PLANT SCIENCE TODAY
Vol 12(2): 1-17
https://doi.org/10.14719/pst.6988

eISSN 2348-1900

REVIEW ARTICLE

A review on adaptive water management for climate-resilient rice: Mitigating greenhouse gas (GHG) emissions

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Received: 31 December 2024; Accepted: 29 April 2025; Available online: Version 1.0: 23 May 2025; Version 2.0 : 31 May 2025

Cite this article: Ajith Kumar M, Raju M, Pazhanivelan S, Selvakumar S, Sivakumar R, Ragunath K, Kalaimathi V. A review on adaptive water management for climate-resilient rice: Mitigating greenhouse gas (GHG) emissions. Plant Science Today. 2025; 12(2): 1-17. https://doi.org/10.14719/pst.6988

Abstract

Rice production is essential for global food security and socio-economic development, as it is a staple food for many people. However, low water-use efficiency/water productivity is noticed due to the high water input in the traditional transplanted rice ecosystem with stagnant water. On the other hand, climate change affects the hydrological cycle through precipitation, causing increasing water demand and major threats to the sustainability of rice cultivation and food security for the growing population. A significant need is to find out the balance between water conservation practices and their influence on greenhouse gas (GHG) emissions, mainly methane. This review gives insight into a comprehensive analysis of sustainable rice production systems that improve water productivity while reducing GHG emissions, a crucial gap in existing research. To overcome this, we evaluate key strategies like aerobic rice, alternate wetting and drying (AWD), direct-seeded rice (DSR), drip-irrigated rice, a system of rice intensification (SRI) and Internet of Things (IoT) based smart irrigation, highlighting the potential water use efficiency and reducing carbon footprints. Notably, we spotlight low methane-emitting rice cultivars and drought resistance right cultivars as promising low-emission rice cultivation solutions. Additionally, this article underscores the adoption of simulation models on water productivity and seasonal GHG emissions in rice. This review provides valuable insight for policymakers and researchers to optimize rice production under changing climatic conditions. This review underscores the need for effective water management practices to enhance food security while reducing environmental impacts.

Keywords: biochar; carbon sequestration; drought-resistance; greenhouse gases; water use efficiency

Introduction

Rice (*Oryza sativa* L.) is the major food crop consumed by billions of people worldwide. It is cultivated around 164 million hectares with an annual production of 756.74 million tonnes and productivity about 4.6 t/ha (1). Among the Asian countries, India has the largest rice area under cultivation 46 Mha, with an annual production of 129 mT. The growing population demands a large increase in food supply and increased urbanization leads to the shrinking of cultivable lands. The increasing rice consumption rate is a primary barrier to global food security. India is the largest rice consumer (143 Mmt consumption) followed by China 100 Mmt (2). Irregular and variation in rainfall events have a negative impact on rice production and the decline in the rice areas in upcoming years (3) According to IRRI report, 35 % of the total world's population will increase by 2025, thereby increasing the water needs for residential purposes, which leads to a decreased supply to the rice growing areas (4). Consequently, water scarcity has become a major global concern for rice cultivation. To ensure food security, it is necessary to investigate alternative methods of rice cultivation with low water consumption cultivation practices.

However, in Asia, rice cultivation alone requires half of the available freshwater. Raising water costs and declining ground and surface water resources lead to improving rice water productivity. The declining groundwater resources affect sustainable rice production and limit the yield of rice. Since rice cultivation is water-intensive, various measures have been developed to improve water use efficiency; however, these measures are necessary to address the growing water scarcity for irrigation and the rising costs associated with water usage. To stop the over-exploitation of surface and groundwater resources and improve the amount of water available for non-agricultural purposes (urban, environmental and recreational) (5). Improving water productivity involves limiting the irrigation water crop growth with the equal or improved yield of rice.

Climate change influences water scarcity due to the increased temperature, leading to increased crop water need and reduced agricultural production. Alternative methods have been developed to reduce water demand and improve water use efficiency (6). Rice requires more water than any cereal crops, which leads to water scarcity for water-saving technologies were developed. Commonly, rice uses 1400 L of water through transpiration and evaporation to produce 1 kg of rice. The intensity of rice production is affected by increased water scarcity, which forces farmers to adopt water -saving cultivation methods. Water use is reduced by 10 %, saving around 150000 million m^3, 25 % of water used by other allied activities. Rice accounts for 15 % of methane emissions around GHG and to reduce emissions, farmers follow several practices. Continuous submergence of the field leads to methane production through biological processes by methanogenic bacteria and it is very harmful and 27 % higher than the effect of carbon dioxide.

Our analysis demonstrates that implementing such water-saving techniques using climate-smart varieties such as drought-resistant varieties and low-methane emitting rice cultivars can transform rice systems into more environmentally sustainable production systems. The analysis here mainly focuses on how organic amendments enhance carbon sequestration over chemical fertilizers and how crop simulation models improve adaptive capacity. This work provides pragmatic lessons for farmers and policymakers on how to weigh the trade-offs among water saving, emission savings and retention of yields. In this manner, this paper advances global debates in food security by demonstrating the efficacy of technology-driven innovations to mitigate the trade -offs between climate-resilient rice production requirements and environmental sustainability under a climate change regime, providing extension support and supporting policy. By linking agronomic, environmental and socio-economic perspectives, this review provides a roadmap for transitioning to climate-smart rice systems, a prerequisite for achieving Sustainable Development Goals (SDGs) 2 (Zero Hunger) and 13 (Climate Action).

Climatic influence of rice cultivation on GHG's

Climate change, characterized by rising atmospheric carbon dioxide (CO_2) levels and rising global temperatures, threatens environmental stability and socio-economic issues worldwide. The Intergovernmental Panel on Climate Change (IPCC) has continuously emphasized the far-reaching implications of these changes, urging comprehensive research to improve knowledge of their long-term effects (7). Historical records indicate an enormous rise in atmospheric CO_2 concentrations, from 284 parts per million (ppm) in 1832 to 397 ppm as of 2013, with the major proportion being due to human activities, including fossil fuel burning and land use changes, emphasizing the anthropogenic character of the crisis. As a global environmental problem of concern, climate change presents major challenges to agricultural production systems (8). Its effects are extensive, ranging from the productivity of crops and livestock to farmers' and consumers' livelihoods. These impacts are realized throughout the entire soil-crop-atmosphere continuum, affecting soil health, plant growth and atmospheric conditions necessary for sustainable agriculture.

Recent observations of climate change include rising temperatures, shifts in the spatial distribution of precipitation and an increase in the frequency of extreme weather events and this will continue to increase and become severe later depending on future emissions scenarios (9). Similarly, Increased droughts and floods, which have an immediate influence on rice production, result from temporal and spatial changes in the frequency and quantity of precipitation.

Rice paddies are one of the major anthropogenic sources of methane (CH_4), a powerful greenhouse gas (GHG) and their emissions are expected to be greatly affected by global warming (10). Agricultural management is important in controlling CH_4 emissions from rice paddies (11). For example, one Chinese study demonstrated that a 1°C increase in air temperature resulted in a 12.6 % increase in CH_4 emissions from rice paddies (12). This increase is thought to be the result of increased carbon substrate availability to methanogens and the promotion of a higher CH_4-to-CO_2 production ratio. Apart from CH_4, air warming can also increase nitrous oxide (N_2O) emissions from rice paddies by as much as 26 % (13). One of the major drivers of global warming is the increasing level of atmospheric carbon dioxide (CO_2), which recently hit a record high of 415 μ mol mol^{-1}, an increase of 149 % over pre-industrial levels (7). Increased CO_2 levels directly affect CH_4 and N_2O emissions through changes in their generation, oxidation and transport within rice fields. For instance, elevated CO_2 levels enhance methanogenic bacteria activity and populations, plant characteristics such as tiller number and aerenchyma formation, enabling improved gas transport and carbon substrate availability. Yet, prolonged exposure to high CO_2 has also been seen to exacerbate a reduction in CH_4 and N_2O emissions of 18 % and 43 %, respectively, as a result of corresponding decreases in biomass and yield over the long term (14). Reduced biomass production constrains the availability of carbon substrates required for GHG production. Based on the Philippines' International Rice Research Institute (IRRI), a 1°C increase in nighttime temperatures will decrease rice grain yield by 10 %. Furthermore, combined rises in atmospheric CO_2 and a 1°C temperature increase have been reported to enhance yield-scaled GHG emissions by 31.4 % and decrease rice yield by 11.8 % (15).

Recently, Climate change plays a major role in agricultural productivity due to increased water scarcity. Raising temperature increases the evaporation loss and directly affects the physiological process of paddy crops. Air temperature has an effect during the phase of plant development. Increased air temperature decreases yield by about 11.1 % under irrigated conditions and 14.4 % by raising the temperature by about 1°C (16). Integration of the CERES model under different rice cultivation methods and resulted in decreasing yield at increasing temperatures, for 1°C, yields declined up to 4-6 % and for 5°C, yields were reduced by nearly 37-40 % (17). It has been inferred that the average water requirement of paddy will rise in the future across different climatic zones, with temperature increases causing about a 23 % rise in water needs and affecting both the quality and quantity of agricultural production (18). Future projections based on base data from 2009 to 2012 indicate that rice's water requirements will continue to rise in the upcoming years (19). Moreover, Temperature and precipitation changes in a particular region can influence the carbon and nitrogen cycles, thereby greenhouse gas emissions (GHG) from the farmland (20).

Role of micronutrient application in greenhouse gas emission

Methane (CH_4) in paddy fields is primarily generated by methanogens, which break down soil organic matter (such as acetate) in anaerobic conditions. This process is closely linked to the transformation of redox ions like iron (Fe), manganese, aluminium and sulphur. During the decomposition of soil organic matter, electron transfer occurs, leading to CH_4 production, with these ions acting as electron donors and acceptors (21). Applying Fe fertilizer reduced seasonal CH4 emissions by 27-44 % during the rice growing season (22). Significant suppression of CH_4 from the rice field observed due to the restriction of methanogenic bacteria by Fe application, but in the case of N_2O emissions, Fe application resulted in an increased emission of about 30-95 %. It was observed that applying copper in the soil reduced the dissolved organic carbon in the soil, thus helping to reduce CH_4 emissions in the rice field (23). However, during the second season, the application of wheat straw enhanced the CH_4 emission from the field without affecting the copper concentration.

Role of water management practices on GHGs in rice

The three greenhouse gases, namely CO_2, CH_4 and N_2O, are mainly responsible for rising atmospheric temperatures and are predominantly anthropogenic. These gases are mainly emitted from industries and agriculture. As per the fifth assessment report of IPCC, there has been a 40 % increase in atmospheric CO_2 from the pre-industrial era of 1750 to the present 2011. Among various sectors, agricultural activities are responsible for 13.5 % of GHG emissions. Flooded rice emits 28 % more potent greenhouse gas CH_4 by providing a favourable environment for the proliferation of methanogens (24).

Changes in the water regime before the rice cultivation and residue management establishment during the fallow period influenced methane (CH_4) and nitrous oxide (N_2O) emissions during the following cropping season. The N_2O is mainly released due to the process of denitrification and nitrification by the microbes due to the application of nitrogen and anaerobic conditions in the field. Emissions throughout the dry and wet fallow periods were moderate, with the lowest emissions occurring during the dry period (25). The study reported that N_2O emission from the submerged paddy condition is (0.51 ± 0.03 mg N/kg soil/day), compared to drained paddy condition (3.36 ± 0.66 mg N/kg soil/day) (26). The accumulation of NO_3^- and NH_4^+ depletion in the paddy soil leads to the increased nitrification and denitrification process and leads to the increased release of N_2O. The application of nitrogen fertilizers plays a major role in N_2O emissions. Practising straw and water management practices between rice crops affects the emissions of methane and nitrous oxide in the flooded rice fields. Being an agrarian country, India is the third largest emitter of GHG and it falls among the 17 highest water-stressed countries globally (27).

Effective practices of rice cultivation on water saving and reduction in GHG's

Water-saving methods were developed by conducting continuous field experiments and adopting some base-level operations like land preparation, laser-mounted land levelling and tillage practices for effective water use in the rice field. Later development of various cultivation practices based on the under climate resilient conditions viz., cultivation of aerobic rice, direct seeded rice (DSR), system of rice intensification (SRI), improved water management practices like alternate wetting and drying, drip and smart irrigations and simulation models were greatly influenced on GHG emissions and improved water use efficiency.

Aerobic rice

Aerobic rice is a modern technique that reduces water usage in the rice field. Aerobic rice reduces the unproductive water flows and improves water use efficiency (WUE). The aerobic method of rice cultivation is a novel approach to growing rice under unsaturated, non-flooded without submerged conditions (28). A two-year experiment showed that aerobic rice cultivation saved nearly 37.4 % and 50.8 % of input water compared to transplanted rice (29). Due to the restriction of nursery raising, field puddling leads to decreased input water usage. In 2009, a study documented that 27 % of water use was reduced compared to the alternate flooding method and water productivity ranged from 0.88 kg grain/m^3 (30).

Additionally, aerobic rice consumed less water (9687 m3/ha) than conventional irrigation, saving approximately 32.9 % to 43.9 % of water (31). Significant differences in energy balance and evapotranspiration water productivity have been observed in aerobic rice, which is considered one of the promising waters saving technologies being evolved to reduce the rice crop's water requirement to solve the water scarcity problem under tropical conditions. Water inputs in aerobic rice are 50 % less (only 470 mm - 650 mm), 64-80 % higher water productivities, 28-44 % less gross return and 55 % less labour use than flooded rice (32).

The emission of CH_4 from aerobic rice is 79.8 % lower when compared to conventional transplanted rice. The three systems of rice cultivation viz., a system of rice intensification, aerobic rice and transplanted rice, were evaluated and it was found that aerobic rice increased water productivity by 50.8 % (29). The same trend was reported: irrigation use was reduced by up to 50 % in sandy loam soil by comparing aerobic rice with transplanted rice (33). Major advantages of aerobic rice are mechanized planting, weed control and lower labour requirements. Nutrient availability to the plants in aerobic conditions is minimal compared to the flooded conditions. Weed management is the major problem in this system and it affects yield significantly. The development of new pests and diseases is more in aerobic conditions. Irrigation water is saved about 32.98 % in aerobic rice compared to the alternate wetting and drying and flooding rice cultivation methods (34). Various water-saving experimental methods are given in Table 1.

Table 1. Water saving or Water use efficiency (WUE) or water productivity (WP) under aerobic rice systems

Location	WUE/WP
IARI, New Delhi (29)	Aerobic rice recorded increased WP (3.52 kg/ha/mm), the lowest recorded in conventional transplanted rice (2.28 kg/ha/mm)
UAS, Dharwad (35)	Sprouted seed in aerobic rice method with 30 cm × 10 cm resulted in increased water use efficiency (70.93 kg/ha/cm)
Japan (36)	Water input in the aerobic system is about 14.5 % to 37.4 % of total water input.
ICAR, Bhubaneswar (37)	Under the aerobic system, water input is reduced up to 42 % to 60 % compared to conventional irrigation, with increased water productivity (4.71 kg grain/ha/mm) than traditional (3.04 kg grain/ha/mm)
Japan (38)	Water productivity ranges from 0.75 to 0.96 kg grain/m^3 compared to the flooding rice conditions 0.22 to 0.73 kg grain/m^3.
Coimbatore (39)	Water use is about 60 % less compared to the conventional systems.

Constrains in adopting the aerobic rice system

Aerobic rice saves up to 50 % of water but is not easily adoptable because it is expensive for mechanized planting, creates extra weed management requirements and has unstable yields because of pest pressures. Small farmers in areas with heavy clay soils or uneven rainfall may not find it suitable because the system is best used in well-drained lands.

Direct seeded rice (DSR)

The conventional transplanting rice method consumes excessive water usage, leading to a decline in the groundwater table and adverse environmental and soil impacts. Intermittent irrigation in dry-seeded rice resulted in reduced water use significantly. (27-37 %) with conventional rice cultivation (35). An experiment with direct-seeded rice with various irrigation methods to perform water-saving irrigation practices, from the furrow-wetted irrigation method, which has 1.26 kg/m^3 improved water productivity and a minimum of 0.66 kg/m^3 was observed in traditional flood irrigation, because rice is sensitive to non-saturated soil conditions, a significant decrease in water application may harm rice yield (40). About 35-57 % of water is saved in direct-seeded rice than in flooding fields (41).

In the Dry direct-seeded rice method, water is saved up to (8-12 %) compared to the transplanted rice, with an improved yield of about 13-18 % (42). Water use improved from 0.36 to 0.46 kg grain/m^3 in the direct-seeded rice and reduced water consumption by 18 %, compared to the transplanted rice (43). In direct-seeded rice, less soil disturbance and alternate flooding period make the soil oxygen-rich and lead to CH_4 emission. It has been reported that CH_4 emission from the rice field was reduced by up to 50 % under the direct seeded rice (44). Alternate Wetting and Drying (AWD) under different water regimes has also been shown to reduce CH_4 emissions from the field by up to 80 % (45). However, weed management remains a major challenge in the direct seeded system. During earlier stages, weeds are highly competitive with the available resources. Nutrient availability is also a challenging factor in this system.

Constrains in adopting direct-seeded rice

While DSR saves water and labour compared to transplanting, weed competition is a problem for smallholders, requiring costly herbicides or additional labour. The method also demands rigorous water management, which may conflict with traditional methods. Dry seeding in wet areas risks crop failure, thus low adoption.

Alternate wetting and drying (AWD)

AWD is an irrigation method that increases irrigation frequency after the disappearance of water in the field. A water table level of 15 cm does not cause yield reduction. Clay/sandy soils have a threshold level of 5-10 cm (46) and 5cm below the water table in sandy loam soils (47). In AWD system two regimes (wetting and drying) of irrigation were practised (Fig. 1). The wetting regime (5 cm standing water) provides the optimal growing conditions during the important growth stages, whereas the drying regime (<20 cm) encourages the water conservation and root oxygenation. Below 20 cm water level lowers, irrigation is given to the rice field. Continuous irrigation to field will cause enormous water input and methane emission from the field. Comparing water productivity under submerged conditions, the AWD saves nearly 13-16 % (53-87 mm) (48). Adoption of AWD, water use is saved by 40 % (49). Establishment of AWD and laser levelling leads to a reduction time of about 11 hours in tube-well irrigation which leads to a lowering application of water by nearly 24.24 % (50), Similarly water use was reduced by approximately 20.44 - 23.01 % due to adoption of AWD (51).

Irrigation water saving was reported to be 47.5 % to 49.3 % in summer sowing crops and about 79.4 % during the monsoon, by practising the wider spacing planting in AWD cultivation with continuous flooding (52). A critical analysis and found that a yield reduction of about 5.4 % and 23.4 % of water is saved by adopting AWD (53). Altering the irrigation schedule in AWD experimented to about 5 to 8 days, which lowered the water use by 40 to 60 % and water productivity by about (76 kg/ha/day) (54).

In alternate wetting and drying conditions, the field is kept under both aerobic and anaerobic conditions this leads to the limit of the process of methanogenic bacteria and it oxidizes CH_4 and avoids emission. Regular aeration of the soil restricts CH_4 emissions due to the controlled population of methanogenic bacteria, thereby reducing CH_4 emissions from the rice field. AWD system has the potential to reduce CH_4 emissions by up to 73 % when compared to traditional flooding rice cultivation (55). The addition of organic matter to the field increases the CH_4 emissions, due to the presence of Methanogenic bacteria in organic matter, because CH_4 transforms carbon from the decomposition of organic substrate into methane (56). By reducing the CH_4 emission from the organic field, aerobic decomposition reduces the methane emissions from the rice fields (57). The addition of cow dung further increases N_2O emission from the field by the process of denitrification and nitrification. AWD reduces the CH_4 emission up to 73 % (55). The adoption of alternate wetting and drying (AWD) and site-specific AWD with different criteria of soil drying (AWDS) irrigation treatments reduced the seasonal total methane emission by

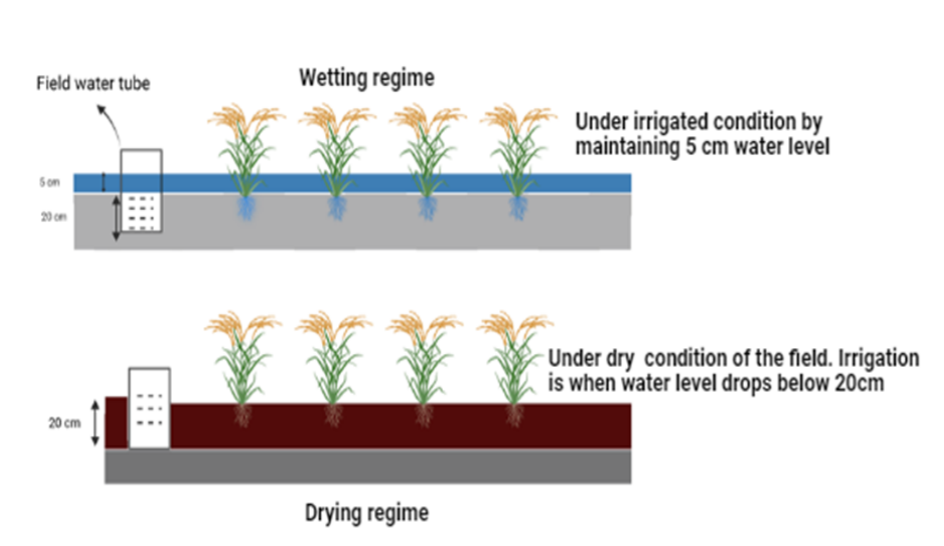

Fig. 1. Alternate wetting and drying (AWD) irrigation regimes for rice production.

35 and 38 % respectively compared to continuous flooding, whereas the difference in seasonal total N_2O emission was not significant among treatments during the three-year study. Increase in N_2O emissions due to the application of nitrogen during topdressing. Because only a small portion of nitrogen is converted into food, the leftover portions are lost through denitrification and ammonia volatilization, during that time N_2O is released from the field (58).

Field water tube plays a major role in the AWD system by monitoring the water level in the field. It is the two-portion porous portion and non-porous portion and it's kept at a depth of 20 cm below the surface, irrigation is given when water level drops below the 20 cm threshold, implementing the AWD drying regime (Fig. 2).

Combined practices of Alternate Wetting and Drying (AWD) with biochar

Biochar is carbon carbon-rich material produced during high temperatures by waste biomass. Biochar plays a major role in controlling the N_2O and CH_4, CN ratio of biochar improves the N mineralization and cation adsorption, which absorbs the NH_4^+ and NO_3^- ions in the soil, thereby reducing the N_2O emission. Biochar application significantly reduces the GHG emissions from the rice field due to the adsorbing of COOH/ OH groups and NO_3. In contrast, straw application elevated the emissions, the combined application of biochar and straw in the rice field reduces the GHG emissions (Fig. 3). An experiment combining AWD with biochar application to improve water productivity by reducing CH_4 emissions and increasing soil organic carbon without yield loss. Biochar application improves the pyrolysis process and increases carbon sequestration (57).

Constrains in adopting the AWD method

AWD saves 24-40 % of water, but training in measuring water levels and field water tubes can be inaccessible to smallholders. Frequent cycle irrigation raises the cost of fuel or electricity, thus not financially viable for farmers with intermittent water supply. Besides, fragmented ownership of land makes uniform adoption challenging.

System of rice intensification (SRI)

During the late 1980's in Madagascar developed SRI, a novel rice cultivation technique for water saving. With the help of these SRI techniques, farmers with limited resources can achieve a yield of 15 t/ha. Additionally, SRI method is feasible with low-fertility soils, low inputs and less dependence on

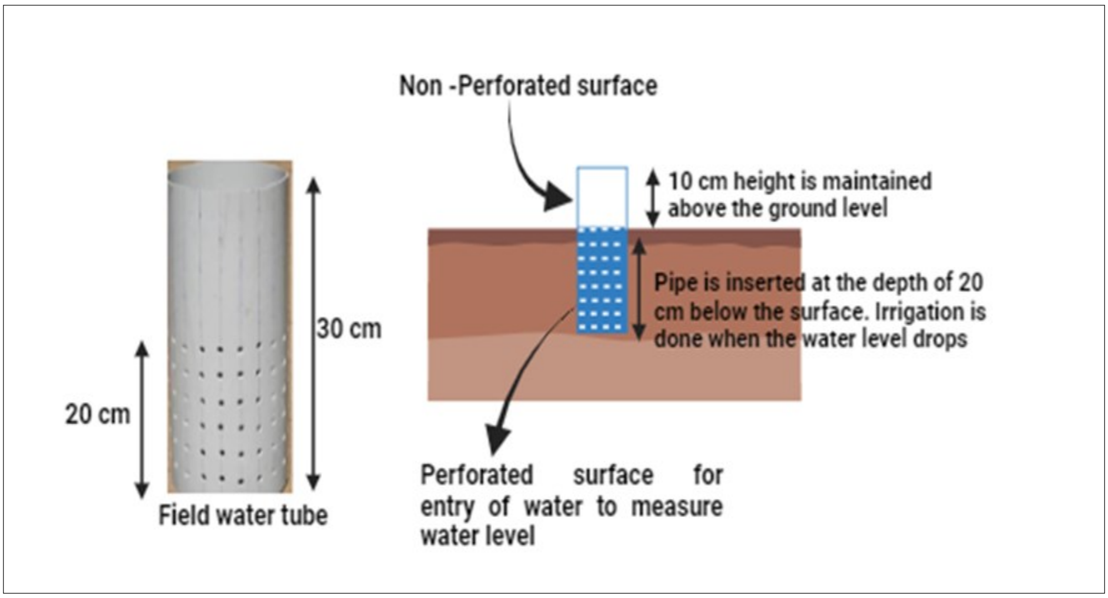

Fig. 2. Perforated plastic field tube to examine the below-ground.

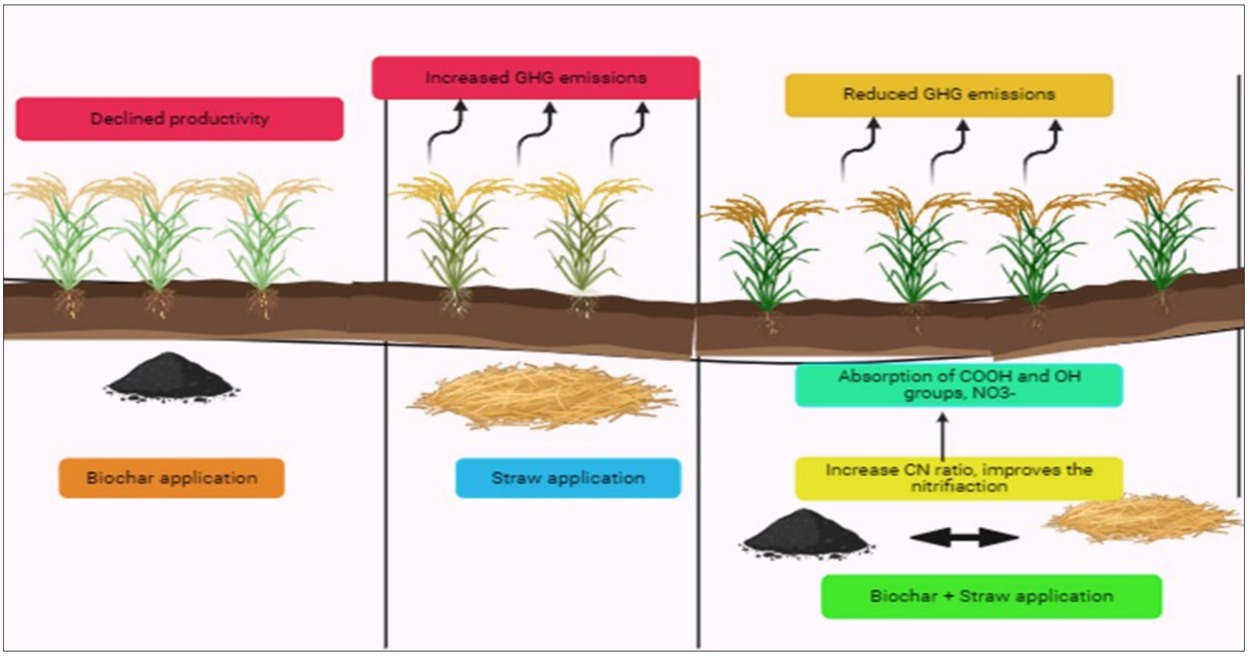

Fig. 3. Application of biochar and straw in the rice field.

outside resources while using less irrigation (59).

In SRI, nearly 50 % of water input is reduced compared to conventional farming and the yield is doubled without the need for added external inputs (59). It was observed that the SRI treatment consumed less water than conventional flooding throughout the two seasons and producing a yield of 1.57 t/ha and water usage by 33 % (345 mm) compared to other treatments (60). However, many farmers find it extremely difficult to implement SRI technology since it requires more labour. SRI method is practised during two seasons and it observed that improved water productivity in this method was about 0.610 kg m^3 and 0.494 kg m^3 respectively (61). The SRI method also resulted in higher fertilizer use efficiency, increased productivity and a 61 % increase in water productivity (62). Organic substrate present in the root exudates increases the methanogenic population, leading to CH_4 emissions. In contrast, lowest CH_4 emissions during the cropping period (8.16 kg C/ha) occurred with SRI method compared to transplanting method (63). Application of vermicompost with the SRI method recorded a yield of about 4.281 kg/ha and 2.5 times higher water productivity than continuous flooding method (1.13 kg/m^3). Furthermore, under SRI, cumulative methane emissions were cutoff about 10-39 % compared to the conventional treatments (64).

Constrains in adopting the SRI method

SRI is more water saving but entails backbreaking work in precise planting and weeding, which is laborious for women and older farmers. Its productivity relies on soil fertility and organic matter, therefore less productive in low-nutrient soils unless with proper training and assistance.

Drip irrigated rice

Drip irrigation is more adaptable to field crops due to the concise use of water. Micro-irrigation systems are emerging in the rice cropping area for efficient water use and maintenance (65). An improved modern-day efficient water use technology is employed in the production of DSR in drip irrigation. Due to the larger amount of water lost through the seepage, percolation and evaporation in the transplanted rice, the water productivity is very low when compared to the drip-irrigated under the DSR system. Drip-irrigated crops are grown well due to the deep percolation of irrigated water and limited soil evaporation. Compared to drip-irrigated rice, continuous flood-irrigated rice under various conditions requires nearly 150-853 mm more water (27.4 to 106.4 %). Reduced evaporation, deep percolation and conveyance losses account for water productivity in drip irrigation. The water use efficiency (WUE) is about 0.0576 t/ha/cm for the surface drip-irrigated rice, while for conventional flooded rice it is 0.0181 t/ha/cm (66). Additionally, 50-61 % of water is saved under drip irrigation systems combined with fertigation, which also improves yield and water efficiency (67). Using the drip irrigation method. Irrigation scheduling by drip at 150 % PE increases the water use efficiency by about 60 % (68). A drip irrigation system needs special maintenance with installation and it requires additional labour due to the periodic checking of clogs in emitters, water flow adjustment and monitoring of soil moisture levels. Cultivating water-saving and drought resistance rice varieties resulted in an improved yield about 95 % (69). The performance of WDR varieties under drip irrigation is shown in Table 2. The Comparison of AWD and drip irrigation for water use efficiency are presented in Table 3.

Constrains in adopting Drip-irrigated rice

Drip systems can conserve up to 60 % of water but are too costly for smallholders. Maintenance difficulties, including clogged emitters and the necessity for fertigation skills, further restrict adoption in poor environments.

Sprinkler irrigation

An increase in soil water tension negatively impacts the rice yield. A decrease in rice grain production was observed as the irrigation threshold shifted from no stress to 40 kPa (70). Higher nitrogen use efficiency of about 26.7 % and water productivity of about 52.8 % under micro sprinklers in direct-seeded rice (71). A reduction in 34 % of irrigation water usage

Table 2. Performance of WDR varieties under drip irrigation and conventional irrigation (69)

Varieties	Drip irrigation field		Conventional field		Water use efficiency (WUE) under drip irrigation (%)
	Yield (kg/ha)	WUE (kg/ha/mm)	Yield (kg/ha)	WUE (kg/ha/mm)	
Hanyou 73	8187	7.69	8584	4.54	40.91
Xieyou 702	7444	6.99	9607	5.08	27.25
Jingfeng	5614	5.27	7372	3.90	26.01
Huhan 3	7798	7.32	7980	4.22	42.34

Table 3. Comparison of AWD and Drip irrigation

Technology	Water saving	Yield impact	GHG reduction	Key observations
Alternate Wetting and Drying	13-40 %	Moderate (5.4 % loss)	73 %	Requires field water tube for continuous monitoring
AWD + Biochar	13-40 %	No yield loss was observed	Reduced emissions	Biochar application enhances the soil carbon storage
Drip irrigation	50-61 % (up to 106.4 %)	Up to 95 %	Reduced emissions	High investments and maintenance

was reported under sprinkler irrigation systems when compared to flood irrigation in *boro* rice. Additionally, they observed a 7.6 % increase in grain yield and a 31 % rise in net profit under the sprinkler irrigation system (72). Furthermore, rice grown under sprinkler irrigation produced 18 % more yield, using 35 % less water than conventional paddy fields (73).

Constrains in adopting the Sprinkler irrigation method

Sprinklers are water-efficient but energy-intensive, increasing operating costs by 30-40 %. Wind evaporation of water and nozzle clogging reduce efficiency, particularly in windy or arid regions adoption of sprinkler irrigation is not suitable and hence make them less convenient for small farmers.

Smart irrigation

Effective water management practices are essential in agriculture to obtain the optimum yield. Smart irrigation methods play a crucial role in the challenges faced by farmers. It enables the remote monitoring and control of the irrigation systems. These technologies improve the efficiency of irrigation management in rice cultivation, thereby reducing the challenges faced by the farmers (74). The optimal usage of water resources in precision farming can be effectively achieved through IoT-based smart irrigation systems. It integrates the real-time monitoring of soil temperature, soil moisture and environmental conditions with online weather forecast data and these systems can accurately determine a field's irrigation requirements. A moisture sensor installed in the field continuously monitors the moisture levels and observes the variations and any fluctuations in the moisture levels are transmitted to the microcontroller for immediate action. Compared to traditional irrigation methods, IoT-based irrigation enhances crop development, optimizes water management and enables remote accessibility (75).

Enhanced crop evapotranspiration measurements, sensor technology, wireless communications, satellite and aerial imagery, cloud computing and the Internet of Things are some of the latest advances in technology being used to assist farmers in determining and meeting crop water requirements. The precise control of irrigation in paddy fields and real-time remote monitoring of moisture content are made possible by the intelligent irrigation system that uses less water and is based on the agricultural Internet of Things. Automated irrigation needs soil moisture information, climatic parameters and temperature (76). Sensors sense the information from available soil moisture in the field with weather components to give real-time information. Electromagnetic sensors measure soil moisture availability in the soil. Information from the sensor is sent to the transmitter, which then uses the microcontroller to convert analog input data to digital data. The data is transmitted via radio frequency and Bluetooth and Wi-Fi are used to send the data to the base station. Several sensors found in the Internet of Things-based irrigation systems are mentioned in Table 3.

An IoT-based irrigation system has been observed to reduce water consumption by 40.29 % and 29.22 %, respectively, in comparison to AWD and basin irrigation (82). The amount of water used in AWD, basin irrigation and IoT-based modern irrigation system was 3924, 3310 and 2343 m^3/ tonnes of paddy. An intelligent irrigation system applied in paddy field undergoing four seasons resulted in water savings of about 18.7 % during the dry season and 19.3 % in the wet season (83). However, the cost of the sensors are high and they are not easily accessible to farmers. Wireless and moisture sensors have been shown to reduce water usage by 65.2 % compared to the conventional flooded irrigation system (84). Automated irrigation saves about 80-90 % water, scheduling the irrigation by regularly monitoring soil moisture and temperature (77). Under transplanted conditions, drip irrigation water saved nearly 41.5 % compared to flooding irrigation systems. Drip irrigation with an automated irrigation system saves water by about 45-50 % (85). The working principle of automation is shown in (Fig. 4), it featuring the real time soil water level monitoring with pump activation, synchronous sensor data processing unit, data output to an LCD display and web server. The effect of smart irrigation on rice cultivation was shown in the Table 5.

IoT in smart farming: Benefits and challenges

The adoption of the Internet of Things (IoT) in the agriculture field has the larger potential to improve the productivity of farming operations significantly by means of automation and reducing the labour requirements (88). The main purpose of the technology is helping the farmers by promoting the improved productivity and profitability, for better living standards. The human interference is gradually reduced due to the implementation of the IoT based solutions. However, despite its advantages, numerous obstacles stand in the way

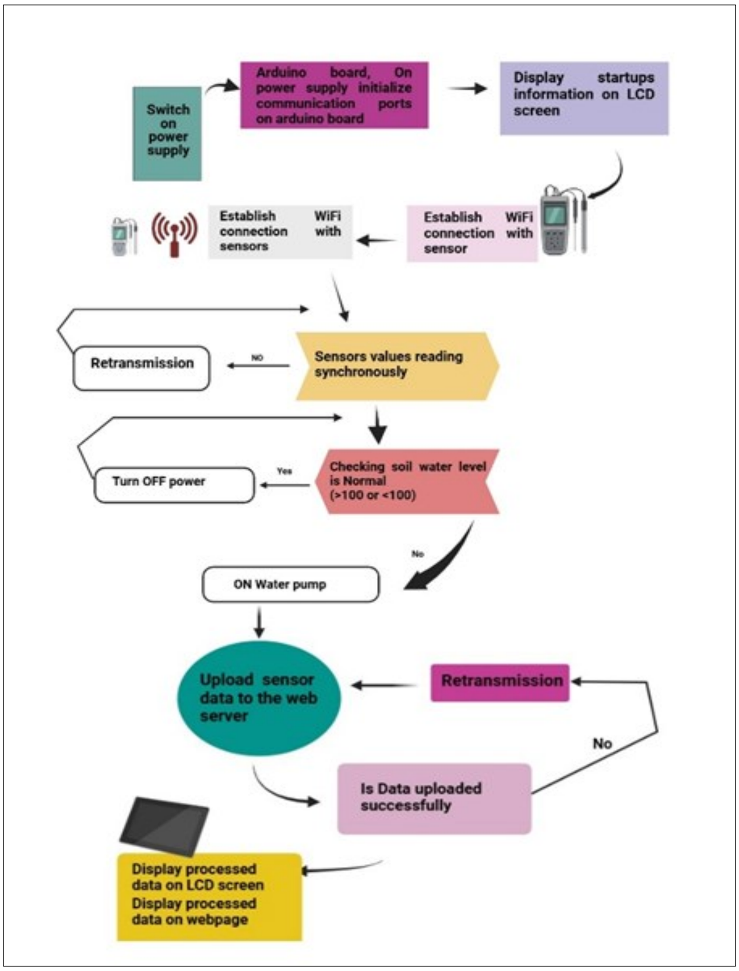

Fig. 4. Automation system representation. LCD - liquid crystal display.

Table 5. The effect of smart irrigation on rice cultivation

Location	Results	Reference
Australia	Adopted the automated gravity surface irrigation system in rice cultivation for two seasons and effectively controlled the 23-31 flush irrigation about 57 % events per season	(86)
Italy	Reduction in the time spent by the workers and flow irrigation. Water consumption ranges in rice field from 2000 mm to 3700 mm.	(87)
Thailand	Used Internet of Things (IoT) based irrigation, Alternate wetting and drying (AWD) and basin irrigation in the rice field. IoT-based irrigation recorded the water footprint about 2343 m^3/tons paddy.	(82)

of its large-scale implementation. These encompass high component prices, weak internet connectivity in rural regions and lack of adequate knowledge among farmers for utilizing such technology (89). Another critical issue in smart irrigation systems is the availability of reliable power sources. To address this, integration of all components such as batteries, fast charges and solar panels in the automation irrigation setups and the identification of a stable power supply are required for the proper functioning of automation (90). Using renewable resources with automation adds a major advantage in sustainable power generation (91). While, IoT-based systems enhance water efficiency, their adoption remains limited due to higher cost of sensors, poor internet connectivity and minimal technical skills among farmers. Smallholders cannot sustain or utilize these high-tech systems without training or subsidies.

Role of remote sensing tools to assess water productivity

Evapotranspiration and water productivity were estimated by using FAO56 method combined with remote sensing data, resulting in equal predicted values. Remote sensing gives the ET_a data to predict the water balance in the field (92). The SEBAL model is widely used to estimate evapotranspiration and water productivity in crops. Plastic mulching practices in water scarcity areas and found 47mm of water saving by estimating through the SEBAL model (93). Using Landsat images, the average water productivity of rice for two years reported to be about 0.52 kg/m^3 and 0.54 kg/m^3, also found that ET_a in two areas banned rice crop cultivation in the water scarcity areas (94).

Despite its usefulness in the estimation of evapotranspiration, low-resolution remote sensing (e.g., 30m Landsat measurements) does not adequately match for field areas below 0.5 ha. Inadequate availability of real-time information and technical expertise further constrains its utility among small-scale farmers.

Role of breeding programmes in GHG emissions and water productivity

Using low methane-emitting and drought-resistant rice varieties positively impacted the ecosystem by controlling the emission of GHG and improving water use efficiency. Evaluation of low methane emitting rice cultivars and drought resistance rice varieties are discussed below.

Breeding of low methane emitting rice cultivars

Globally, rice cultivation area plays a major role in emitting methane gas from the field. The micro-organism viz., (*Methanogenic archaea*) favours the emission of methane from the field. A variety Heijing 5 (low methane emission properties and crossed with three high-yielding varieties, Huayu, Jiahua and Xiushui and grown in outdoor cultivation and greenhouse gas chamber cultivation, resulting in low methane emissions from the outdoor and GHG chamber nearly reduction of about 70 % methane emission when compared to the normal growing high yielding rice varieties field (95). Low-methane-emitting rice cultivars, namely Francis and Rondo. Rondo performed low methane emissions during all the stages of the rice growth periods and change in soil microbial properties (96). Methane emissions among ten rice varieties ranged from 8.83 g/m^2 and 18.63 g/m^2, the variety IR 36 recorded low methane emissions. The increase in methane emissions is due to increased biomass (97). The concept of low-methane crossing with high-yielding rice cultivars emerged in the early 2000s. According to FAO, the global methane emissions from the rice field in 2019 were approximately 0.148 t/ha/year of methane emitted into the atmosphere (98). A theoretical calculation and reported the possibility of lowering the methane emissions by cultivating low methane emitting cultivars and decreasing the methane emissions by 0.104 t/ha/year annually and this would be equal to 2.59 t/ha/year of CO_2 in the climate impact terms (99).

Breeding programmes for the drought-resistant rice varieties

Rice areas are the major source of greenhouse gas (GHG) emissions due to the water stagnation over the cultivation period. Water saving and drought resistance rice (WDR) has high water saving and tolerates drought conditions, simultaneously reducing the GHG emissions from the rice field. Water-saving and drought-resistant rice varieties (WDR) were first adopted in China and were characterized as the noval rice variety. They can save water or withstand drought conditions, with the same high output potential and good quality as existing rice varieties (100). The main feature of the WDR drought resistance is that it can maintain a high water status to maintain normal metabolism under water-constrained environments. The cultivated rice variety (*Oryza sativa* L.) originates from the wild rice (*Oryza ruffipogon* L.) in swamp areas with dry and wet conditions, adapted to both irrigated and watered-less conditions. The long-term evolution of these varieties leads to the formation of two different ecological types, depending upon the requirement of water (101). Conventional breeding methods and molecular techniques developed water-saving and drought-resistant rice (WDR) to produce a higher rice yield with limited water usage. In recent years more varieties of WDR are registered and made available to the farmers. Hybrid WDR variety Hanyou-73 (HY73), demonstrated strong adaptability under both flooding and dry cultivation conditions (102). However, the effect of WDR on GHG emissions is not clear. To address this, a two-year field experiment to evaluate the effect of the WDR on rice productivity and GHG emissions, treatments like continuous flooding (F), Dry cultivations (D) and alternate wetting and drying (AWD), by using a WDR variety and common variety. By comparing with the continuous flooding treatment, AWD treatment reduced the CH4 emissions by 7 % to 64 % and global warming potential (GWP) by 9 % to 39 %, dry treatment (D) has observed the maximum reduction of CH_4 by about 70 % to 90 % and GWP by 65 % to 74 % (103). This study suggests that the dry cultivation of WDR rice method has potential to reduce the GHG emissions and maintain optimum yields under changing climatic conditions. The different methods of fertilizer application controlled N_2O emissions. N_2O flux was recorded at its peak due to surface fertilization by the surface application of fertilizer. Apply the fertilizer at a depth of 5 cm and reduce N_2O fluxes by about 89 %. Under both flooded and limited irrigation conditions, water-saving and drought-ressitant (WDR) rice vatirties recorded the lowest global warming potential (GWP), as they because it produced the maximum yield than a conventional varieties (104).

The drought resistant index (DRI) is measured by the varieties that have adaptive mechanisms under drought conditions and compared with yield. Varieties like Huhan-3, Zhonghan-210, Zhonghang-3, Jinhuangzhan, Yunlu-99, Mowanggunei, Qingsizhan1 are originated from China, variety Huhan-3 which has a higher drought tolerance index (0.93) and suitable to grow under the severe drought conditions and remaining varieties have the moderate drought resistance character (Fig. 5). The nephuong variety originates from Vietnam and has a drought index of about (1.89) less suitable for drought conditions. Hanyou-73 is a water-saving and drought-resistance rice varieties experimented with conventional paddy varieties like (Hyou-518) under different regimes found that variety (Hanyou-73) performed better under water-limited conditions (105).

Carbon Sequestration in Cropland

Rice cultivation covers an area of about 153 Mha worldwide and it has greater potential in sequestering atmospheric CO_2. Compared to other terrestrial ecosystems, rice soils have a higher carbon density and represent a significant reservoir of carbon (106). The major causes of higher carbon potential in the rice ecosystem are elevated water table and low decomposition rate. The enrichment of carbon (C) sequestration in rice fields not only improve soil fertility status but also mitigates atmospheric CO_2. Crop residues are the major source of soil organic matter and organic amendments are intentionally added to the field to improve the soil properties. The C input varied depending on the crop type, soil fertility and climatic conditions. In rice-rice cropping systems, C input values range from 1.6 to 2.1 mg C/ha/yr under no fertilizer conditions and 2.6-5.1 mg C/ha/yr under fertilized field conditions (107). Under the chemical fertilization conditions in rice-rice cropping systems, the C input range from 2.93 - 5.11 mg C/ha/yr (108). However, lower C input of 0.27 and 0.26 mg C/ha/yr have also been observed in the same region (109). Rice plants emit carbon from the paddy soils and also absorb CO_2 during photosynthesis. This shows that rice plants' contribution to CH_4 emission varies depending on varieties and other cultural management

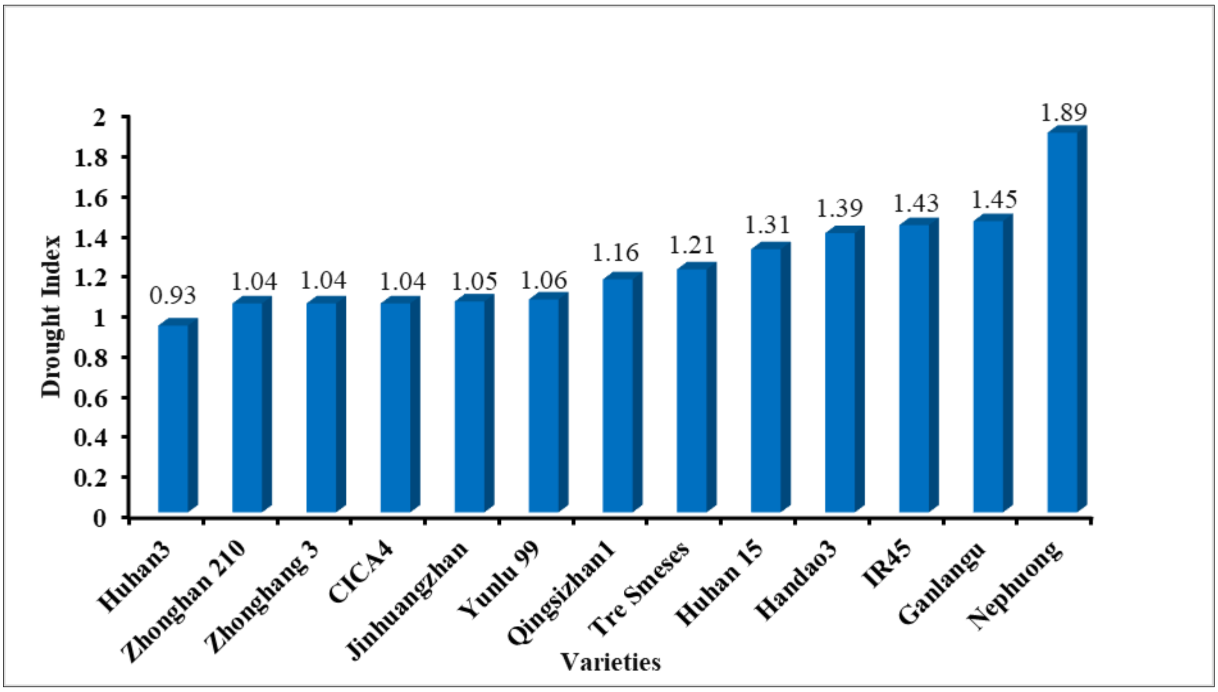

Fig. 5. Evaluation of drought-resistant varieties across different geographic origins.

practices adopted. The initial soil C level, quantity, quality and C loss are majorly affected by the C sequestration efficiency. CH_4, N_2O and CO_2 emission shows significant differences with the application of integrated plant nutrient system-based fertilizer for cow dung, poultry manure and vermicompost (110). The carbon budget was positively influenced, with the contributions of (52-54 kg C/ha) from cow dung, from poultry manure (62-64 kg C/ha) and from vermicompost about (53-56 kg C/ha). The estimation of the carbon sequestration potential of cropland soil by different methods and the performance of carbon sequestration under fertilizer and organic amendments are shown in (Table 4-6).

From the two-year experiments, the carbon sequestration in paddy fields is influenced by the application of fertilizer and organic amendments (cow dung, vermicompost, poultry manure) (Table 6) (110). Application of fertilizer resulted in negative carbon sequestration (-164 to -24 kg C/ha) and net carbon losses of about (-24 kg C/ha). Additionally, fertilizers failed to contribute carbon capturing (-6.5 to -7 kg C/ha) indicating soil carbon depletion. Fertilizers are used for boosting crop yields in short periods, during that time they fasten the decomposition rate and fail to maintain the carbon stock for the long term. Applying organic amendments has significantly improved soil carbon sequestration (68-94 kg C/ha). Net carbon gains show a positive value (22-26 kg C/ha), followed by soil organic carbon, total Soil organic stock and soil organic carbon budget also show positive contributions because organic inputs can replenish soil carbon stocks and maintain the stability of the carbon through microbial activity. Organic amendments contribute to better soil quality and improve the carbon content in the soil and they have long-term benefits for the soil due to the lower decomposition rate (111). But applying the fertilizers had a detrimental effect on carbon dynamics and wasn't available for the long term in the soil due to the higher decomposition rate.

Long-term experiment was conducted over 31 years in lowland paddy soil and 25 years for uplands soils (Table 7) (112). Significant differences were observed in the combined application of organic inputs and fertilizers for lowland and uplands soil properties, which showed improved carbon dynamics and crop yield. In lowland soils by the application of organic input and fertilizers, resulted that higher soil organic carbon (19.9-25.74 g/kg), while comparing with uplands soils (7.98-12.1 g/kg), likewise similar trend was observed in the soil parameters. In addition, lowland soils provided more stable yields (6.29-11.2 mg C/ha), influenced by aerobic and nutrient availability in the lowland paddy soils. Significant difference observed in lowland paddy soil is due to the slower microbial activity and higher physical and chemical stabilizations. In upland soil, the lack of fertilization and application of the fertilizers during the field experiment observed that decline in soil organic carbon (1.2-3.8 mg C/ha) over the 25 years of long-term practice (113).

Carbon sequestration in paddy soil estimates ranges

Table 6. Carbon sequestration for two years (100)

Parameters	Treatment	
	Fertilizer	Organic amendments
Net C sequestration (kg C/ha)	-24	22 - 26
C sequestration (kg C/ha)	-164 to -24	68 - 94
C capturing (kg C/ha)	-6.5 to -7	4.6 - 6
Bulk density (g/cm^3)	1.39	1.38
Organic carbon (g/kg)	12.10	12.32 - 12.46
Total Soil organic stock (kg/ha)	2523	2550 - 2579
Soil Organic carbon budget (kg C/ha)	-21	19 - 35

Table 7. C sequestration in the lowland and upland soils under long-term fertilization (112)

Parameters	Lowland soil	Upland soil
Soil organic carbon (g/kg)	19.9 - 25.74	7.98 - 12.1
Bulk density (g/cm^3)	1.09 - 1.28	1.29 - 1.38
Silt + Clay (g/kg)	896 - 929	854 - 882
C sequestration (mg C/ha)	42.0 - 36.1	32.9 - 21.4
Yield (mg/ha/yr)	6.29 - 11.2	9.95 - 1.68
C input	4.98 - 0.53	4.42 - 0.10

Table 8. Estimation of carbon sequestration potential of cropland soil by different methods (100)

Carbon sequestration potential	Area	Estimation model
0.01 - 0.57 t C/ha/year	60 Mha	Statistical model
19.29 t C/ha/year	140 Mha	Statistical model
15.38 -19.23 t C/ha/year	130 Mha	Empirical formula
0.156 - 0.68 t C/ha/year	130 Mha	Agro-C model
0.92 - 1.31 t C/ha/year	130 Mha	Century + DNDC

from 0.01-19.29 t C/ha/year, depending upon the area and methodology used (Table 8) (100). By using statistical models, the carbon estimation ranges from 0.01-0.57 t C/ha/year for 60Mha (million hectare) and 19.29 t/ha/year for 140Mha, respectively. Carbon sequestration potential was observed 15.38-13.23 t C/ha/year by using an empirical formula under 130Mha. In the Agro-C model and Century + DNDC model, carbon sequestration was recorded at 0.156-0.68 t/ha/year and 0.92-1.31 t/ha/year. Paddy soils have been reported to possess a high carbon content and significant carbon sequestration capacity in crop land of China (114). The sequestration potential of Chinese cropland has also been estimated at -4.94 t/ha/year, i.e., cropland soils releasing 4.94 t/ha/year of carbon (115).

Strategies to improve carbon sequestration in paddy fields

To extend the rice area cultivation by practising SRI method

System of Rice Intensification (SRI) is a sustainable farming system that majorly focuses on sowing younger seedlings, wider spacing, intermittent irrigation (alternate wetting and drying) and organic inputs. All these combined improve the growth of roots and microbial populations in soil. Improved aeration and wider spacing enhance the environment for aerobic soil microbes, which enable decomposition of organic matter into stable humus instead of methane emission. Organic manure inclusion in SRI also enhances soil organic carbon (SOC) storage in the long term. Additionally, periodic flooding reduces methane emission, indirectly improving paddy ecosystems' net carbon balance.

To achieve the balanced nutrition, integrated nutrient management practices are followed to enhance the humification process

Integrated Nutrient Management is the combined application of organic manures (farm yard manure, compost, green manure) and inorganic fertilizers to sustain soil fertility and health. Organic materials provide a carbon source for the soil microbes and help in the development of stable soil organic matter through the humification process. Balanced nutrition guarantees healthy growth of crops, leading to increased biomass production, which can be returned to the soil as crop residues, enhancing long-term SOC accumulation. The addition of legumes in the rotation with the rice crop can also increase below-ground biomass and carbon storage in the field.

Introduction of high yielding varieties, gene modified plants with better root, shoot ratio, containing phenolics compounds in roots

Introduction of rice varieties with a greater root: shoot ratio and characteristics like higher lignin or phenolic compounds in roots can greatly increase below-ground carbon input. Root systems that are deeper and denser add more root biomass to the soil, which is decomposed slowly and contributes to stable carbon pools. Phenolic compounds retard microbial degradation, thereby enhancing longer residence time of root-derived carbon in the soil. In addition, high-yielding crop varieties generate more biomass, resulting in higher soil organic carbon (SOC) under residue return management. AWD system of cultivation favours the greater root: shoot ratio (116).

Improving the process of biological nitrogen fixation and mycorrhizae

Application of Biological Nitrogen Fixation (BNF) (e.g., Rhizobium-legume, or cyanobacteria in rice paddies field) and arbuscular mycorrhizal fungi (AMF) enhances nutrient cycling and soil health. BNF mitigates reliance on synthetic nitrogen fertilizers, which are energy-intensive to manufacture and can result in N_2O emissions (a major contributor of GHG).

Practising high PhytOC rice cultivars - phytoliths are silica bodies produced by the plants, helps for carbon accumulation in soils

Phytoliths contain 66 % to 91 % silicon dioxide (SiO_2) and include a minor percentage of organic carbon, between 0.2 % and 5.8 %, that gets trapped inside the silica structure. Trapped carbon is called phytolith-occluded carbon (PhytOC) (117). The global rice cultivation is around 167.2 million hectares and produces an average of around 750 million tonnes annually (FAO, 2020). India retains the maximum portion of rice cultivation area at 26.1 % (43.79 million hectares) of the entire world. Rice crops are capable of removing an average of 204 to 620 kg/ha of silicon (Si), with approximately 85 % of the Si uptake localized in the rice straw (118). The Continuous application of rice straw from the field without proper Si application has resulted in reduced plant-available silicon (PASi) in most of the traditional rice-growing areas of India (119). Soil phytoliths could also affect

PASi concentrations; upon decomposition of plant residues, phytoliths amorphous silica (ASi) forms are released into the soil and they are one of the most soluble forms of silicon (120). Using 51 rice cultivars with combined application of PhytOC, observed that C content in the cultivars ranges from 1.21 to 7.21 mg/g, additionally PhytOC flux ranges from 0.006 to 0.035 mg e CO_2/ha/year. The higher PhytOC containing rice cultivars having better CO_2 bio-sequestration and potential for reducing the changing climatic conditions (121).

Prediction Methods for Water Productivity by Different Simulation Models for Rice Cultivations

AQUACROP model

The AquaCrop model represents the yield response and simulates crop-water productivity by using several parameters and input data (122). AquaCrop model can simulates rice crop yield and response to water in different climatic conditions. It needs climate data, crop growth characteristics and crop management practices to run simulations. Water productivity was reported as 0.46, 0.60 and 1.02 kg/m^3 during the cropping period and predicted yields for the year 2040 were projected to vary, between -0.02 to 19.85 % during the cropping season (123).

APSIM model

The Agricultural Production Systems Simulator model has been parameterized, calibrated and validated under diverse environments. APSIM - Oryza model is used to evaluate the performance of yield based on irrigation, soil and fertilizer management. The onset of rainfall was predicted by APSIM model, resulting in improved the water use by 132 mm and thereby increasing yield by around 6000 kg/ha. Supplemental irrigation given to the field under the delayed onset of rainfall by 54 %, improved water productivity by 4 kg/ha/mm (124).

CERES - Rice model

CERES - rice model is used to predict the water balance effects in rice. In SRI method maturity and rice yield is identified by using this model (125). Different irrigation systems were evaluated with the CERES model to improve the water use in rice and confirmed that AWD performed well and increased yield by 9.2 % (126). Climate change adversely affects the rice yield and is predicted to yield at a reducing rate using the CERES-Rice model (17).

Evapotranspiration and water requirement in rice estimated by using CROPWAT results in an increased temperature of about 3.0°C, it increases the water requirement by 3.7 % than the normal water use (127). Using the CERES model yield reduction is decreased by about 6 % due to the increase in temperature 1°C (128). Yield reduction in aerobic rice was projected up to 10 %, while in flooded conditions, it ranges from +5 to -11 % yield reduction by predicted through a simulation model (129).

Models Used for CH_4 Emission from the Rice Field

DAYCENT and DNDC

Denitrification-decomposition-model (DNDC) has different modules to calculate N_2O, CH_4 and CO_2 day by day. DAYCENT and DNDC models are used to stimulate the CH_4 in the rice field (130). Average CH_4 emissions in the stubble incorporation method is 138, 178 and 148 kg C/ha/year (131). CH_4 flux across 11 rice systems ranged from 4.6 to 436.5 kg C/ha/year by using DNDC models (132). Similarly, CH_4 emissions were reported to range from 113.5 to 164.5 kg CH_4/ha (44). Emissions of CH_4 were also estimated using remote sensing tools for 1.44 million ha in China (133). Carbon loss was reported in the range of 1.23-1.32 t/ha/year by using (DNDC) model (114).

Conclusion

Rice is the major food source for millions of people. Rice area contributes to the major emissions of GHG and it is part of the cause of global warming and leads to climate change. The rice ecosystem is the major contributor to carbon sequestration in the soil. It increases the emission of GHG from the soil. To overcome high greenhouse gas (GHG) emissions and excessive water use in traditional rice cultivation, there is an alternate need for a strategic shift towards sustainable cultivation practices that balance productivity with environmental challenges. This review highlights several water-saving rice production methods, such as the SRI, DSR, drip-irrigated rice, aerobic rice and sensor-based irrigation. The System of Rice Intensification (SRI) emerges as practically impactful water productivity by about 61 % and recorded lower methane emissions of about 8.16 kg C/ha through its innovative cultivation practices. When combined with drought-resistant rice cultivar *viz.*, Huhan 3 is capable of growing in all the stages of drought conditions and it as recorded a drought tolerance index of (0.93) and a potential yield of 8586 kg/ha even under water stress, these offer a better solution for climate-vulnerable regions. SRI method, integrated nutrient management practices and the use of PhytOC rice cultivars improve carbon sequestration and reduce the emission of GHG. By application of organic amendments in the paddy soil had a significant positive effect on carbon sequestration when compared to the application of chemical fertilizers., low methane-emitting rice cultivars were observed to emit 0.148 t/ha/year of CH_4 into the atmosphere. Practicing the cultivation of these varieties has significant potential to control emissions from the rice ecosystem.

Alternate Wetting and Drying (AWD) also holds equal promise, reducing methane emissions by up to 73 % without affecting the rice yields, particularly when combined with biochar practices. Even with current constraints of infrastructure requirements, intelligent irrigation systems are the way forward for smart water management with possible savings of 50-90 %. Our results indicate that organic amendments enhance carbon sequestration and are superior to chemical fertilizers in long-term soil health dividends. Emerging new rice cultivars with low methane emission and high-yielding characters will be helpful to the farmers to get better yields and improved water use and helpful for planning for the upcoming season. Providing skilled education and innovative methods offers a practical way for farmers to improve rice production towards greater resilience and environmental sustainability. Implementing these with success, we highlight the importance of regional adoptions, farmer training and policy facilitators through subsidies and investments in infrastructure. Future research must concentrate on fine-tuning these in local contexts, breeding next-generation low-emission varieties and establishing economic incentives for uptake. Integrating these water-saving and emission-reducing practices with indigenous knowledge and frontier technology, the world rice economy can evolve towards a more climate-resilient and sustainable future without sacrificing its key role in food security.

Acknowledgements

The authors thank the Department of Agronomy and Centre for Water and Geospatial Studies, Tamil Nadu Agricultural University, Coimbatore, for extending their guidance and support.

Authors' contributions

AKM and RM participated in conceptualization of the original review draft. PS, SS and carried out the literature review. AKM prepared the original draft. SR, RK, and KV reviewed and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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