Yield t ha^{-1}
India (2017) [23]	–5%	–30%	+37%
India (2023) [41]	–6%	–20%	+17%

5. Discussion

5.1. Overview

To provide an overview of these studies, the results of the above tables are summarized in Table 4 below. By showing ranges and median values, not just mean values, readers can get a better idea of what central tendencies can be discerned from the data. As stated already, GHG emissions are subject to many factors, which makes for both variation and variability.

Table 4a. Improvement (reduction) in CO_2e emissions per hectare.

	n	range	median	mean
SRI **Δ** from CRC	8	–1% to –74	–34%	–35%
AWD **Δ** from CRC	16	+6% to –89%	–39%	–41%
SRI **Δ** from AWD	2	–5% to –6%	–	-5%

Table 4b. Improvement (increase) in yield (tonnes rice produced per hectare).

	n	range	median	mean
SRI **Δ** from CRC	7	–3% to +150%	+51%	+66%
AWD **Δ** from CRC	15	–10% to +11%	+3%	+2%
SRI **Δ** from AWD	2	+17% to +37%	–	+27%

Table 4c. Improvement (reduction) in CO_2e emissions per kg rice produced.

	n	range	median	mean
SRI **Δ** from CRC	7	–11% to –88%	–62%	–54%
AWD **Δ** from CRC	15	+5% to –88%	–45%	–42%
SRI **Δ** from AWD	2	–20% to –30%	–	–27%

Overall, the data show that both SRI and AWD offer a significant reduction in GHG emissions on a per hectare basis (mean reductions of 35% and 41%, respectively) compared with CRC practices. SRI, however, offered a 27% greater reduction in emissions per kilogram of rice produced (mean reductions of 54% vs 42%, respectively). While AWD and SRI have similar capacity to reduce GHG emissions, SRI has greater capacity to improve yields, with a mean increase of 66% vs 2%. Such agronomic performance has been demonstrated in many studies not included here as they do not address or analyze GHG emissions [13].

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The study by Gathorne-Hardy et al. [15], which was not included in the above analysis as noted above, found that SRI management reduced GHG emissions by 61% per kg of rice, which is close to the mean value of the seven studies that included both yield and per kg data. The increase in grain yield reported of ~60%, was also well within the range above, and the authors noted that this increase was achieved despite somewhat lower inputs of nitrogen, phosphorus and potassium (NPK) fertilizers [15].

The studies that compared SRI and AWD respectively with CRC practices do not provide direct evidence of the differences between AWD and SRI because the CRC bases for comparison were not the same. The data in Tables 1 and 2 are consistent with a conclusion that SRI yields are higher than AWD yields on average. The two studies that directly compared SRI and AWD also support this inference, both showing that SRI achieved yields of 17% and 37% more than AWD under similar soil and other conditions. Both studies also found a modest 5–6% improvement in GHG emissions in SRI compared with AWD, which is not a material difference. The two SRI-AWD studies concluded with a significant difference in the GHG emissions per kg of rice produced, which is consistent with the inference that can be drawn from Tables 1 and 2.

5.2. Carbon Sequestration

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. One study found in the literature search [18] found that soil carbon sequestration in SRI-managed rice fields ranged from 27.5 to 96.2 t CO2e ha-1 year-1, more than double the soil carbon sequestration found in CRC fields in the same study. SRI enhances the soil's potential for carbon sequestration because of the greater biomass of rice plants both above and below ground [18], without the trade-off in higher methane emissions that can be caused by greater soil organic matter [42].

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 CO2e emissions reduction in GHG emissions [18]. If substantiated by further research, the carbon sequestration potential of SRI not only extends 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 is therefore highly desirable.

5.3. 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 a significant step towards SRI. Even if AWD does not offer improved yields, the saving in water and electricity costs for pumping may be material. Water consumption can be lowered with AWD by as much as 25-30% without negatively affecting yield [43]. 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 or SRI in some areas.

Once farmers have overcome the challenges of water management by implementing AWD, they will find the transition to SRI – managing plants, soil and nutrients differently – less challenging. Once there, they can enjoy the numerous other benefits of SRI. Aside from improved yield, input costs are reduced for seed, energy and fertilizer, leading to higher returns for farmers [44]. SRI also produces rice seed and grains that are of higher quality than CRC rice [45], and the plants are more resistant to biotic and abiotic stresses [13] as well as being more resilient to cold temperatures, storm damage, and pests and diseases [46,47]. Of course, if farmers can move directly from CRC to SRI practices, so much the better.

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6. Conclusions

This paper reviewed the published literature on greenhouse gas emissions from AWD and SRI and compared these to the emissions from CRC practices. Our findings show that both the System of Rice Intensification (SRI) and alternate wetting and drying (AWD) outperform CRC practices by significantly reducing per hectare GHG emissions. The higher yields observed in these trials with SRI management suggest that it will perform better than AWD alone in terms of per kg of rice produced. Also, there is evidence that the gains from practicing SRI for reducing GWP will be further increased when carbon sequestration in the soil is taken into consideration.

This review offers evidence that for the sake of both climate change mitigation and adaptation, farmers should be encouraged and assisted to move to SRI methods of rice production. SRI offers additional benefits in terms of crop resilience to increasingly extreme and unreliable weather patterns. Seven rice-producing nations have already included SRI in their Nationally Determined Contributions (NDCs) for mitigation of GHG emissions, and six have endorsed it to aid farmer in adaptation to climate change [48].

While the GHG emissions can be reduced by AWD alone, when viewed in total, SRI provides multiple benefits beyond AWD, even if it requires some greater effort 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 [12,49].

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 [50]. When food security is considered by policymakers, 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.

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