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10. Environmental Footprint of Paddy Production in India

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Abstract:

Rice production in India, while essential for food security and livelihoods, poses significant environmental challenges due to its substantial water use and greenhouse gas (GHG) emissions. This book chapter explores sustainable agricultural practices aimed at reducing the ecological footprint of paddy production in India. Key strategies include modifying irrigation methods to optimize water usage and reduce emissions, selecting suitable rice cultivars that require less water and produce fewer residues, and integrating soil management practices to enhance soil health and efficiency. Techniques such as the System of Rice Intensification (SRI) and Direct Seeded Rice (DSR) are highlighted for their role in conserving water. Additionally, the use of nitrification inhibitors and biochar is discussed for their potential to lower GHG emissions from rice fields. The role of modern technology, including drip irrigation and Internet of Things (IoT)-based systems, is also examined for their effectiveness in improving water and nutrient delivery directly to the plant roots, thus enhancing overall crop productivity while maintaining environmental sustainability. Furthermore, underscores the importance of policy support, farmer education, and community engagement in promoting and adopting these sustainable practices. Through a combination of these strategies, it is possible to address the dual imperatives of ensuring food security and advancing environmental sustainability in Indian rice production.

Keywords:

Ecological footprint, Paddy production, methane and N2O emissions

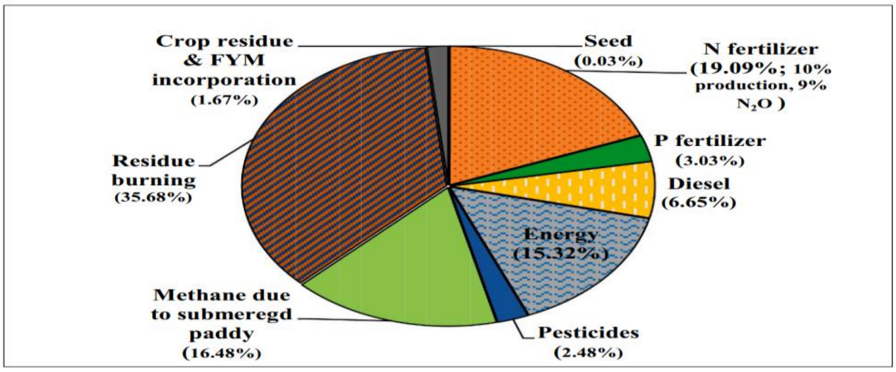
10.1 Introduction:

Rice (*Oryza sativa*) is a major and nutritional staple food primarily in Asia and India is the world's second-largest producer, grown in an area of 43.86 Mha and an annual production reaching 130.29 million tonnes (Anonymous[a], 2022). The leading rice-producing states were West Bengal, Uttar Pradesh, Punjab, Telangana, Odisha, Tamil Nadu, Chhattisgarh, Andhra Pradesh, Bihar and assam. Paddy production intimately associated with country's food security and a key source of livelihood and employment. However, rice cultivation is a major concern to scientific community and a considerable threat to sustainable agriculture as it is a major source of vital and long-lasting GHGs like CH_4 and N_2O. Around 30% and 11% of global agricultural CH_4 and N_2O, respectively, are emitted from rice fields with 467 GWP (Gupta *et al*., 2021). Environmental footprint or ecological footprint measures impact of human activities on environment, including number of natural resources used and number of harmful gases produced. In the context of rice production, this encompasses emission of greenhouse gases such as methane (CH_4) from anaerobic decomposition processes in flooded fields, and nitrous oxide (N_2O) from the application of nitrogenous fertilizers through processes such as denitrification (Anonymous[b], 2022). These emissions contribute to the carbon footprint of rice cultivation. Furthermore, rice consumes 35-43% of freshwater for irrigation. Among the field crops, rice has the highest water requirement 1140 mm (Vijayakumar *et al*., 2022). India also exports a large quantity of water (virtual water) through the export of rice. It is a water-intensive crop, particularly under traditional management practices like crop manually transplanted into soil that has previously been tilled and puddled (i.e. pulverized under standing water and compacted) practising so require significant amount of water which led to unsustainable practices like excessive groundwater extraction, and the pervasive use of agrochemicals deteriorated soil health, for example in the States like Punjab and Haryana. Its water and carbon footprint are higher than any other field crop which forms a critical component of its overall ecological footprint. Hence it is necessary to analyse ecological footprint of paddy production comprehensively. As it is crucial for policymakers, farmers, and researchers alike as they strive to balance the dual imperatives of ensuring food security and environmental sustainability. This chapter briefly discuss about ecological footprint of paddy production in India, highlighting the key drivers of environmental impact, and the potential and sustainable strategies for reducing the ecological footprint.

10.2 Environmental Impacts of Paddy Production:

10.2.1 Production of GHGs in Paddy Fields:

In paddy field, crop management practices like Nitrogen fertilizer use, crop residue burning and diesel consumption were the prominent factors contributing to GHG emissions. Standing water creates anaerobic condition in the soil, which facilitates methanogenesis and denitrification resulting in simultaneous CH_4 and N_2O production.



(Kashyap and Agarwal, 2021)

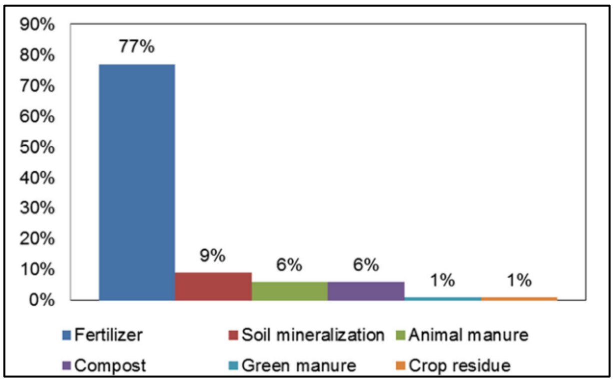
Figure 10.1: The percentage contribution of different sources to the carbon footprint of rice cultivation

A. CH_4 Emissions:

Due to waterlogged condition in paddy soils, causes anaerobic situation (absence of O_2) due to prevention of transportation of oxygen into soil. So, for respiration process microorganisms use alternative electron acceptors which further cause soil reduction. When redox potential abruptly drops, then methanogenesis process starts. It is a process where organic matter gets decomposed in absence of O_2 which lead to formation of CH_4. When soil is under aerobic environment, decomposition occurs in the presence of oxygen with release of carbon dioxide. After the production of CH_4, it releases to the atmosphere by the pathways of (i) diffusion loss of dissolved CH_4 across the water–air and soil–water interfaces, (ii) ebullition loss by the release of gas bubbles, and (iii) plant transport into the roots by diffusion and conversion to CH_4 gas in the aerenchyma and cortex of rice plants and concurrent release to the atmosphere through plant micropores (Davamani *et al*., 2020). In the rice-growing season, maximum CH_4 produced in the soil is released by diffusive transport via the aerenchyma system instead of diffusion or ebullition (Gupta *et al*., 2021)

B. N_20 Emissions:

N_2O is produced by the microbial transformation of nitrogen (N) in soils. This transformation of N to N_2O involves two biological processes, i.e., the loss of N as N_2O during the nitrification of $NH_4{}^+$ under aerobic conditions, and the reduction of $NO_3{}^-$ to N_2 during denitrification process. During the denitrification process, anaerobic condition prevails which leads to N_2O production as an intermediate product. Nitrogen fertilization level and water management are the main factors regulating N_2O emission in the paddy soil after flooding, an exclusive soil layer has developed in the paddy fields i.e oxidizing and reducing layers in cultivated layer. When fertilizer is applied, in the oxidized layer, at the water–soil interface, the ammonium N is nitrified and $NO_3{}^-$ is produced, it moves towards the reduced layer and denitrified by producing N_2O as an intermediate product (Xing *et al*., 2009). where rice plants act as a conduit for dissolved gases from the root zone to the atmosphere, N_2O is a water-soluble molecule and hence can be up taken by plant roots and transported to leaves via the transpiration stream (Gupta *et al*., 2021)



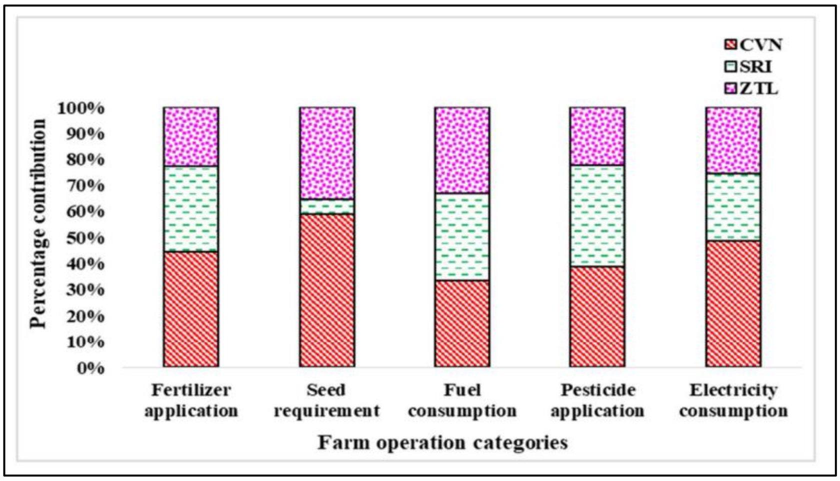
(Gupta *et al*., 2021)

Figure 10.2 Different sources of N_2O from Indian agriculture

C. CO_2 Emissions

The production and emission of CO_2 depend on soil processes, environmental conditions, and the amount and properties of organic matter added to soil. Depending on microbial activities, the organic materials begin to decompose that result in emissions of different gases, especially CO_2. At surface soil, CO_2 is released through respiration of roots and different flora and fauna. Application of urea fertilizer, residue burning, and tillage practices in the rice fields add CO_2 emissions. Rice fields contribute less amount of CO_2 as compared to CH_4 and N_2O as flooded soils have very poor conditions for C oxidation. Ebullition contributes about 13–35% of CO_2 and 94–97% of CH_4 respectively. In the availability of water and urease enzymes, urea fertilizer applied in the fields converted to NH_4^+, OH^-, and HCO_3, and this bicarbonate finally evolves into CO_2 and water (Gupta *et al*., 2021).

D. Carbon equivalent emissions of different farm operations under various cultivation practices



(Gangopadhyay *et al*., 2022)

Figure 10.3. percentage contribution of different categories of farm operations

Gangopadhyay *et al.* (2022) concluded that percentage contribution of different categories of farm operations (viz. fertilizer application, seed requirement, crop protection, fuel consumption, and irrigation) to the total carbon-equivalent emission (t CO_2^- eq ha^{-1}) was highest for conventional cultivation (CVN) followed by System of Rice Intensification (SRI) and Zero-tillage cultivation (ZTL). Emissions from different types of farm operations were 4.78 t CO_2^- eq ha^{-1}, 3.23 t CO_2^- eq ha^{-1} and 2.53 t CO_2^- eq ha^{-1} under CVN, SRI and ZTL, respectively. The contribution of farm inputs to total carbon equivalent emissions (t CO_2^- eq ha^{-1}) was 56.82%, 55.08 % and 55.34% under CVN, SRI and ZTL, respectively (Fig 3). Whereas 24.6–122.2% increase in the GHG emissions was observed because of nitrogen fertilization treatment (corresponding to the CVN cultivation of the study) compared to no nitrogen fertilization treatment (corresponding in part to SRI plots of the study).

10.2.2 Crop Residue Burning Emissions:

Very common practice among farmers in paddy fields is crop residue burning as it generates enormous amounts of unused stubble, that is burnt to save cost and time causing excessive particulate matter emissions and air pollution contributing to global warming. Burning of rice straw causes gaseous emission of 70% CO_2, 7% CO, 0.66% CH_4, and 2.09% N_2O (Sravani *et al.*, 2024)

10.2.3 Water Footprint:

Rice cultivation consumes 35-43% of the total irrigation water. Water levels in paddy field largely determines the quantum of methane emission, besides organic matter content, soil & canopy temperature, etc. Rice consumes 2500 to 5000 L water to produce 1 kg grain. Rice has a high environmental footprint because of high water, high energy, and more fertilizers. The availability of fresh water for irrigation is decreasing drastically in recent years due to increasing demand and withdrawal from other sectors. Also, the groundwater table in many rice growing regions is lowered at an alarming rate and created a sustainability threat. Indiscriminate use of fertilizers in agriculture leads to increased water pollution in many rice growing areas. For example, in Punjab, the nitrate concentration reached above the safe level due to the leaching of nitrogen fertilizers to ground water table and other surface aquifers. Climate change also brought more frequent droughts and floods to minimize the yield loss and crop failures under changing climate, farmers started depending more on artificial irrigation through irrigation pumps which increases cost of cultivation (Vijayakumar *et al*., 2022).

10.2.4 Usage of Nitrogen Fertilizers:

Overall, nitrogen fertilizer uses in rice emitted 1.72 ± 0.39 t CO_2 eq/ha of this, indirect emissions due to fertilizer production comprised 53.3%, and the rest was accounted for by direct field emissions from fertilizer application (Kashyap and Agarwal, 2021). N_2O emissions from soil in rice amounted to 0.80 ± 0.25 of which fertilizer use contributed the majority (85% in rice), while farmyard manure and crop residue incorporation accounted for the rest. The use of HYV seeds require higher fertilizer and water inputs, which lead to higher CF and grey WF. The increase in use of fertilizers to boost productivity is reflected in the GHG emission trends. N_2O emissions were found to increase exponentially beyond a fertilization rate of 200 kg N/ ha. With the declining fertilizer N use efficiency, this might be a possibility in the future, if steps to decrease fertilizer use are not taken on an urgent basis. Therefore, reducing N fertilizer use is the greatest hotspot for mitigation. The number of inputs (including water) required to achieve a certain yield level needs to be carefully considered and region-specific benchmarks need to be set. Excessive use of nitrogenous fertilizers can also lead to water pollution through runoff and leaching.

10.2.5 Other Emissions:

Use of fuel for various field operations like rotavators, mechanical transplanters, seed drills, harvesters, transportation for taking produce to mills etc have also contributed to GHG emissions.

10.3 Strategies to Reduce Environmental Footprint in Paddy Production:

Emission of GHGs especially N_2O and CH_4 from rice fields can be minimized by adapting several management practices such as Altering Irrigation methods, Tillage practices, managing organic additives, uses of appropriate rate and quantity of N fertilizers, selecting suitable cultivar, tillage practices, cropping regime, cover crops, use of nitrification inhibitors, etc. In rice ecosystem, production of GHGs mainly depends on crop management practices but changes in management system also offer opportunities for mitigation options. Some of the mitigating strategies are mentioned below.

10.3.1 Altering Irrigation Methods:

Changes in soil moisture by irrigation affect soil redox potential, which can greatly regulate the release and consumption of GHGs rate. Different irrigation practices such as mid-season irrigation, alternate wetting and drying, intermittent irrigation, and controlled irrigation have been observed to reduce N_2O and CH_4 emission than traditional irrigation pattern without affecting crop productivity. As it enhances soil oxidative conditions by enhancing root activity, this increases the diffusion of oxygen into the paddy soils leads to suppression of microbial activity under anaerobic conditions which reduces the methane and N_2O emissions (Hadi *et al*., 2010) demonstrated that 34% and 54% of CH_4 and N_2O emission, respectively, were reduced by applying intermittent irrigation than traditional flooding irrigation. Also, importantly it reduces amount of irrigation and enhance water use efficiency (Gupta *et al*., 2021)

Chaurasiya *et al*. (2022) stated that conventional puddled transplanting (PTR) method for crop establishment is water and energy intensive. To conserve water and maximise its efficient use, improved crop management practices must be identified they include dry direct seeding of rice (dDSR), improved medium-duration rice varieties and alternate wetting and drying (AWD) irrigation management. These have separately been shown to reduce the irrigation water requirement for rice cultivation while maintaining yields like those of traditional high yielding long-duration varieties. Combining all three management practices reduced irrigation water use by an average of 18% while improving irrigation water productivity by 21%, without significant reduction in grain yield under shallow AWD of 10 cm depth in dDSR and up to 15 cm depth for PTR. This combination is a novel approach to sustainably improve farmers' rice productivity. They suggest that farmers in eastern India and similar rice-growing agro-ecologies could reduce the irrigation water applied and increase water use efficiency while maintaining rice crop productivity by combining dry direct seeding with a medium-duration rice variety under AWD irrigation management.

Drip irrigation has proved its superiority over other methods of irrigation due to the direct application of water and nutrients in the vicinity of the root zone. Because of its low water use with a reasonable yield, drip irrigated rice has greater scope in areas where water availability is limited especially in well-irrigated areas. Internet of Things (IoT) based irrigation systems are found to be more accurate in supplying irrigation to the rice crop. Similarly, several sensors are now available for the accurate measurement of moisture in the field.

10.3.2 Tillage Practices:

Soil tillage has a substantial effect on N_2O and CH_4 emissions during rice production because it affects the soil physiochemical as well as biological properties, which stimulates the microbial production of CH_4 and N_2O. As, it decreases soil pores which restrict methane entrance into the soil for oxidation, resulting in less methane uptake by rice soils cutting out emissions.

10.3.3 Nitrification Inhibitors:

Slow-release N fertilizers also called nitrification inhibitors have a large potential to decrease N_2O as well as CH_4 emission from rice paddy field by delaying nitrification process and also lowering the availability of NO_3 for denitrification.

Linquist *et al*. (2012) reported different types of nitrification inhibitors such as dicyandiamide, hydroquinol, nitropyrimidine, and benzoic acid can significantly decrease N_2O emissions. The application of urease, dicyandiamide, and hydro quinol as nitrification inhibitors to the soil was found to significantly decrease CH_4 emissions from rice soil by inhibiting CH_4 oxidation and CH_4-oxidizing microorganisms (Xu *et al*., 2002).

Some naturally plant-derived materials also have capability to delay nitrification process such as neem cake, neem oil, and karanja seed extract which can treat as natural nitrification inhibitors.

10.3.4 Biochar Application:

Biochar is highly porous carbon material produced from slow pyrolysis (heating in the absence of oxygen) of biomass. It can potentially play a major role in the long-term storage of carbon with a very slow chemical transformation and increased residence time, ideal for soil amendment. It has got advantages in terms of its use as a fertilizer when mixed with soil, its ability to stabilize as well as reduce emissions of harmful gases in the atmosphere. When amended to soil, nature of the biochar helps in increases the fertility, water retention capability of the soil as well as increasing the rate of mineral delivery to roots of the plants (Sravani *et al.*, 2024).

10.3.5 Selection of Suitable Rice Cultivars:

Mechanism of exudate and aerenchyma effects under field conditions should be explored because alterations among different types of rice cultivars have been accredited to the deviation in production, oxidation, and transport capacities of CH_4 emission (Lou *et al*., 2008). Varieties with short duration, low water consumption, low amount of residue production need to be selected for cultivation to enhance resource use efficiency and restrict emissions. Recently, PUSA 44 seeds are banned due to consumption of high quantity of water, has a long duration of maturity and leaves high quantity of stubble after harvest which lead to ground water depletion and stubble burning issue, hence PR-126 is recommended as it completes its lifecycle within 92 days by PAU, Ludhiana to Punjab farmers (Anonymous[c] ,2024)

10.3.6 Reducing Emissions from Manure Compost or Manure:

As it improves soil structure and nutrient supply to growing crops and thus lowering the need for mineral fertilizer, resulting in decrease of the GHG emission (Supprattanapan *et al*., 2009). In paddy field incorporation of green manure crop such as Cowpea, Sesbania, Azzola, and Mungbean had a large potential to reduce N_2O and CH_4 (Bharati *et al*., 2020) as slow release of nitrogen from decomposing green manure residue, reduced N leaching losses. Using composted rather than fresh rice straw reduced emissions by 58-63%.

10.3.7 Management of Soil Chemistry and Microbiology:

By understanding enzymology, microbiology and physiology of methanogenic and denitrifying bacteria we can manipulate soil chemistry which ensure efficient reduction in emissions. There are several management options which include addition of lime, manure, biochar, integrated fertilizer residue management, controlled-release fertilizer, nitrification inhibitors, and herbicide which manipulates soil conditions and microbial populations. Herbicides at recommended doses have been recorded to affect the dynamics of methanogenic and denitrifying bacterial population and activity. Application of bensulfuron methyl and pretilachlor significantly reduced N_2O and CH_4 emission by minimizing denitrification enzyme activity, microbial biomass carbon, and readily mineralizable C content (Das *et al*., 2011).

10.3.8 Others:

- Promoting sustainable cultivation techniques such as the System of Rice Intensification (SRI) and Direct Seeded Rice (DSR) to minimize water usage.
- Implementing practices like composting, biochar production, and mechanization to manage crop residue sustainably and enhance soil nutrient retention.
- Encouraging the use of Alternate Wetting and Drying (AWD) methods to periodically dry soil and reduce methane emissions.
- Addressing the risk of reduced genetic diversity by diversifying the high-yielding rice varieties cultivated.
- Preventing soil degradation through improved soil management practices to avoid erosion and nutrient depletion.
- Changing cropping patterns to optimize resource use and crop yields.
- Utilizing solar PV water pumps and zero-till 'happy-seeder' implements that allow wheat seeding directly into fields with rice residue, reducing carbon footprint and cultivation costs.
- Raising awareness among farmers about the benefits of precise fertilizer application to lessen environmental impacts.
- Supporting the transition to sustainable agricultural practices through training, education, and financial incentives from government policies.
- Engaging local communities in water conservation and environmental protection initiatives.
- Ensuring that environmental solutions are economically feasible and culturally suitable for farmers to encourage widespread adoption.

10.4 Conclusion:

Agricultural soil acts as a source and sink of important greenhouse gases (GHGs) like methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). Rice paddies have been a major concern to scientific community, because they produce the threatening and long-lasting GHGs mainly CH_4 and N_2O. Soils under anaerobic condition are favourable for CH_4 production. In soil, N_2O is produced through the microbial mechanism of nitrification and denitrification under aerobic and anaerobic conditions respectively. production of both the gases is greatly influenced by water availability within the root zone of crop. Soil microorganisms are mainly responsible factors for the production and emission of CH_4 and N_2O in rice paddy. Crop residue burning was also found to be the principal determinant Since factors contributing to CF vary regionally, mitigation efforts that consider regional diversity would be more effective than the efforts based on assessments at country level. Nitrogen fertilizer use was found to be the greatest GHG hotspot that should be targeted for mitigation. This would also reduce grey water footprint which has increased over the years, despite the increase in productivity, due to a surge in fertilizer use. Raising awareness, encouraging, and incentivizing alternative practices among farmers is necessary. Understanding ecological footprint of paddy production lays legitimate targets for research community

10.5 References:

1. Anonymous[a] .2022. Agricultural Statistics, 2022. Statistics at a Glance, Statistics Division, Directorate of Economics and Statistics, Ministry of Agriculture, GOI. http://desagri.gov.in.
2. Anonymous[b] .2022. EIB (2022), India sustainable rice cuts water use and emissions. India sustainable rice cuts water use and emissions (eib.org).
3. Anonymous[c], 2024. Sale of PUSA 44 seeds banned by Punjab government. Sale of PUSA 44 seeds banned by Punjab Govt: The Tribune India.
4. Bharati V, Kumar V, Mohanty S and Roy S. 2020. Performance of rice-wheat cropping system under resource conservation and various nutrient management practices. *Int J Conser Sci*. 8(3): 2022-2026.
5. Chaurasiya A, Dutta SK, Singh AK, Kumar S, Kohli A, Homa F, Kumar A, Gathala MK and Laing AM. 2022. Layering smart management practices to sustainably maintain rice yields and improve water use efficiency in eastern India. *Field Crops Research*. 275: 108341.
6. Das S, Ghosh A and Adhya TK. 2011. Nitrous oxide and methane emission from a flooded rice field as influenced by separate and combined application of herbicides bensulfuron methyl and pretilachlor. *Chemosphere*. 84(1): 4-62.
7. Davamani V, Parameswari E and Arulmani S. 2020. Mitigation of methane gas emissions in flooded paddy soil through the utilization of methanotrophs. *Science of the total environment*. 726: 138570.
8. Gangopadhyay S, Banerjee R, Batabyal S, Das N, Mondal A, Pal SC and Mandal S. 2022. Carbon sequestration and greenhouse gas emissions for different rice cultivation practices. *Sustainable Production and Consumption*. 34: 90-104.
9. Gupta K, Kumar R, Baruah KK, Hazarika S, Karmakar S and Bordoloi N. 2021. Greenhouse gas emission from rice fields: a review from Indian context. *Environmental Science and Pollution Research*. 28(24): 30551-30572.

10. Hadi A, Inubushi K and Yagi K. 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. *Paddy and Water Environment*. 8: 319-324.
11. Kashyap D and Agarwal T. 2021. Carbon footprint and water footprint of rice and wheat production in Punjab, India. *Agricultural Systems*. 186: 102959.
12. Linquist B, Van Groenigen KJ, Adviento-Borbe MA, Pittelkow C and Van Kessel C. 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*. 18(1): 194-209.
13. Lou Y, Inubushi K, Mizuno T, Hasegawa T, Lin Y, Sakai H, Cheng W and Kobayashi K. 2008. CH4 emission with differences in atmospheric CO2 enrichment and rice cultivars in a Japanese paddy soil. *Global Change Biology*. 14(11): 2678-2687.
14. Sravani A, Madhukar B, Mounika S and Pallavi KN. 2024. Crop Residue Management: Balancing Nutrients and Soil Health. Advaces in Agronomy: Unveiling the essence of Agronomy. *Stella International Publication*. ST23-0021.
15. Supparattanapan S, Saenjan P, Quantin C, Maeght JL and Grunberger O. 2009. Salinity and organic amendment effects on methane emission from a rain-fed saline paddy field. *Soil Science and Plant Nutrition*. 55(1): 142-149.
16. Vijayakumar S, Karunakaran V, Gobinath R, Basavaraj K, Goud BR, Sha N, Manasa V and Aravindan S. 2022. Sustainable rice production in India through efficient water saving techniques. *Chronicle of Bioresource Management*. 6(1): 032-038.
17. Xing G, Zhao X, Xiong Z, Yan X, Xu H, Xie Y and Shi S. 2009. Nitrous oxide emission from paddy fields in China. *Acta Ecologica Sinica*. 29(1): 45-50.
18. Xu X, Boeckx P, Van Cleemput O and Zhou L. 2002. Urease and nitrification inhibitors to reduce emissions of CH_4 and N_2O in rice production. *Nutrient Cycling in Agroecosystems*. 64: 203-211.