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Unlocking the Energy-Water-Carbon Nexus in Rice Cultivation: A Comprehensive Review

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Abstract

Rice cultivation, as a cornerstone of global food security, holds significant environmental implications due to its carbon, water, and energy footprints. Energy, carbon and water footprint assessments can be powerful tools to guide sustainable food production systems. Due to higher water losses in conventional rice culture, the irrigation water footprint associated with rice cultivation increases, thereby elevating the energy and carbon footprint. Improper use of resources like fertilizers, pesticides, labour and fuel may lead to higher energy consumption. Several alternative rice production systems like Direct Seeded Rice (DSR), Alternate Wetting and Drying (AWD), System of Rice Intensification (SRI) as well as better nutrient management practices have been developed and refined to reduce energy, carbon and water footprint associated with rice cultivation. This review presents a comprehensive analysis of the intricate interplay between these footprints, highlighting potential trade-offs and synergies that warrant attention within the context of rice cultivation. Moreover, this review discusses in detail the significance of selecting appropriate rice cultivation techniques, such as direct seeded rice, SRI and alternate wetting and drying suitable for different ecologies in comparison to transplanted method of rice cultivation.

Keywords: Carbon, DSR, Energy, Footprint, SRI, Water.

Introduction

Rice plays a pivotal role in the food and livelihood security of the Asian people. As the continent wise data shows, more than 90% of rice production and consumption takes place in Asia and more than two billion people are getting 60-70% of their energy requirement from rice and its derived products (FAO, 2021). In India, it is the staple food for more than two-thirds of the Indian population contributing to 40% of the total food grain production (Nayak *et al.,* 2020). Globally, rice is grown in 164.8 million hectares with an annual production of about 507.2 million metric tons of paddy (USDA, 2020-21). Globally, India holds first position in terms of rice area and second position in terms of production of rice after China. In India, the rice crop is grown on about 43 million hectares area, with a production of 122 million tones and productivity of 3878 kg ha^{-1} (Nayak *et al.,* 2020). The states including West Bengal, Uttar Pradesh, Andhra Pradesh, Telangana and Punjab alone contribute to more than 50% of the total rice production of the country. The demand for rice is projected to increase in the next 30 years by nearly 70% to maintain the present per capita availability which is 69 kg per annum (Muthayya *et al.,* 2014). However, it is difficult to meet the increasing demand for rice with conventional methods of rice cultivation.

Producing more rice with less water is a formidable challenge. A lot of irrigation water is used to produce rice through conventional method, as a result water scarcity is increasing, especially in most of the rice growing regions (Vijayakumar *et al.,* 2023a). The amount of water applied to produce 1 kg of rice ranges from 800 to 5000 L (Surendran *et al.,* 2021). Rice growing farmers, often apply more irrigation water although rice crop needs a much lower amount for normal growth and yield. The inefficient irrigation in rice causes a rapid decline in ground water table, groundwater pollution and greenhouse gas (GHG) emissions (Vijayakumar *et al.,* 2018). Therefore, it is difficult to meet the increasing demand for rice with conventional methods of cultivation.

Along with water, energy is another major component of rice production. In rice cultivation, energy is used as well as produced, most notably in the form of bioenergy (Alam *et al.,* 2005; Vijayakumar *et al.,* 2019). The energy requirement of rice cultivation is directly related to the management techniques followed and inputs used during the growing season (Mariano *et al.,* 2012; Yadav *et al.,* 2017). Greater energy efficiency in food production systems is required since the projected energy production growth is inadequate and conventional energy sources are limited (Vijayakumar *et al.,* 2023b). Understanding the energy budget in rice cultivation helps in making informed decisions regarding resource allocation to enhance energy use efficiency. Energy footprint (EF) of rice is the equivalent energy associated with various farm operations *viz.,* land preparation, sowing, transplanting, weeding, harvesting and post-harvest management. A production system is considered efficient when it produces higher energy output and consumes comparatively lesser energy (Kumar *et al.,* 2021). By quantification of energy footprints, farmers can choose the most efficient energy sources to maximize the yield by spending less input energy to various farm operations. Energy analysis is also an important tool for judging the rice-based production system efficiency and achieving the Sustainable Development Goals (SDGs).

Growing rice in flooded fields create the ideal anaerobic conditions for bacteria to thrive on decomposing organic matter (mainly rice straw residue) and release methane (Mahato, 2014; Kumar *et al.,* 2016). Poor absorption of nitrogen by rice crop, often overused by farmers, leads to N_2O emissions (Vijayakumar *et al.,* 2022). Burning of rice residues and waste in the value chain add to GHG emissions (Bhaduri *et al.,* 2023). Burning is a convenient way for farmers to quickly dispose large volumes of leftover rice straw (Vijayakumar *et al.,* 2021). Thus, all these practices in rice cultivation increase the GHG emission and ultimately Global warming potential (GWP). According to the Kyoto protocol, carbon footprint (CF) is the total amount of GHGs in terms of carbon dioxide (CO_2) equivalent coming from the product's life cycle, including its storage, use, and disposal (Kijewska and Bluszcz, 2016). Not all GHGs affect climate change in the same way. To easily compare the CF of various products, they are converted to the amount of CO_2 using appropriate factors. The GWP of N_2O and CH_4 are 298 and 25 times that of CO_2, respectively. The CF in rice include the total amount of CO_2, nitrous oxide (N_2O) and methane (CH_4) that are generated during the rice cultivation and the rice value chain (Danish and Wang, 2019; Bhaduri *et al.,* 2023, Grant *et al.,* 2004). Higher production and release of these gases will increase the CF of rice cultivation. In general, the CF of 1 ton of rice varied from 1.11 to 1.57 ton CO_2-eq in the 100-year horizon (Alam *et al.,* 2016). It has recently been estimated that the global food system is responsible for about a third of GHG, second only to the energy sector; it is the number one source of methane and biodiversity loss. The effects of changing climate, rising temperatures, more frequent droughts, floods, and intense typhoons are devastating rice farms and farmer livelihoods (Vijayakumar *et al.,* 2023d). Thus, cultivation of rice in conventional transplanted system may accelerate the global climate change.

Due to higher CF in the recent years, there has been a shift in the regular climate. Climate change induced global warming had a significant impact on rainfall pattern (Vijayakumar *et al.,* 2023e). There was either late onset of monsoon or early cessation of rains. The late onset of monsoon resulted in delay of sowing due to which there were unfavourable conditions at critical growth stages there by reducing the yields. The early cessation of rains caused water deficit during peak period of water requirement which in turn had a great impact on the yields (Vijayakumar *et al.,* 2023d). Irrigation to rice crop is limited in many rice growing areas due to unavailability of power (electricity) and water scarcity. Climate change increased food insecurity from 135 million in 2019 to 345 million in 82 countries by June 2022, as the war in Ukraine, supply chain disruptions, and the continued economic fallout of the COVID-19 pandemic pushed food prices to all-time high. The farming families in Sub-Saharan Africa, South Asia, and Southeast Asia are disproportionately poor and vulnerable. About 80% of the population in this region is at risk from crop failures and hunger due to climate change. A severe drought caused by an El Nino weather pattern or climate change could push millions more people into poverty. The above reasons indicate how the assessment of energy, carbon and water footprint is important.

The carbon, energy, and water footprints are interlinked with each other. Water footprint influences both the energy and carbon footprint by consuming more electricity or fuel and by emitting CH_4. Along with water, fertilizers and other inputs in energy footprint are also reasons for higher carbon footprint by producing CO_2 and N_2O (Surekha *et al.,* 2023). Hence, energy, carbon and water footprints are interrelated with each other **(Figure 1)**. In comparison to other field crops, rice has a higher carbon, energy and water footprint in India and abroad (Sah *et al.,* 2018). Different rice production systems have varying impacts on GHG emissions, and the choice of system should consider both short-term and long-term goals. Some systems may be better suited for immediate GHG emission reduction, while others may offer better long-term sustainability. Therefore, the identification of energy, carbon and water efficient rice cultivation system is important to food security, and sustainable intensification. In this review, we meticulously reviewed the nexus between energy, water and carbon footprint of rice under different rice establishment methods.

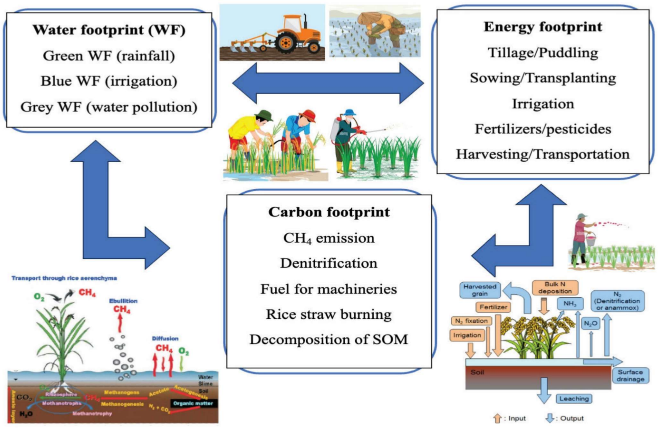

Figure 1: Water, carbon and energy nexus in rice cultivation

Energy footprint of different rice production systems

The identification of energy-efficient rice production systems is gaining importance due to factors such as the increasing demand for rice resulting from population growth, changing societal energy consumption patterns, the recent oil crisis, and pollution caused by the fuel used in agricultural operations` (Bhardwaj *et al.,* 2016). Agriculture is experiencing a faster rate of energy consumption growth than other economic sectors due to the use of mechanized cultivation techniques and soil nutrient materials, particularly fertilizers (Kamoshita *et al.,* 2010). Numerous energy-intensive processes are necessary to produce rice, including tillage, transplanting, irrigation, fertilizer application, pesticide spray, harvesting, transportation, etc. (Mohanty *et al.,* 2014; Vijayakumar *et al.,* 2023c). The use of fertilizers, fossil fuels for machinery, and pesticides has resulted in GHG emissions and environmental pollution (Mansoori *et al.,* 2012). Conventional transplanted method of rice cultivation requires larger energy inputs particularly for water, chemical fertilizers, pesticides, and seeds. This not only contributes to the degradation of soil, water, and air resources, but also reduces economic benefits for farmers and the nation (Pooja *et al.,* 2021). Thus, improving energy use efficiency is one of the criteria for achieving agricultural sustainability, as it lowers production costs and environmental pollution (Mohammadi *et al.,* 2010).

Singh *et al.,* (2019) investigated the energy expenditure in rice cultivation and identified irrigation water use as the largest energy-consuming component, followed by chemical fertilizers. The distribution of energy inputs in rice cultivation was as follows: seed (0.3%), human labour (0.5%), agri-machinery (0.8%), biocides (7.2%), diesel fuel (8.8%), electricity (17.7%), chemical fertilizers (24.7%) and irrigation water (40.0%). Another study by Paramesha *et al.,* (2022) reported that fertilizers (42.7%) had the highest share of non-renewable energy sources, followed by diesel (12.4%) and machines (8.6%). A similar finding was reported by Bockari-Gevao *et al.,* (2005). They found that fertilizers account for the 7700 MJ of energy per hectare with a total energy input of 12400 MJ. A study in North Eastern Region of India showed that the land preparation, application of chemical fertilizers, farm yard manure and seeding and/or transplanting operations consumed more than 80% of energy input in different rice cultivation systems (Mandal *et al.,* 2015). These results emphasize the significant role of land preparation, irrigation and chemical fertilizers in energy consumption during rice cultivation. The total input energy of rice cultivation could be significantly reduced by supplementing chemical fertilizers with FYM, as the use of chemical fertilizers makes farming exceptionally energy-intensive (Billore *et al.,* 1994).

In the modern production methods, direct sowing of seeds on to puddled soil (wet seeding by drum seeder or broadcasting of either sprouted or direct seeds) holds unique relevance because it reduces time, labour, and energy consumption while boosting profitability (Subbaiah and Balsubramanian, 2000) therefore, considered more economical as compared to transplanting. Similarly, the adoption of system of rice intensification (SRI), alternate wetting and drying (AWD), direct seeded rice (DSR) and mechanical transplanting practices in rice cultivation makes the crop cultivation economically viable and environmentally sustainable (Vijayakumar *et al.,* 2023a). Farmers are facing the problem of labour shortage during peak season that delay the timely transplanting and sowing of succeeding crop in the rice-based system. The shortage of labour during the peak period and escalating fuel prices, in turn increase the production cost.

SRI vs TPR

There are differences in energy consumption and energy efficiency among different rice establishment methods. SRI requires less water, fertilizer, seed, and labour inputs, thereby minimizes overall energy requirements and contributing to energy savings in rice cultivation (Srinivas *et al.,* 2022). The SRI method saves approximately 2 MJ of energy per kilogram of rice produced compared to the conventional method. The energy consumption for producing 1 kg of rice is reported as 4.41-4.51 MJ in SRI, while it is 6.36-6.47 MJ in the conventional method. The SRI method achieved a significant reduction in input consumption while increasing output, resulting in improved energy efficiency. SRI method uses 75% lower seed rate than conventional method. SRI method uses only 19 kg of seeds for a hectare of paddy field, as opposed to the conventional method's 76 kg. Because of this, around 1000 MJ of energy is saved (Truong *et al.,* 2017). SRI contributes to a decreased use of chemical fertilizers and pesticides since weeds are controlled through mechanical weeding or manual labor and 50% of the external plant nutrient requirement is supplied through organic sources.

Additionally, SRI contributes to energy savings by utilizing a lesser amount of water for irrigation. SRI significantly reduces irrigation water use by keeping the soil moist rather than in a flooded condition. Das *et al.,* (2014) compared the energy productivity of SRI with conventional rice culture. They found that SRI exhibited the highest energy productivity (0.68 kg MJ^{-1}), while conventional rice culture had lower energy productivity (0.59 kg MJ^{-1}). The mean specific energy of DSR was 3.31 MJ/kg, which was significantly higher than those of SRI (2.76 MJ/kg), modified SRI (2.73 MJ/kg), and transplanted rice (2.89 MJ/kg) (Htwe *et al.,* 2021). Additionally, the highest energy use efficiency (EUE) was observed in the modified SRI (9.60), followed by SRI (9.46), transplanting (8.55) and DSR (8.35). Similarly, Nirmala *et al.,* (2021) reported that the SRI method exhibited higher energy use efficiency (6.6), energy productivity (0.21 kg MJ-1), and lower specific energy (4.69 MJ kg-1) compared to conventional practices. This indicates that SRI is more efficient in terms of energy utilization, resulting in higher productivity per unit of energy input.

DSR vs TPR

The transplanting system consumes more energy in terms of diesel fuel, electricity, irrigation and human labour. In contrast, in DSR, herbicides accounted for the major input energy (Eskandari and Attar, 2015). The total energy output was higher in the transplanting system (114,720 MJ ha^{-1}), while the highest energy ratio was observed in DSR. The DSR method also had higher energy efficiency (2.8) compared to the transplanting method (2.3). DSR utilized more energy to produce one unit of rice grain. The direct seeding method required 85% more energy for weed control and inter-cultivation compared to the transplanted method (Chaudhary *et al.,* 2017). This higher energy requirement was attributed to the use of a greater quantity of herbicides in DSR. In contrast, flooding in the transplanted method reduced the weed burden, leading to lower herbicide use (Rao *et al.,* 2021).

Contrary to previous results, Lal *et al.,* (2020) reported an 18.4% lower energy input in DSR compared to transplanted rice (TPR). The major energy savings were observed in diesel (160%), machinery and labor (66%), making dry-DSR more energy-efficient with only a minor yield penalty. The net energy of TPR was 2.3 and 13.4% higher than wet-DSR and dry-DSR, respectively. Tillage operations for land preparation account for a considerable amount of energy input in rice production. One of the main advantages of No-Tillage (NT) systems over traditional tillage was the minimal energy needed for land preparation. Energy input in DSR and conventional TPR systems was 13% and 19% more than that for the NT-DSR and NT-TRP, respectively. The mechanized TRP system required a larger energy input for sowing and transplanting than any other approach because it used machines for transplanting and more labour to set up a mat-type nursery. On the other hand, direct seeding required 22% less energy than TPR because of the absence of nursery preparation (Mandal *et al.,* 2015).

Energy budget of different rice seeding methods

The energy use efficiency and energy productivity were found to vary among the different rice establishment methods. The use of seed-cum-fertilizer drill is the energy efficient method for establishing rice under dry direct seeding, compared to manual line and broadcast seeding. The drill-seeding of rice increased energy use efficiency by 13% compared to line-seeding and broadcast seeding (Saha *et al.,* 2021). For each unit of energy consumed in the fields, drill seeding resulted in 0.47 yield units, manual line-seeding achieved 0.42 yield units and broadcast seeding obtained 0.38 yield units (Saha *et al.,* 2021). Utilizing drill-seeding method for rice crop establishment will maximize the energy use efficiency and energy productivity in rice cultivation. Rice fields are submerged for most of their growth period. Therefore, puddled transplanted rice (PTR) is considered an energy-intensive and more GHG-emissive crop compared to other cultivated crops. To achieve higher productivity, the PTR system primarily relies on indirect and non-renewable energy sources, such as fertilizers, machinery, chemicals, irrigation, seeds, fuel and electricity (Mansoori *et al.,* 2012).

The investigation on specific energy requirement of various rice cultivation practices revealed that drum-seeded rice requires significantly lower specific energy, with reductions of 19.0% and 16.8% compared to broadcasting of dry seeds and sprouted seeds, respectively (Bhardwaj *et al.,* 2016). It suggests that using the drum-seeding method can lead to energy savings in rice cultivation compared to broadcasting of seeds. The transplanting method of rice cultivation demands more water and this system suffers from more surface evaporation and percolation loss of water, which, in turn, increases the frequency and duration of irrigation. Additionally, this system requires puddling to make the soil soft and easy for transplanting. All of these processes lead to an increased input energy requirement in the transplanted rice system (Begum *et al.,* 2006). Using surface water resources rather than groundwater sources can help reduce the amount of electricity and diesel fuel needed to deliver water for rice cultivation.

The tillage method employed in rice cultivation has a significant role in fuel consumption, water input and operational efficiency. Compared to puddling, non-puddled strip and zero tillage reduced fuel consumption for mechanical transplanting by 11-18%. Additionally, strip tillage reduced tillage time and fuel consumption by 50-70% (Hossen *et al.,* 2018). Adoption of conservation tillage and efficient residue management enhanced energy productivity from 15.8% to 21.0% and energy use efficiency from 17.1% to 22.4% compared to conventional practice (Singh *et al.,* 2022). The experiment on No till (NT) and Conventional tillage (CT) with different mulching systems revealed that NT rice system required 48.3% less energy (8,479 MJ ha^{-1}) than CT system (16,465 MJ ha^{-1}) and the energy productivity was higher in NT (45437 MJ ha^{-1}) than CT (44834 MJ ha^{-1}). The NT system had higher net energy (36,958 MJ ha^{-1}), energy use efficiency (5.36), energy productivity (0.36 yield kg MJ^{-1}) and lower specific energy (2.76 MJ kg^{-1}) compared to CT (Yadav *et al.,* 2020). Absence of tillage operations like plowing, tilling and leveling under NT led to a reduction in energy input, whereas the CT with multiple tillage operations required nearly double the amount of fossil fuel as energy input in operating the field machinery **(Table 1)**.

Table 1: Comparison of energy use between no-till and conventional tillage systems in rice

S. No.	Energy use	Input energy for NT (MJ ha^{-1})	Input energy for CT (MJ ha^{-1})	Energy saving in NT over CT (%)
1.	Machine operations	157	4546	96.5
2.	Diesel consumption	3942	4195	93.9
3.	Pesticides	981	621	36.7
4.	Other operations	3399	7103	52.1
5.	Total consumption	8479	16465	48.3

Source: Yadav et al., (2020)

Hence, an appropriate tillage system selection is an important consideration for crops which helps in reducing energy consumption and plays a great role in energy budgeting. Farmers should be taught to decrease unnecessary energy use in order to optimize energy use in rice production systems. It is essential to use machinery, fertilizer, and other inputs under the supervision of agricultural specialists. One of the most significant strategies to reduce energy usage in the context of herbicides is to increase farmers' awareness about non-chemical weed control. Despite the fact that direct seeding systems have the advantage of consuming less energy, improving the productivity of rice under this system will motivate farmers to adopt it on a large scale **(Table 2)**.

Table 2: Energy budget of different rice production systems

S. No.	Production system	Input energy MJ ha^{-1}	Output energy MJ ha^{-1}	EUE	References
1.	SRI	25378	221221	8.70	Troung *et al*., (2017)
	Conventional transplanting	32794	199372	6.07	
2.	SRI	6895	149884	21.7	Das *et al*., (2014)
	Integrated rice culture	6925	151942	21.9	
	Conventional rice culture	7250	132232	18.2	
3.	Drum seeding	11255	64240	5.71	Bhardwaj *et al*., (2016)
	Broadcasting	11208	53660	5.64	
	Transplanting	11520	64940	4.79	
4.	Wet DSR	15809	162210	10.3	Lal *et al*., (2020)
	Dry DSR	14156	143123	10.1	
	Transplanted rice	16051	176286	11.0	
5.	DSR	34623	98677	2.85	Eskandari and Attar (2015)
	Transplanting	49878	114720	2.30	
6.	No tillage	8479	45437	5.36	Yadav *et al*., (2020)
	Conventional tillage	16465	44834	2.72	
7.	No tilled DSR	9162	100782	11.00	Mandal *et al*., (2015)
	Mechanized TRP	15371	132191	8.60	

Carbon footprint

Agricultural operations, such as tillage, irrigation, fertilizer application, inter-cultivation, and harvesting, contribute to greenhouse gas (GHG) emissions, with a substantial effect on global warming and climate change (Yadav *et al.,* 2018). A significant portion of GHG emissions (10-14%) that contribute to climate change is produced during agricultural production (Jantke *et al.,* 2020). In India, agriculture is one of the significant contributors to the national economy, accounting for 19% of the total GHG emissions (Sharma *et al.,* 2011). Within agriculture, wetland rice production contributes to 55% of agricultural GHG emissions globally. Rice production accounts for the emission of 97 million metric tonnes of carbon dioxide equivalent annually, ranking fourth in importance after enteric fermentation (40%), livestock manure management (23%) and fertilizer use (13%) (FAO, 2017). Therefore, any new technology with the potential to reduce GHG emissions from wetland rice could make a significant contribution to global warming mitigation.

In rice production, irrigation water contributes to methane emissions, NPK fertilizer applications contribute to nitrous oxide emissions (Hoben *et al.,* 2011; Venterea *et al.,* 2012) and the use of diesel machinery contributes to carbon dioxide emissions (Afiyanti *et al.,* 2018). These emissions collectively contribute to the CF of rice production. Continuous flooding, nitrogenous fertilizers, and machinery are responsible for higher GHG emissions from rice field (Pathak *et al.,* 2014). Constant flooding and the use of organic manures are the primary sources of methane emissions in conventional rice culture (Pathak *et al.,* 2014). When compared to other crops, transplanted rice produces the most GHGs, with emissions reaching 1112 kg CO_2 eq./ha (Soni *et al.,* 2013). Rice cultivation practices that optimize irrigation water usage may offer a means to reduce the CF, contributing to climate change mitigation. The CF of rice cultivation varies with the season and the method of rice crop establishment. For example, in Indonesia, the highest CF during the dry and rainy seasons was observed in the Belitung Islands and East Nusa Tenggara province, respectively. This is primarily due to paddy cultivation in these regions, which demands more water due to their topography and dry weather conditions, leading to significant water requirements in these areas.

Meanwhile, the lowest CF in both the dry and rainy seasons was recorded in Yogyakarta province, which employs several agricultural practices that are more water-efficient, including SRI and AWD practices.

During the dry season, complete AWD is an effective water management practice to replace conventional flooding, as it can help mitigate GHG emissions, conserve water and increase yield. Incomplete AWD reduces methane emissions by 10.62% but increases nitrous oxide emissions by 5.94%, while complete AWD reduces CH_4 emissions by 23.10% but increases N_2O emissions by 14.79% (Sriphirom *et al.,* 2019). Although both AWD systems increase N_2O emissions, their total GWP remain lower than those of conventional flooding, with a reduction of 5.32% under incomplete AWD and 10.83% under complete AWD. In terms of rice yield, enhancements are observed only under complete AWD, with a 2.42% increase attributed to a higher number of tillers and panicles. The CF is reduced by 13.95% under complete AWD but increases by 3.44% under incomplete AWD. In another study, the AWD method reduced seasonal CH_4 emissions by 47% per hectare and the CH_4 emission factor by 88% per hectare per day. Moreover, AWD decreased the overall GWP by 41% and improved water productivity by 32% compared to the conventional flooding method. AWD also increased paddy productivity by 3% while reducing irrigation water consumption by 27% and associated costs by 24% (Mohammad *et al.,* 2018).

Production inputs such as fertilizers, insecticides, organic manure, fossil fuels, machinery, and irrigation systems have a major impact on GHG emissions (Soni and Soe, 2016). Fertilizer, especially nitrogenous fertilizer, is a significant contributor to the CF and energy consumption. If nitrogen use efficiency is enhanced or properly managed through improved agronomic practices, it can reduce total emissions by 30 to 50% (Liu *et al.,* 2016). Similarly, Paramesha *et al.,* (2022) observed that the highest GHG emissions were from nitrogenous fertilizers (72.1 kg CO_2 eq./ha), followed by machinery (68.5) and diesel fuel (67.9), with the least GHG emissions from insecticides (5.9) due to their low usage. In contrast to previous study results, Kramer *et al.,* (1999) reported that the combustion of diesel fuel by farm machinery had a greater contribution to GHG emissions, followed by fertilizers in the Dutch region. Periodic soil testing, as well as the use of organic sources of nutrients such as green manure, Azolla, and farmyard manure (FYM), can help limit the indiscriminate use of fertilizers (Mohammadi *et al.,* 2013).

Growing fertilizer-responsive, high-yielding cultivars in nutrient-poor soil results in the increased use of chemical fertilizers and higher GHG emissions. The increased usage of diesel fuel, due to intensive tillage and increased mechanization, results in additional GHG emissions. It emphasizes the potential for conservation tillage to save energy and reduce GHG emissions by reducing the use of machinery and fossil fuel combustion. To conserve energy and reduce GHG emissions, farmers must implement conservation tillage and better crop management techniques. The GWP of dry direct-seeded rice (DDSR) and wet direct-seeded rice (WDSR) was lower by 76.9% and 58.5% in 2014, and 75.4% and 62.2% in 2015, compared to transplanted rice (Tao *et al.,* 2016). The use of DDSR can decrease the CF of rice by more than 30%, mainly by reducing input requirements for irrigation and energy, resulting in a lower GWP (Kumar *et al.,* 2018). Transplanted rice (TPR) recorded the highest CF of 2470 kg CO2-e./ha, which were 3.3% and 8.4% higher than those of wet and dry DSR, respectively (Lal *et al.,* 2020).

The CF of rice cultivation varies between regions and states, with differences in crop management practices and input utilization contributing to these variations. Excessive consumption of fertilizers, pesticides, and fuel can result in higher carbon footprints in specific areas. For example, in Karnataka state, Raichur district recorded the highest CF (1532 kg-CE ha^{-1}), closely followed by Ballari and Koppal districts, each with 1368 kg-CE ha^{-1}, compared to the state's average carbon input of 1081 kg-CE ha^{-1} (Sridhara *et al.,* 2023). The CF of Raichur district and Ballari and Koppal districts was 42% and 27% higher than the state average due to excess consumption of fertilizers, pesticides, and fuel by 129%, 32% and 140%, respectively, over the state average (Sridhara *et al.,* 2023). Dash *et al.,* (2023) quantified the CF of major rice production systems, namely aerobic rice (AR), shallow lowland rice (SLR), SRI, deep water rice (DWR), and zero-tilled direct-seeded rice (ZTR) in India. They concluded that DWR had the highest seasonal cumulative CH_4 emission (115.1 kg ha^{-1}), while AR had the lowest cumulative CH_4 emission (34.5 kg ha^{-1}). The higher seasonal cumulative N_2O emission was observed in the AR system (1.40 kg ha^{-1}), followed by SRI (1.10 kg ha^{-1}), and the least was in DWR (0.86 kg ha^{-1}). Among these systems, DWR had the highest estimated seasonal mean GWP (3.92 t ha^{-1}), while AR had the lowest (1.48 t ha^{-1}).

The CF per tonne of rice production among these systems varied from 0.57-0.87 t C-eq t^{-1} rice, with the lowest value found under ZTR, while the SRI system recorded the highest CF. The zero-tilled direct-seeded rice system saved 28.3%, 34.0%, 48.6% and 53.3% of C-eq emissions per tonne of rice production compared to DWR, AR, SLR and SRI, respectively. However, total GHG emissions were lower in AR compared to ZTR due to a lower carbon stock. Therefore, if the focus is on short-term or immediate GHG emission reduction, AR appears to be a good option. However, for a long-term strategy, ZTR, with its lower CF and higher soil carbon stock potential, needs to be promoted with incentives. They also concluded that although CF in SRI was higher, this system is potentially higher yielding and sequesters more carbon in the soil.

Yadav *et al.,* (2020) conducted a field trial to determine the carbon-efficient rice production system among No till (NT) and Conventional tillage (CT) with different mulching systems (RSM-Rice straw mulch, GLM-Gliricidia mulch, BMM-Brown manuring mulch of cowpea, and NM-No mulch). They found that total CO_2-e emissions from NT were lower (1,080 kg CO_2-e ha^{-1}) compared to CT (1,292 kg CO_2-e ha^{-1}). The difference of 212 kg CO_2-e ha^{-1} between CT and NT was attributed to the increased use of diesel-operated power tillers for field preparation under CT (247 kg CO_2-e ha^{-1}) compared to NT (15 kg CO_2-e ha^{-1}). An increase in diesel consumption under CT had a major contribution to high GWP and total CO_2-e emissions. Regarding the mulching treatments, GLM and BMM mulches had slightly higher CF (3-8%) compared to RSM and NM. However, yield improvement, energy use efficiency, and economic profitability were significantly higher in these mulches compared to RSM and NM. The reduction in tillage operations resulted in lower energy consumption and saved fossil fuel, leading to the lowest GWP under NT (Pratibha *et al.,* 2015). This implies that the adoption of conservation agriculture practices, such as no tillage or reduced tillage along with in-situ mulching, will reduce the energy footprint by saving diesel, water, and other intensive inputs. This approach represents a better option for maximizing yield and profit in direct-seeded upland rice cultivation **(Table 3)**.

Table 3: Carbon footprint of different rice production systems

S. No.	Rice production system	CO_2 e kg ha^{-1}	Reference
1.	Transplanted rice	2099	Lal *et al*., (2020)
2.	Wet DSR	2035	Lal *et al*., (2020)
3.	Dry DSR	1939	Lal *et al*., (2020)
4.	Manual broadcasting	4984	Nguyen *et al*., (2022)
5.	Blower seeding	4991	Nguyen *et al*., (2022)
6.	Drum seeding	4995	Nguyen *et al*., (2022)
7.	Mechanical transplanting	4679	Nguyen *et al*., (2022)
8.	No tillage rice	1080	Yadav *et al*., (2020)
9.	Conventional tilled rice	1292	Yadav *et al*., (2020)

The combination of ZT and rice residue retention could potentially be an option to build up soil carbon, lower GHG emissions, with a relatively less negative impact on crop yield compared to rice residue retention/incorporation and green manuring alone in lowland transplanted rice in the tropics (Dash *et al.,* 2017). The comparison of drip irrigation with a plastic-film-mulch system (DP) with conventional flooding (CF) reveals that the GWP was 36 and 4 g m^{-2} $season^{-1}$ for CF and DP, respectively (Fawibe *et al.,* 2019). The GWP was reduced by 89% under DP compared to CF. The potential loss of soil organic carbon (SOC) caused by higher soil aeration under the non-flooded system has the capability of increasing GWP. Nevertheless, the use of plastic-film-mulch could possibly mitigate the loss of SOC. This indicates that drip irrigation with ground cover rice production using mulching will reduce both the water and carbon footprint (Samoy *et al.,* 2022).

The carbon footprint of rice production is a complex issue influenced by various factors, including water management, fertilizer use, regional variations, and specific practices. Efforts to reduce GHG emissions in rice production should consider a combination of practices and techniques that promote sustainability, increased yields, and economic profitability while minimizing the impact on climate change.

Water footprint

Water is the most essential ingredient for all living things. Three major sectors i.e., agriculture, domestic consumption and industry are competing for water, thus it is going to be a scarce commodity worldwide. The irrigation water utilized for land preparation processes does not find utilization in plant transpiration, thus leading to loss from paddy fields (Mallareddy *et al.,* 2023). This phenomenon distinguishes rice cultivation from other forms of irrigated crops. The water requirement of rice depends on many factors encompassing environmental conditions, the growing season, length of the growing period (LGP), weather parameters, soil type, and other hydrological parameters (Nayak *et al.,* 2022). Numerous studies have reported a range of 1000–2000 mm ± 350 mm as water demand in rice cultivation **(Table 4)**. The compilation of data from various studies reflects a broader range of seasonal water usage, spanning from 660 to 5280 mm. The wide variation in seasonal water requirement for rice farming was mainly attributed to deep percolation losses which notably varies across different soil types (clay loam: 1566 mm; sandy loam: 2262 mm). Other factors include climate, varied management practice and hydrological circumstances.

Table 4: Typical seasonal water outflows and input in lowland rice

S. No.	Item	Water outflow and input (mm)
1.	Land preparation	160-1560
	Crop growth period requirement	
2	*Evapotranspiration*	
	i) Wet season	400-500
	ii) Dry season	600-700
3.	*Seepage and percolation*	
	i) Heavy clays	100-500
	ii) Loamy/sandy soils	1500-3000
	Total seasonal water input	**660-5280**

Source (Tuong and Bouman, 2003)

DSR not only reduces the reliance on fresh and groundwater resources, but also demonstrates an enhanced ability to harness rainwater effectively. DSR has the capacity to reduce the total water footprint associated with rice production (Chakrabarti *et al.,* 2014) and boasts a substantially lower water footprint (953.8 m^3 per ton), in stark contrast to the transplanted rice (1071.1 m^3 per ton). The effects of different crop establishment methods *viz.,* Dry Seeding (DS), Wet Seeding (WS) and Transplanted method (TP) on irrigation input and water productivity in the Muda Irrigation Scheme, Malaysia from 1988 to 1994 revealed that crop establishment methods such as DS and WS significantly reduced irrigation and total water input during the pre-crop establishment period, due to reduced land preparation compared to TP. However, during the crop growth period in the main field, TP had a significantly shorter crop growth duration (110 days) and lower total water input compared to DS and WS. DS rice required significantly less irrigation water for unit production and exhibited higher water productivity (1.48 kg m^{-3}) compared to WS (0.62 kg m^{-3}) and TP (1.00 kg m^{-3}) (Cabangon *et al.,* 2002). The advantage of WS rice over TP rice depends on the balance between the reduction in depletion and outflow before crop establishment and the increase in the same during the crop growth period. Dry seeding can advance the establishment of the wet-season crop, does not require pre-saturation irrigation, and shortens the land preparation period considerably compared with WS and TP rice. These factors lead to a reduction in seepage and percolation, evaporation and evapotranspiration, and irrigation water amount.

Crop evapotranspiration accounted for 26.8% and 27.9% of the total water input in TPR and DSR, respectively. Runoff accounted 20.4% and 7.9%, while deep percolation beyond 100 cm depth accounted for 55.9% and 67.5% in TPR and DSR, respectively. This indicated that DSR had 14.6% more deep percolation, which has the potential to contribute to groundwater recharge. Additionally, 23.6% of irrigation water was saved under DSR fields compared to TPR during the crop period (Gulati *et al.,* 2022). DDSR yielded 6040 kg/ha (only 5.5% less than PTR) and saved 32.6% of irrigation water, and 48.9% of labor compared to PTR (Ramesh *et al.,* 2023). Thus, DDSR is a promising solution for areas with water scarcity and labor shortage.

The SRI practices combined with the AWD method of irrigation resulted in a remarkable water saving (22.2%) compared to continuously flooded rice cultivation (Thakur *et al.,* 2011). Similarly, in sandy loam soils of the ICRISAT farm, SRI demonstrated water savings of 22% and 38% during the dry and wet seasons, respectively compared to conventional methods (Viraktamath and Kumar, 2007). The water savings in the AWD system were primarily attributed to the reduction in seepage and percolation losses. Furthermore, the SRI method required 1,463 liters of water to produce 1 kilogram of rice, whereas continuously flooded rice cultivation required 2,778 liters of water for the same rice production (Thakur *et al.,* 2011). This highlights the significant water-saving potential of the SRI method. The water productivity with AWD-SRI management practices was nearly double (0.68 grams per liter) compared to the water productivity of continuously flooded rice cultivation (0.36 grams per liter).

AWD practices reduced water input, amounting to 26-29% during the *kharif* season and 22-27% in the *rabi* seasons. The AWD practice also improved the water use efficiency by 27-33% during the *kharif* season and 20-29% in the *rabi* season. Furthermore, the consumptive water footprint was reduced by 2-3% and 2-5%, and blue water footprints were reduced by 7% and 4-5% in *kharif* and *rabi* seasons, respectively (Biswas *et al.,* 2021). The reduction in evapotranspiration by approximately 6% in both *kharif* and *rabi* seasons contributed to water saving. Pan *et al.,* (2017) reported a 24 to 71% reduction in water input under AWD based on a two-year study. AWD method resulted in a 3% increase in paddy productivity, accompanied by a significant decrease in irrigation water consumption by 27% and associated costs by 24%. As a result, it improved water productivity by 32% compared to the CF method (Mohammad *et al.,* 2018).

Dry Direct Seeding (DDS) method required approximately 983 mm of water, while providing a water productivity of 6.27 kg ha^{-1} mm^{-1}. In contrast, the transplanting method required 1238 mm of water with a water productivity of 5.03 kg ha^{-1} mm^{-1}. The DDS method, by avoiding puddling and facilitating rainfed cultivation up to 45 days post sowing, reduced the duration of water requirement and resulted in reduced overall water consumption compared to transplanting (Suresh *et al.,* 2004). Moreover, the study by Tao *et al.,* (2016) contributes further insights by establishing a reduction of 24.7% in irrigation water consumption for DDSR compared to wet DSR and a reduction of 13.3% in comparison to transplanted rice. Additionally, the water productivity of DDSR was 11.6% higher than transplanted rice, while wet DSR had a water productivity 13.4% higher than transplanted rice. It is worth noting that wet DSR recorded higher water productivity compared to transplanted rice and DSR due to increased grain yield **(Table 5)**.

Table 5: Water productivity of different rice production systems

S. No.	Production system	Total water productivity (kg hamm^{-1})	Irrigation water Productivity (kg hamm^{-1})	Reference
1.	Conventional tilled puddled transplanted rice	1.93	-	Guru *et al.* (2017)
	Reduced tilled DSR in vatter conditions	2.43	-	
2.	SRI	5.8	15.8	Raj *et al.,* (2017)
	PTR (Puddled transplanted rice)	3.5	8.0	
	DSR (Direct seeded rice)	3.4	8.2	
3.	ICM (Integrated cultural management)	2.86	-	Das *et al.,* (2014)
	SRI	2.98	-	
	CRC (Conventional rice culture)	2.63	-	
4.	Aerobic rice irrigation at 75% CPE	-	8.61	Duary *et al.,* (2022)
5.	Aerobic rice drip irrigation 1.5 Epan in raised bed system	4.10	-	Bhavana (2022)
	Aerobic rice with surface irrigation	3.26	-	
6.	Surface irrigation (Aerobic rice)	4.6	4.5	Pascual *et al.,* (2022)
	40 cm drip line spacing	5.5	5.5	
	60 cm drip line spacing	7.7	7.4	
	80 cm drip line spacing	6.1	6.0	
7.	Continues ponding	3.5	3.6	Poddar *et al.,* (2022)
	AWD	3.9	4.0	
	Saturation	4.6	4.8	

The irrigation input for wet seeded rice on puddled soil was significantly higher (2817 mm) compared to other establishment methods (puddled transplanted rice (PTR), non-puddled transplanted rice (NPTR), surface seeded rice on non-puddled soil (NWSR) and dry seeded rice (DSR) in both wet and dry seasons (Evangelista *et al.,* 2014). This higher irrigation requirement can be attributed to several factors, including the need for water during the puddling process, the cracking of puddled soil during crop establishment which necessitates additional irrigation and the longer duration of the wet seeded crop in the main field compared to transplanted crops. These factors collectively contribute to the higher irrigation input associated with direct seeded rice cultivation. In general, DSR recorded higher water productivity compared to transplanting method. For example, the comparison of water productivity of DSR and transplanting methods reveal that the water productivity in DSR ranged from 0.40 to 0.46 kg grain m^{-3} of irrigation water, while under transplanting, it varied from 0.29 to 0.39 kg grain m^{-3} of irrigation water (Gill *et al.,* 2006). Adopting improved DSR resulted in labor savings (40-45%), water savings (30-40%), fuel/energy savings (60-70%) and reduced greenhouse gas emissions (Yaduraju *et al.,* 2021).

The total water input of transplanted flooded rice with the average flooding depth of 3.9 cm and the average flooding period of 114.0 days was 1255.0 mm. In contrast, for direct seeded flooded rice, the total water input (1022.8 mm) was significantly lower than transplanted rice as the average flooding depth and the average flooding period were 2.6 cm and 93.5 days, respectively. Furthermore, for direct seeded rice with AWD, the average flooding depth was even lower (0.8 cm), the average flooding period was significantly reduced to 13.5 days and the total water input was 607.5 mm. This indicates that compared to transplanted flooded rice, both direct seeded flooded rice and direct seeded rice with AWD significantly reduced flooding depth, flooding period and total water input. Specifically, when compared to transplanted flooded rice, direct seeded flooded rice demonstrated a 34.1% reduction in flooding depth, a 17.8% reduction in flooding period and a 22.1% reduction in total water input. Similarly, direct seeded rice with AWD exhibited even greater reductions, with a 79.5% decrease in flooding depth, an 88.2% reduction in flooding period and a 53.7% decrease in total water input.

Conservation agriculture plays a major role in reducing water footprint. For example, strip and zero tillage methods reduced irrigation water input for transplanting by 22% and 28%, respectively (Hossen *et al.,* 2018). Strip and zero tillage also improved soil physio chemical properties. The delay of first flood irrigation until 55 days after sowing (DAS) of DDSR (Dry DSR) decreased the number of irrigations required from eight to four in 2014 and from twelve to seven in 2015. Furthermore, the amount of irrigation water applied was significantly reduced from 376 mm to 185 mm in 2014 and from 477 mm to 284 mm in 2015. The slight drought stress in the early vegetative growth stage did not negatively affect the plant growth or yield (Jiang *et al.,* 2016). This emphasizes that number and frequency of irrigation influence the crop water requirement.

The highest grain yield of 4.56 t ha^{-1} was obtained with continuous ponding, which outperformed AWD with a yield of 4.30 t ha^{-1} and saturation with a yield of 3.97 t ha^{-1}. However, when considering crop water productivity (CWP), saturation achieved a CWP of 0.428 kg m^{-3}, which was 13.5% higher than AWD (0.377 kg m^{-3}) and 24.9% higher than continuous ponding (0.343 kg m^{-3}). Despite having the highest grain yield, continuous ponding had a lower CWP compared to saturation and AWD (Poddar *et al.,* 2022). Enriquez *et al.,* (2021) conducted a study comparing the water use between traditional continuous flooding and AWD methods. Their findings revealed that AWD reduced water use by 16-28% in both pump and canal-based irrigation systems compared to traditional continuous flooding. This indicates that AWD is an effective approach for reducing water consumption in rice production. Aerobic rice saved water by 11.2% and 28.4% in 2018 and by 5.72% and 32.98% in 2020, compared to AWD and conventional flooding (CF), respectively. This suggests that aerobic rice has the potential to significantly reduce water usage compared to AWD and CF methods (Hussain *et al.,* 2021).

Perennial rice

Perennial rice holds the promise of substantially reducing the carbon, water, and energy footprints associated with traditional annual rice cultivation. This innovative approach to rice farming entails cultivating rice varieties that have longer life cycles and can persist for multiple years, as opposed to the conventional practice of replanting each season. Perennial rice systems can contribute to a decreased carbon footprint by minimizing the need for frequent soil disturbance through tillage and replanting. Reduced soil disturbance prevents the rapid decomposition of organic manures, thereby reducing the release of carbon dioxide and other GHGs stored in the soil. The establishment of a perennial root system also enhances carbon sequestration in the soil, further mitigating atmospheric carbon levels. Similarly, perennial rice systems generally exhibit deeper and more extensive root systems, enabling them to access water resources more effectively. This increased water use efficiency is especially valuable in water-scarce regions, where traditional rice cultivation may require intensive irrigation. By tapping into deeper water sources and reducing surface evaporation, perennial rice can conserve water resources and contribute to improved water management. Perennial rice systems promote healthier soil structures due to reduced disturbance and continuous root growth. This, in turn, enhances soil water retention and nutrient cycling. The longer life cycle of perennial rice reduces the frequency of land preparation, planting, and other labor-intensive tasks. This results in lower energy requirements for machinery operation and reduced use of fossil fuels. Furthermore, the decreased need for annual replanting and associated inputs like fertilizers and pesticides can contribute to energy savings. The adoption of perennial rice has the potential to revolutionize rice cultivation by offering a more sustainable and environmentally friendly alternative to traditional annual systems. By addressing the carbon, water, and energy footprints of rice production, perennial rice contributes to a more resilient and sustainable agricultural future.

Conclusion

Based on this review it is concluded that the method of rice crop establishment, irrigation method and crop management practices followed, climatic conditions and resource availability during crop growing season are the major determinants of energy, carbon and water footprint of rice crop. The conventional transplanted rice cultivation leads to more water and energy carbon footprint while alternate rice production systems such as SRI, AWD, DSR (drum-seeding and broadcasting) and better nutrient management practices like SSNM, use of nutrient decision support tools like a nutrient expert, leaf colour chart, chlorophyll meter, nano-fertilizers, slow releasing fertilizers and legumes in the off-season will help to reduce the carbon, water and energy footprint in rice cultivation. Although micro-irrigation and fertigation were found to be more efficient in terms of energy, water and nutrients than conventional transplanted rice, still its adoption is less. Appropriate interventions are required for all farming communities through proper subsidy policies to ensure large-scale adoption. To reduce the utilization of fossil fuels in rice cultivation, the development of renewable energy (solar energy, biofuels) driven machinery and its adoption is vital. Suitable governmental policies/promoting schemes and subsidies to machinery and irrigation accessories will ensure its large-scale adoption. Hence, method of establishment, irrigation method followed, better crop management practices, climatic conditions and resource availability during crop growing season will decide the energy, carbon and water footprint of rice crop.

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