



RESEARCH ARTICLE

Productivity-emission trade-offs across conventional, organic and natural farming in rice-wheat systems of northwest India

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Abstract

Agriculture is a significant contributor to greenhouse gas (GHG) emissions, particularly in intensively cultivated rice-wheat systems in northwestern India, where management practices strongly influence emission intensity and mitigation potential. This study compared GHG emissions under conventional, organic and natural farming across 27 locations in Kaithal, Kurukshetra and Karnal districts within a single agroclimatic zone over two cropping years (2023–24) for rice and wheat. Data was analysed using cool farm tool (CFT), supported by field surveys, soil physicochemical characterisation and yield records. Findings showed clear differences among farming practices. Conventional had the highest emissions, 83.47 % and 36.5 % in rice and wheat. Organic reduced emissions to 31.9 % and 9.35 % while, natural recorded the lowest emissions at 31.6 % in rice and 7.18 % in wheat across both years. Rice cultivation emerged as the dominant contributor to total emissions, with Kurukshetra contributing the greatest amount (36.16 %), followed by Kaithal (32.44 %) and Karnal (31.40 %) across both the years and crops. The productivity of rice yields is 18 % lower under organic and 8.99 % lower under natural as compared to conventional farming. Wheat productivity declined by 16.38 % under organic and 40 % under natural relative to conventional farming. These findings highlight the trade-offs between productivity and environmental performance. While conventional maximise yields, natural farming presents a greater potential for GHG mitigation and reduced environmental footprints, supporting long-term sustainability in rice-wheat production systems and informing climate-smart agricultural practices and also supports policy initiatives that promote sustainable, climate-smart farming strategies for future food production systems.

Keywords: conventional farming; cool farm tool; greenhouse gas emissions; natural farming; organic farming; residue management; rice-wheat system

Introduction

Agriculture remains a central pillar of the Indian economy, supporting livelihoods for a large proportion of the population while simultaneously exerting significant pressure on natural resources, including soil, water, forests, biodiversity and land resources. In addition to its socioeconomic importance, agriculture is also a major contributor to greenhouse gas (GHG) emissions, primarily carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), arising from crop cultivation, fertiliser application, irrigation, residue management and on-farm energy use. Recent assessments of Indian agroecosystems indicate that rice-based systems and nitrogen (N)-intensive cropping practices are the primary sources of agricultural GHG emissions, particularly CH₄ from flooded fields and N₂O from fertiliser-induced soil processes (1, 2). Given India's extensive agroclimatic heterogeneity and intensification of food production, understanding how management practices influence emission pathways is essential for achieving climate mitigation targets while sustaining food security.

Indian agriculture encompasses a wide range of farming systems, spanning high-input conventional agriculture to organic and natural farming approaches. Conventional farming systems,

characterised by the intensive use of synthetic fertilisers, chemical pesticides, mechanised operations and irrigation, remain dominant in the irrigated rice-wheat regions of northern India. Although these systems have contributed substantially to yield enhancement and food self-sufficiency, they are also associated with elevated GHG emissions because of energy-intensive fertiliser production, increased N₂O emissions following N application and fossil fuel consumption from machinery and irrigation pumping (3–5). Studies conducted in rice-wheat systems of the Indo-Gangetic Plains consistently show that fertiliser mismanagement and residue burning further exacerbate emission intensity under conventional practices (6, 7).

Organic farming systems represent an alternative approach that minimises synthetic inputs through the use of organic manures, compost, crop residues, green manures and biological pest management. Evidence from long-term field studies suggests that organic farming can reduce fossil energy use and increase soil organic carbon (SOC) storage, thereby contributing to lower GHG emissions per unit area (8, 9). However, yield performance under organic systems remains variable across crops, seasons and regions. Low yields may offset emission reductions when expressed on a yield-scaled basis, particularly in high-demand cereal systems such as rice and wheat (10, 11).

Natural farming systems, including zero budget natural farming are emerging as low-input, ecologically driven alternatives that rely on farm-derived inputs, enhanced soil biological activity and internal nutrient cycling. Although comprehensive field-scale GHG assessments under natural farming remain limited. Recent studies suggest that reduced dependence on synthetic N fertilisers and improved soil biological functioning may contribute to lower N₂O emissions and enhanced carbon retention in soils (8, 12). Nevertheless, uncertainties remain regarding the long-term yield stability, nutrient efficiency and emission performance of natural farming systems across different agroclimatic zones of India.

A balanced evaluation of farming systems requires an integrated assessment of both productivity and emissions. While organic and natural farming systems may result in lower emissions per unit of land area, yield penalties relative to conventional systems can result in higher emissions per unit of output in certain contexts (2, 13). This issue is particularly critical in India, where smallholder farming predominates and productivity varies widely with soil type, climate and management intensity. Nutrient management plays a decisive role in this balance, as the fertiliser source, rate and timing strongly influence N₂O emissions, nutrient use efficiency and crop yields (3). Consequently, integrated analyses that jointly examine GHG emissions, yields and nutrient efficiency are essential for identifying climate-smart nutrient management strategies suited to Indian conditions.

Accurate quantification of farm-level GHG emissions across diverse farming systems increasingly relies on standardised carbon accounting approaches. Digital emission accounting frameworks and models such as denitrification-decomposition (DNDC), cool farm tool (CFT) and Intergovernmental Panel on Climate Change (IPCC)-based carbon accounting approaches for estimating CO₂, CH₄ and N₂O (14, 15). Such tools enable systematic comparisons of farming systems, cropping seasons and nutrient management regimes, thereby supporting mitigation planning and policy development. Given the spatial and management heterogeneity of Indian agriculture, standardised tools are particularly valuable for generating consistent and comparable emission estimates across regions.

Despite the growing focus on sustainable agriculture and climate change mitigation, comprehensive comparative data on GHG emissions, nutrient use efficiency and productivity across conventional, organic and natural farming systems in India remain scarce, particularly across seasons and agroclimatic zones. Most existing studies focus on individual farming systems or isolated management interventions, limiting their applicability for integrated decision-making at the policy and farm levels. Addressing this knowledge gap is critical for supporting evidence-based transitions toward low-emission, resource-efficient agricultural systems.

In this context, the present study aims to quantify and compare GHG emissions from conventional, organic and natural farming systems in India while simultaneously evaluating crop yield performance and nutrient use efficiency across seasons and agroclimatic zones. By integrating emissions accounting with agronomic indicators, this research seeks to generate robust scientific evidence to inform climate-smart agricultural strategies tailored to Indian conditions.

Materials and Methods

Study site description

This study was conducted to assess GHG emissions under 3 distinct farming practices-conventional, organic and natural-across 27 agricultural sites within the same agroclimatic zone of Haryana, India. Emissions were estimated using activity-based data using the CFT framework rather than direct field emission measurements. Site selection was based on similarities in climatic conditions, soil types and cropping patterns to minimise confounding variability. Within each district, farms representing conventional, organic and natural farming were selected in close proximity to ensure comparable rainfall, temperature and edaphic conditions. This design allowed isolation of the effects of farming practices on GHG emissions while controlling for agroclimatic influences. All the sites followed a rice-wheat cropping system and were managed consistently under their respective farming practices for a minimum of 5 years before sampling, ensuring that management-induced effects on soil properties were well established.

The selected sites represented 3 farming systems, with each system replicated across the districts of Kurukshetra (29°52'–30°12' N, 76°26'–77°04' E), Karnal (29.69° N, 77.00° E) and Kaithal (29.8° N, 76.4° E), which were selected for the study because these are the major wheat/rice cropping districts in Haryana state. The geographical areas of these three districts are Kaithal (2317 km²), Karnal (2520 km²) and Kurukshetra (1530 km²) (16). These districts are a part of the Indus-Ganges Plain (upper Yamuna Basin) and the soil type is sandy loam alluvial soil. It is slightly alkaline with low salinity (low EC). Available N content is low, whereas available phosphorous (P) is high and potassium (K) is in medium range. Soil moisture is average to good and moderate level of SOC (Table 1). In rice-wheat system a kharif crop rice, is grown in the warm, subhumid monsoon season during the summer, whereas wheat is a rabi crop during the cooler, drier winter season. Both crops are generally grown in one year. The studied region has a subtropical continental monsoon climate with hot summers and cold winters. The average annual rainfall during the previous 5 years was 704.7 mm in Karnal, 601.7 mm in Kurukshetra and 515.6 mm in Kaithal (17). In this region, approximately 80 % of the annual rainfall is generally received from June to September and the temperatures rise beginning in March and continue through late June. May and June are the hottest months, with a mean daily maximum temperature of approximately 40 °C. During the winter, the temperature starts decreasing by the middle of November, with January being the coldest month. Year-specific climatic conditions, including rainfall and seasonal temperature variation, were incorporated indirectly through activity-based input data and temporal sampling across two consecutive cropping cycles.

Table 1. Basic soil properties (means ± SDs) of the study sites

Sl. No.	Soil parameter	(Mean ± SDs)	Soil /fertility status
1	pH	8.09 ± 0.21	Slightly alkaline
2	EC (mS/cm)	0.27 ± 0.09	Low salinity
3	Available N (kg/ha)	113.19 ± 25.21	Low
4	Available P (kg/ha)	72.90 ± 8.35	High
5	Available K (kg/ha)	261.50 ± 32.81	Medium
6	Moisture content (%)	8.23 ± 4.39	Average to good
7	Soil organic carbon	0.81 ± 0.31	Medium

EC: electrical conductivity, N: nitrogen, P: phosphorous, K: potassium.

Description of farming practices

Conventional farming systems are characterised using synthetic fertilisers, chemical pesticides and mechanised field operations. Organic farming systems rely on organic nutrient inputs such as farmyard manure, compost and green manures, along with biological pest management practices and exclude the use of synthetic agrochemicals. Natural farming systems follow low-input principles with minimal or no external nutrient inputs, emphasising on-farm resource recycling, microbial formulations and the enhancement of soil biological activity. Information on crop management, nutrient application, irrigation, residue management and tillage practices was documented for each farm.

Experimental design and farm selection

This study followed a field-based observational design that integrated soil sampling, farm surveys and yield data collection. A total of 27 farms were included in the study, comprising 9 farms under each farming system (conventional, organic and natural farming) distributed across the 3 selected districts. The selected farms presented consistent long-term management histories under their respective farming systems, ensuring reliable comparisons across treatments. The sampling framework was designed to capture both spatial and temporal variability while maintaining adequate replication for analysis.

Soil sampling procedure

Soil samples were collected over 2 consecutive cropping years to capture seasonal and interannual variability. Sampling was conducted after the wheat harvest during April 2023 and April 2024 and after the rice harvest during October 2023 and October 2024. At each site, soil samples were collected from 0–15 cm depth using a soil core sampler with a diameter of 7 cm.

For each crop season, 3 replicate samples were collected from all the sites. This resulted in 81 soil samples per crop season (27 sites × 3 replicates × 1 depth). Across both crops and sampling years, a total of 324 soil samples were collected.

Soil physicochemical analysis

Soil bulk density was determined using the core method to support soil carbon stock estimation. The SOC content was analysed using the dichromate oxidation method (18). Soil pH was measured using a soil-water suspension (1 : 2.5) and the cation exchange capacity (CEC) was determined to assess the soil nutrient retention capacity (19). These parameters were selected because of their strong influence on nutrient cycling and GHG emissions.

Farm survey and questionnaire design

A structured questionnaire was developed in accordance with the data input requirements of the CFT. The survey collected detailed information on crop type, yield, fertiliser and manure inputs, including fertiliser type, application rate, timing and method of application, as well as irrigation frequency, residue management, fuel consumption and field operations. Rice fields were irrigated using groundwater through tube wells and through the local canal network under flooded conditions, while wheat received 4–5 supplemental irrigations during the crop season. Crop yield was calculated using farmer-reported harvest data validated through field observations and representative plot sampling. Grain yield (kg) from sampled field areas was converted to a hectare basis (kg ha⁻¹) using standard area conversion factors. Additional information on the farm size, cropping history and management duration was also

recorded. Surveys were administered through direct farmer interviews to ensure data accuracy and completeness.

Assessment of greenhouse gas emissions

The CFT is a practice-based GHG accounting model at the farm scale that can be used in a wide range of farming scenarios. The CFT is an online GHG emissions calculator specifically built for the agricultural systems. The cool farm alliance created CFT, which allows users to compute the yearly GHG emissions associated with agricultural production. The program considers context-specific elements that affect GHG emissions, such as pedoclimatic characteristics, production inputs and other field and farm-level management strategies. It measures the contribution to the atmosphere made through the application of fertilisers, the processes occurring in soils, the management of crop residues, irrigation and the use of energy, in accordance with the guidelines of the IPCC (20). Region-specific soil and management data from Haryana were used as inputs in the CFT, while emission factors remained unchanged and were based on default IPCC-aligned coefficients embedded in the model. The tools enable estimation of GHG emissions both per unit area and per unit of agricultural output. The resulting outputs were comparatively interpreted across farming systems, districts, crops and years using descriptive statistics.

Results

Evaluation of total greenhouse gas emissions under different farming practices

Greenhouse gas emissions from rice crop

Greenhouse gas emissions (kg CO₂-eq.) differed substantially among the farming systems and across years (Fig. 1). The highest emissions were observed under conventional farming, with median values increasing from approximately 2300 kg CO₂-eq. in 2023 to about 3100 kg CO₂-eq. in 2024. Organic farming resulted in intermediate emissions, with median values of approximately 2000 kg CO₂-eq. in 2023 and 2500 kg CO₂-eq. in 2024. Natural farming consistently demonstrated lower GHG emissions than organic and conventional farming systems, with the lowest emissions observed in 2023 (≈ 2050 kg CO₂-eq.), although emissions increased to approximately 2400 kg CO₂-eq. in 2024. In all the other farming systems, emissions were notably higher in 2024 than in 2023, producing greater GHG emissions than organic and natural farming.

Greenhouse gas emissions from wheat crop

Total GHG emissions (kg CO₂-eq.) from wheat production varied considerably across the different farming systems and years (Fig. 2). Conventional farming generated the highest GHG emissions during both study years, with median values of approximately 1300 kg CO₂-eq. in 2023 and 1100–1200 kg CO₂-eq. in 2024. The conventional system also demonstrated greater emission variability, as reflected by wider interquartile ranges.

Conversely, organic and natural farming systems produced substantially lower GHG emissions, with median values consistently below 150 kg CO₂-eq. Organic farming displayed a marginal increase from approximately 120 kg CO₂-eq. in 2023 to approximately 140 kg CO₂-eq. in 2024, whereas natural farming consistently recorded the lowest emissions, with median values of approximately 90 kg CO₂-eq. in 2023 and approximately 110 kg CO₂-eq. in 2024. These findings underscore a pronounced effect of the farming system on wheat-associated GHG emissions,

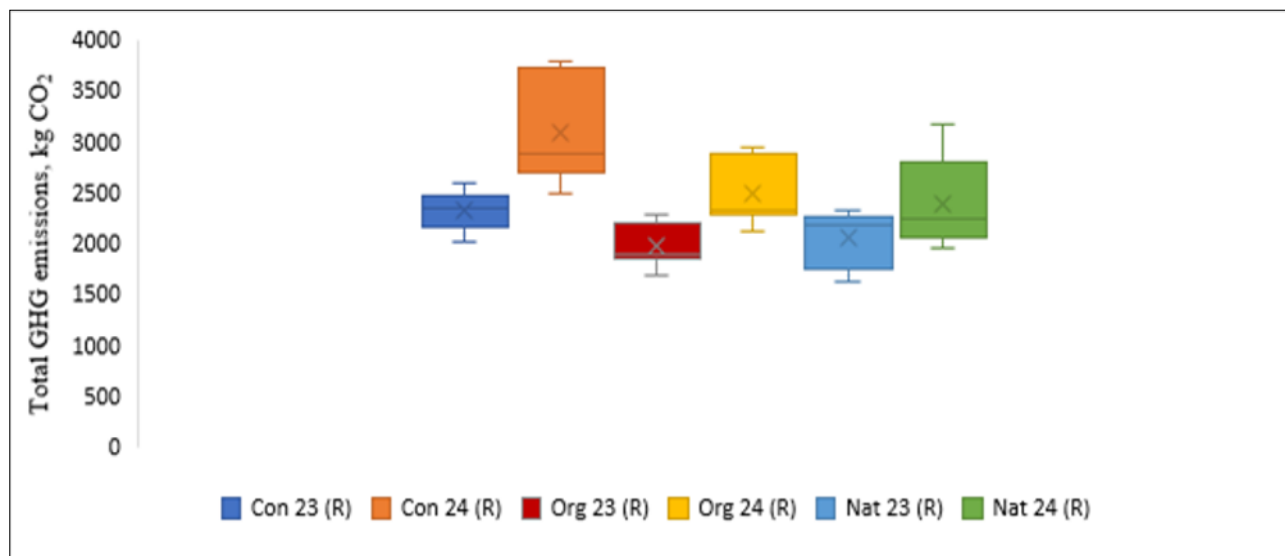


Fig. 1. Greenhouse gas emissions from different farming practices for rice crops.

Con 23 (R): conventional 2023 (rice), Con 24 (R): conventional 2024 (rice), Org 23 (R): organic 2023 (rice), Org 24 (R): organic 2024 (rice), Nat 23 (R): natural 2023 (rice), Nat 24 (R): natural 2024 (rice), GHG: greenhouse gas.

following the pattern conventional > organic $\approx$ natural, with comparatively minimal interannual variation in organic and natural systems relative to conventional management.

In conventional farming practices for wheat and rice, the types of fertilisers used include urea, diammonium phosphate (DAP), muriate of potash (MOP) and single super phosphate (SSP), specifically for rice. In organic farming, the fertilisers consist of manure and vermicompost. Natural farming practices utilise jeevamrith and ghanjeevamrith as fertilisers.

The application rates for these fertilisers vary by farming practice. For wheat crops, conventional methods typically involve applying fertilisers 3 times, while organic practices apply them twice. For rice crops, the application rate is 4 times in conventional farming, 3 times in organic farming and 6 times in natural farming practices.

Greenhouse gas emissions under the rice-wheat cropping system

Substantial differences in total GHG emissions (kg CO₂-eq.) were observed between crop types and study years (Fig. 3). Compared

with wheat production, rice production consistently generated considerably greater GHG emissions during both 2023 and 2024. In 2023, rice demonstrated median emissions of approximately 2100 kg CO₂-eq., whereas wheat recorded notably lower median emissions of approximately 450 kg CO₂-eq. This trend persisted in 2024, when rice emissions rose to approximately 2600–2700 kg CO₂-eq., whereas wheat emissions remained relatively modest at approximately 500 kg CO₂-eq.

Relative to conventional farming, organic farming reduced emissions by approximately 69 % in rice and 51 % in wheat systems, indicating the significant influence of reduced synthetic inputs and biologically driven nutrient management on emission mitigation. Natural farming demonstrated the lowest overall emission intensity among all farming systems. For both crops, GHG emissions are expected to increase in 2024 relative to those in 2023, demonstrating a distinct temporal effect. Rice not only displayed higher median emissions but also exhibited greater variability, as evidenced by broader interquartile ranges and more extended whiskers,

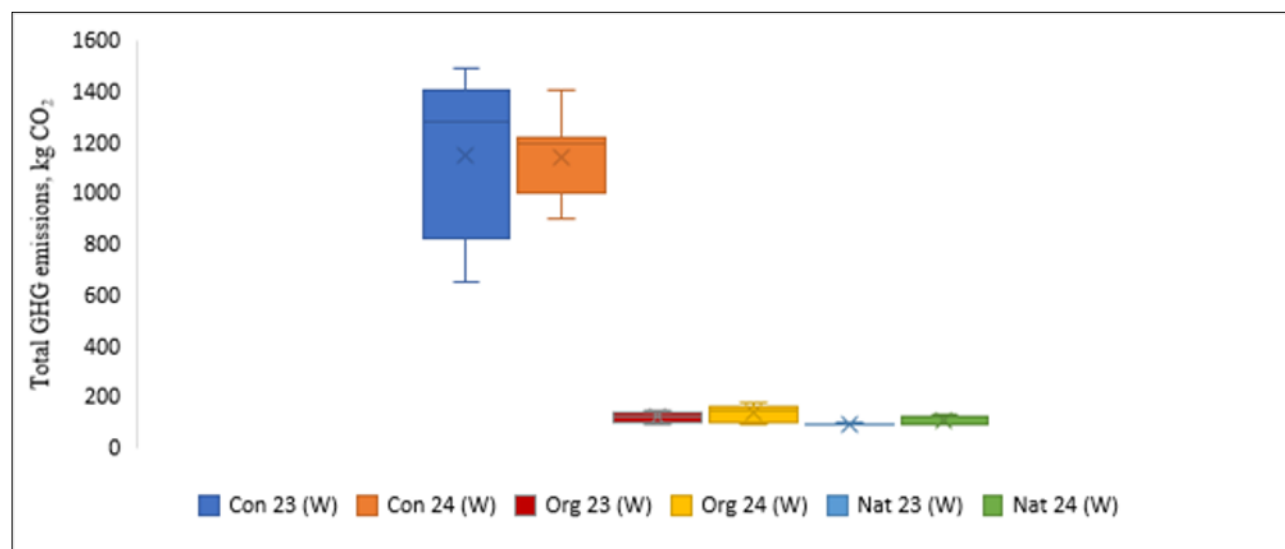


Fig. 2. Greenhouse gas emissions from different farming practices for wheat crops.

Con 23 (W): conventional 2023 (wheat), Con 24 (W): conventional 2024 (wheat), Org 23 (W): organic 2023 (wheat), Org 24 (W): organic 2024 (wheat), Nat 23 (W): natural 2023 (wheat), Nat 24 (W): natural 2024 (wheat), GHG: greenhouse gas.

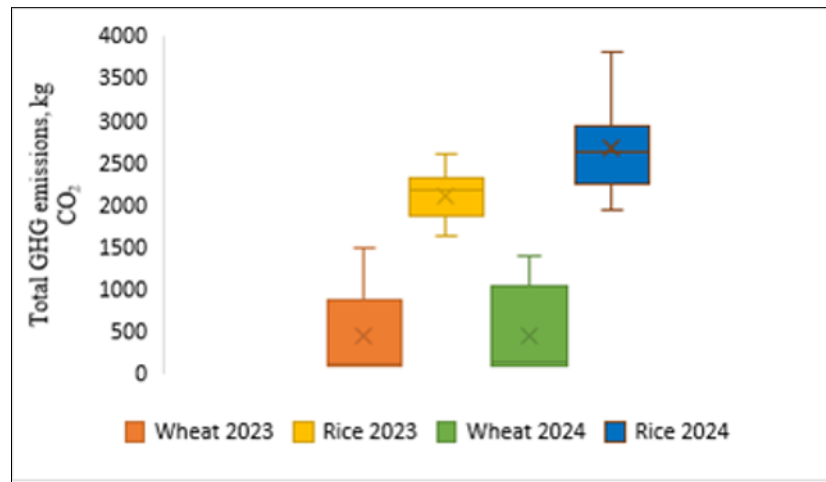


Fig. 3. Greenhouse gas emissions from wheat-rice cropping.

especially in 2024. Wheat emissions remained low every year, with far less variation. These results highlight a significant crop-specific impact on overall GHG emissions, with substantially greater rice-generating emissions than wheat-generating emissions.

Production yield of rice-wheat crops under different farming practices

The yield performance varied considerably among the different farming practices, crop types and years (Fig. 4). In wheat, the conventional farming consistently resulted in the highest yields, organic farming resulted in intermediate results and natural farming resulted in the lowest. In rice, the conventional farming resulted in the highest yields, natural farming resulted in intermediate results and organic farming resulted in the lowest. Under conventional, wheat yield is about 2200–2300 kg in 2023 and 2050–2150 kg in 2024. Rice maintained higher yield levels throughout the study period, at approximately 2700–2800 kg in 2023 and 2600–2700 kg in 2024. In organic farming, wheat yields showed a 15–25 % reduction compared to conventional, with approximately 1700–1800 kg in 2023 and 1800–1900 kg in 2024. Rice yields showed greater

variability, especially in 2023 (range: 1000–3000 kg; median: 1900–2000 kg), whereas 2024 recorded improved consistency (median: 2100–2200 kg), resulting in a reduced gap relative to conventional. Natural farming produced the lowest yields, especially for wheat. Wheat yields ranged from 1100–1200 kg in 2023 and 1400–1500 kg in 2024, corresponding to 40–50 % lower yields than conventional. In comparison to conventional, rice yields increased and showed significant variability, with median yields of about 2100–2200 kg in 2023 and 2400–2500 kg in 2024, with interquartile ranges reaching as high as 3600 kg. Across all systems, rice consistently produced higher yields than wheat by 500–1000 kg. Yield variability increased progressively from conventional to organic and natural farming systems.

The comparatively lower yields observed under organic and natural farming systems were likely associated with reduced synthetic nutrient inputs, slower nutrient mineralisation from organic amendments and lower overall nutrient availability compared with conventional farming systems.

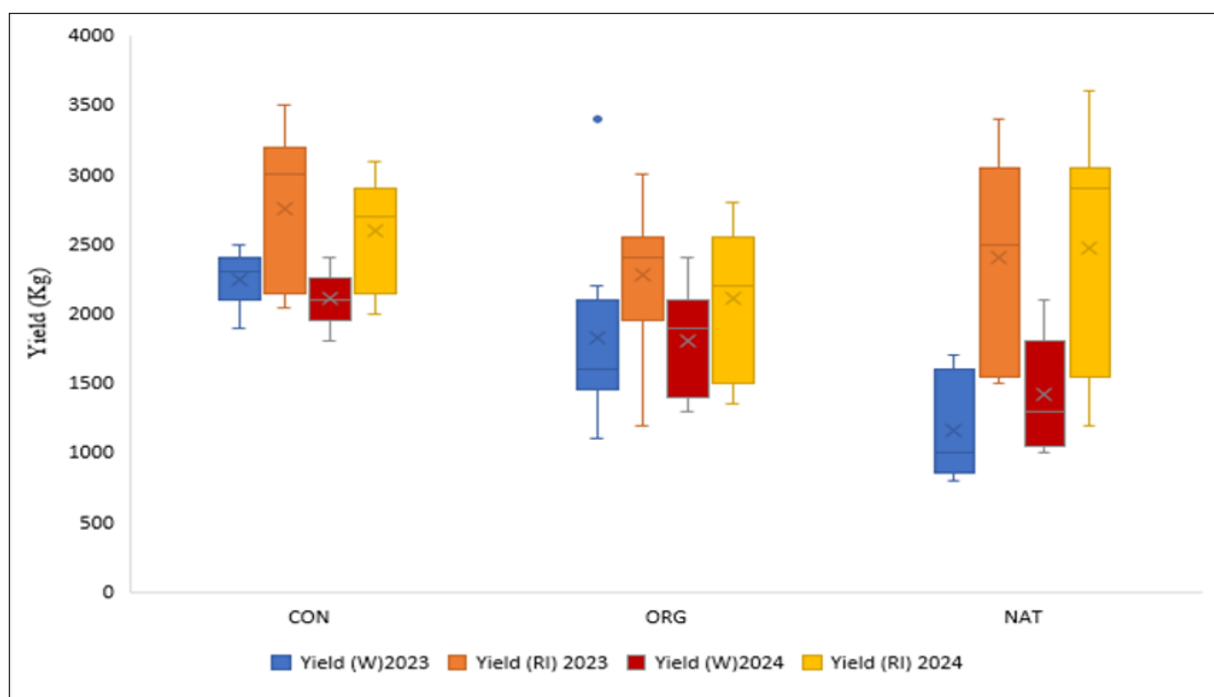


Fig. 4. Yield production in wheat-rice cropping systems across different farming practices.

Yield (W) 2023: yield (wheat) 2023, Yield (RI) 2023: yield (rice) 2023, Yield (W) 2024: yield (wheat) 2024, Yield (RI) 2024: yield (rice) 2024, CON: conventional, ORG: organic, NAT: natural.

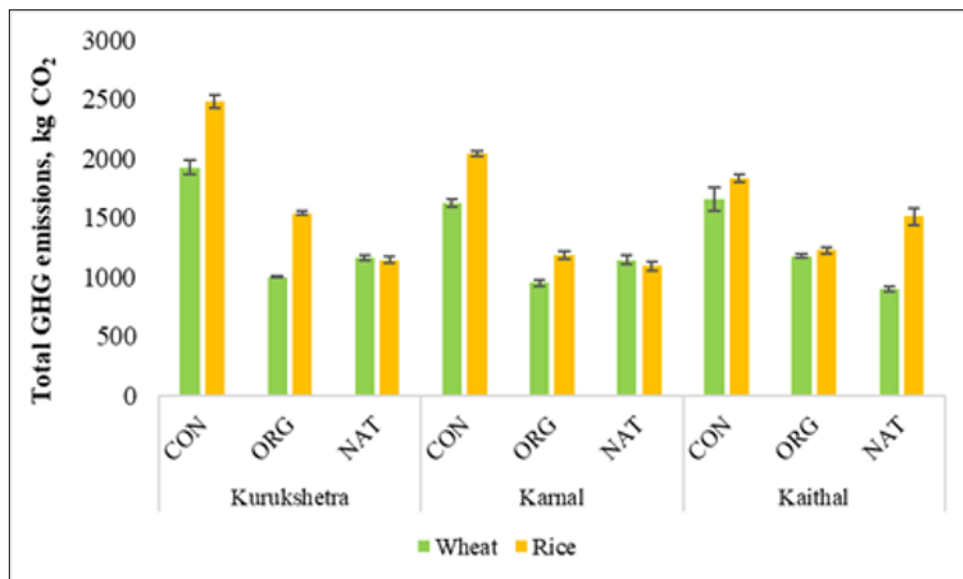


Fig. 5. Variation in district-wide greenhouse gas emissions.

CON: conventional, ORG: organic, NAT: natural, GHG: greenhouse gas.

District wise variation in greenhouse gas emissions

Kurukshetra recorded the highest total GHG emissions among the districts, followed by Karnal and Kaithal. Kurukshetra demonstrated (Fig. 5) maximum emissions for wheat (~1950 kg CO₂-eq) and rice (~2500 kg CO₂-eq) under conventional systems. Under the conventional system, Kaithal recorded the lowest emissions (rice ~1850 kg CO₂-eq; wheat ~1650 kg CO₂-eq), followed closely by Karnal, which also exhibited comparatively lower values (rice ~2050 kg CO₂-eq; wheat ~1650 kg CO₂-eq). In contrast, both natural and organic farming systems consistently demonstrated reduced emissions levels across all districts, indicating a consistent and uniform downward shift relative to conventional practices. Across all districts and crops, conventional farming consistently resulted in the highest GHG emissions, whereas both organic and natural farming systems generally exhibited lower emissions, with variations depending on crop type and district. The relative performance of organic and natural farming systems varied across

districts, indicating the influence of local management practices and environmental conditions on emission patterns. In Kurukshetra, compared with organic (~1000 and ~1550 kg CO₂-eq) and natural (~1150 and ~1150 kg CO₂-eq) emissions, conventional emissions were ~1950 kg CO₂-eq (wheat) and ~2500 kg CO₂-eq (rice) respectively. In Karnal, conventional systems emitted ~1650 kg CO₂-eq and ~2050 kg CO₂-eq (rice), whereas organic farming reduced emissions to ~950 kg CO₂-eq and ~1200 kg CO₂-eq, respectively and natural farming resulted in ~1150 kg CO₂-eq and ~1100 kg CO₂-eq respectively. Similarly, in Kaithal, conventional emissions were ~1650 kg CO₂-eq (wheat) and ~1850 kg CO₂-eq (rice), whereas organic (~1180 kg CO₂-eq and ~1230 kg CO₂-eq) and natural (~900 kg CO₂-eq and ~1500 kg CO₂-eq) systems exhibited lower values respectively. Compared with wheat, rice consistently emitted more GHGs across all districts and among all farming practices.

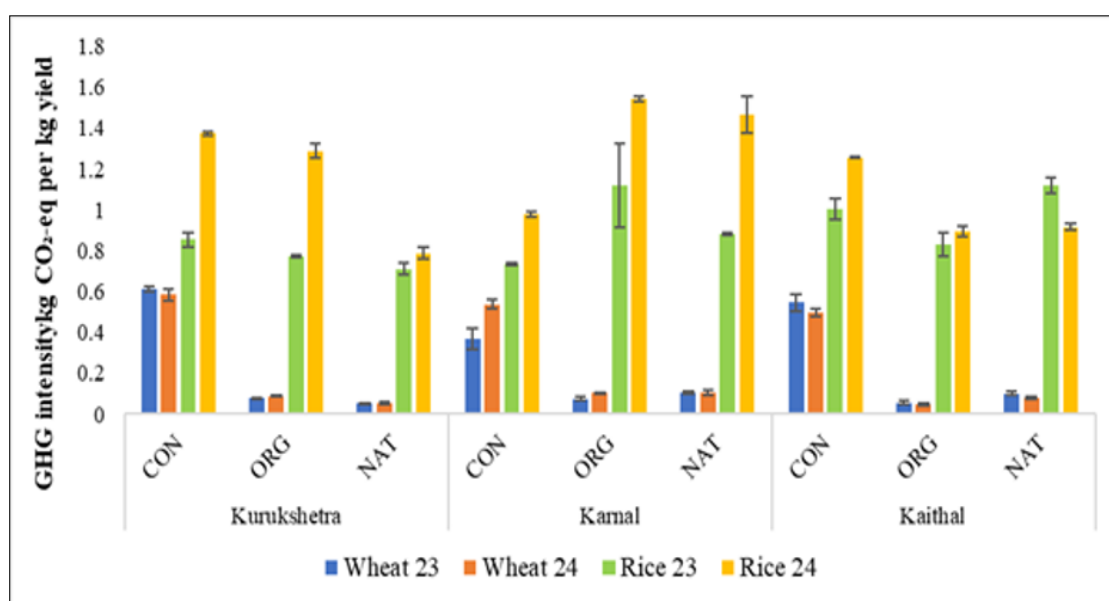


Fig. 6. Greenhouse gas emission intensity (kg CO₂-eq per kg of yield) for wheat and rice across various farming systems.

CON: conventional, ORG: organic, NAT: natural, GHG: greenhouse gas.

Greenhouse gas emission intensity per kg yield

Greenhouse gas intensity (kg CO₂-eq per kg yield) varied considerably between crop types and farming systems (Fig. 6). In terms of all the observations, compared with wheat, rice demonstrated consistently greater GHG emission intensity. The rice GHG intensity ranged from approximately 0.75 to 1.60 kg CO₂-eq kg⁻¹ yield, whereas the yield of wheat was substantially lower, typically remaining below 0.65 kg CO₂-eq kg⁻¹ yield. In conventional management systems, the highest GHG intensity was recorded for rice, with values surpassed 1.10 kg CO₂-eq kg⁻¹ yield and reached 1.60 kg CO₂-eq kg⁻¹ yield in certain instances. The wheat GHG intensity under conventional management ranged from 0.40 to 0.65 kg CO₂-eq kg⁻¹ yield. Organic management resulted in relatively reduced GHG intensity for both crops, with rice values predominantly falling between 0.75 and 1.10 kg CO₂-eq kg⁻¹ yield and wheat values mainly remaining below 0.15 kg CO₂-eq kg⁻¹ yield. Natural farming systems displayed intermediate rice GHG intensity levels, which typically ranged from 0.85 to 1.30 kg CO₂-eq kg⁻¹ yield, whereas the wheat GHG intensity remained low, primarily below 0.12 kg CO₂-eq kg⁻¹ yield. Greenhouse gas intensity consistently remained higher in rice than in wheat across all farming systems.

Discussion

Greenhouse gas emissions from rice crops

Compared with organic and natural agriculture, conventional agriculture tends to result in greater GHG emissions, largely owing to the intensive use of synthetic inputs, mechanical field operations and frequent soil disturbance. Fertilisers based on synthetic N accelerate N mineralisation, which in turn promotes nitrification-denitrification processes and increases N₂O emissions. Similar findings revealed that conventional agricultural practices can increase direct soil N₂O emissions and that volatilised N can affect N₂O emissions because a portion of this N is deposited on agricultural and nonagricultural soils and water and is subjected to transformations that may result in N₂O emissions (3, 21, 22). Conventional farming contributes significantly to CO₂ emissions because fossil energy is consumed in groundwater extraction (irrigation), tractor and machinery use and industrial manufacturing of fertilisers, all of which result in the combustion of fossil fuels and associated GHG emissions. Use of heavy machinery for harvesting and incorporating residues also increases the decomposition and release of GHGs from soil organic matter (23, 24). When crop residues are burned in the open field, significant amounts of CO₂, CH₄ and N₂O are released into the atmosphere. Organic and natural farming are considered environmentally sustainable approaches that help mitigate GHG emissions through practices such as crop rotation, reduced tillage, composting, cover cropping, mulching, green manures, biological pest control and the use of organic or natural biofertilisers (25, 26). These practices enhance soil carbon and N sequestration, improve soil health, microbial diversity and climate resilience while reducing soil carbon and N losses (27, 28). Compared to conventional systems, organic farming can increase SOC stocks by 18–28 % over 20 years and reduce N₂O emissions by about 40 % per hectare, whereas natural farming can lower overall GHG emissions by 30–40 % (29, 30). In the present study, compared with conventional farming, organic farming and natural farming systems were reported to result in lower GHG emissions. Climate-smart agricultural practices also estimated lower CH₄ emissions compared

to conventional farming, which may be due to the avoidance of puddling and less frequent irrigation (31). Organic farming released approximately 40 % less N₂O than conventional systems did on an area basis in Switzerland (32). Life cycle assessment (LCA) studies have shown that compared with conventional systems, organic systems often have lower GHG emissions per hectare and per kilogram produced for crops such as lettuce, potatoes and leek production systems (33).

Greenhouse gas emissions from wheat-rice cropping across different farming practices

The crop emission patterns over time reveal that a higher level of wheat emissions in 2023 than in 2024 is probably because, in 2023, more fertiliser was used, there may have been more residue retention or the conditions after harvesting were warmer, which facilitated the soil respiration. On the other hand, the difference in rice emissions between 2023 and 2024 can be accounted for by an increased amount of rainfall, longer flooding periods and more residues being available, all of which resulted in more CH₄ production under anaerobic conditions. Compared with wheat, rice emits more GHGs because of the burning of leftover residue, field conditions and water management. Wheat emits much less CH₄ because most of the time, the soil oxygen level is high, so CH₄ formation is naturally suppressed; hence, relatively low levels of GHGs are produced. Compared with wheat (3–4 t ha⁻¹), rice yields greater amounts residual biomass (approximately 5–7 t ha⁻¹), thereby greatly increasing the potential for emissions during decomposition or burning (34). Rice straw has a high silica content and it possesses low palatability for livestock, thereby limiting its utility as fodder; therefore, it is commonly burned, resulting in the release of CO₂, CH₄, N₂O and black carbon (35). Methane is produced in flooded rice soils because waterlogged conditions create an anaerobic soil environment that favour the activity of methanogenic microorganisms, which decompose organic matter and release CH₄ as a GHG (36–38). Similar findings have been reported from eastern India, where studies on site-specific nutrient management in transplanted and direct-seeded rice systems also observed CH₄ emissions under comparable conditions (39, 40). These studies further demonstrate that optimised fertiliser management not only enhances crop yield but also reduces GHG emissions by improving N-use efficiency and minimising excess N losses. Similarly, assessments of crop patterns and adaptation strategies in South Asian rice-based systems have highlighted the importance of water management, residue handling and balanced nutrient inputs. These practices have been identified as not only the most effective approaches for reducing emissions but also those most compatible with maintaining crop yields under changing agroclimatic conditions (14).

District-wise variation in greenhouse gas emissions

The different emission patterns at the district level, Kurukshetra > Karnal > Kaithal, were most likely due to changes in cropping intensity, the amount of irrigation needed and how residues were managed. Energy-related emissions in Kurukshetra are particularly high because of intensive rice cultivation and large-scale groundwater pumping. Moreover, fully flooded conditions allow CH₄ to form. Karnal has only a moderate level of emissions, whereas Kaithal exhibited comparatively lower GHG emissions. Previous studies reported that better water management practices, more efficient residue handling and the use of less energy-intensive inputs, combining no-tillage with surface irrigation and mulching

results in higher yields and improved water use efficiency (41, 42). The synergy of no-tillage and drip irrigation enhances crop resilience to climate change, leading to the development of sustainable agricultural strategies that balance productivity, resource conservation and environmental protection.

Natural farming systems continually have the lowest GHG emissions, mainly because of their lack of external inputs, reduced soil disturbance, lower energy consumption and enhanced biological nutrient cycling. Organic farming systems usually exhibit intermediate levels of emissions, which mirror the reduced use of synthetic inputs; however, there are still challenges with residue management, especially in rice-based systems.

Collectively, these results underscore the importance of combining mitigation strategies specific to both the crop and the region such as better residue management, less tillage, N application optimisation, site-specific nutrient management and water-saving irrigation techniques for the effective reduction of GHG emissions and the continuing productivity in the rice-wheat production systems of India.

Greenhouse gas emission intensity per kg yield

The present study stated that rice consistently showed higher yield-scaled GHG emission intensity than wheat across all farming systems, highlighting the greater emission potential of rice-based production systems. Among the different farming practices, conventional recorded the highest emission intensity, especially in rice. These findings are in alignment with previous study, which reported higher yield-scaled emissions under conventional rice cultivation systems involving puddled transplanting, continuous flooding and intensive synthetic fertiliser application (6). Such practices create anaerobic soil conditions that stimulate CH_4 production and increase N_2O emissions through excessive N fertilisation. Although the emission values observed in the present study were comparatively higher, the overall trend remained consistent with their findings. In contrast, organic farming resulted in comparatively lower GHG intensity for both rice and wheat. This reduction may be linked with lower dependence on synthetic fertilisers and improved soil carbon sequestration, which supports the observations of previous study, which also documented reduced emission intensity under organic management systems (43). Similarly, natural farming systems showed lower emission intensity than conventional farming, particularly in wheat. Conservation-based and natural farming practices such as zero tillage, residue retention, direct-seeded rice, alternate wetting and drying (AWD) and integrated nutrient management substantially reduce yield-scaled GHG emissions by improving resource-use efficiency and minimising CH_4 emissions from flooded soils (44). However, the comparatively higher emission intensity observed in the present study may be attributed to site-specific environmental conditions, differences in irrigation and residue management, variability in nutrient application strategies and crop productivity levels. Overall, the results clearly indicate that crop type and management practices strongly influence yield-scaled GHG emissions, with sustainable management approaches such as organic and natural farming showing greater potential for reducing agricultural emissions and promoting climate-resilient production systems.

Productivity–emission trade-offs among conventional, organic and natural farming systems

In rice production, both organic and natural farming showed

substantial GHG mitigation potential relative to conventional farming, with emission reductions of 31.9 % and 31.6 % respectively, though accompanied by yield reductions of 18.0 % and 8.99 %. The calculated trade-off ratios are 1.77 for organic and 3.52 for natural farming. This stated that natural farming achieved higher productivity–environment balance, wherein each 1 % reduction in yield corresponded to a 3.52 % decrease in GHG emissions, compared with only 1.77 % under organic farming. In contrast, wheat production showed an inverse pattern, while organic and natural farming reduced emissions by 9.35 % and 7.18 % respectively. The associated yield reductions were considerably larger at 16.38 % and 40.0 %, yielding trade-off ratios of 0.57 and 0.18. In wheat production, the ratios indicate that emission reductions were relatively small compared to the productivity losses. However, organic farming still performed better than natural farming in achieving a more favourable balance between mitigation and yield loss. These findings emphasise that the effectiveness of alternative farming systems, both agronomically and environmentally, varies significantly depending on the crop. Natural farming is particularly successful with rice, while organic farming is more efficient for wheat. This highlights the need for assessments that take crop-specific contexts into account when evaluating sustainable agricultural transitions.

Cool farming tool inputs and limitations of natural farming

Cool farming tool has been successfully utilised in numerous cropping systems, such as rice-wheat, maize-wheat and potato-based systems, under different nutrient and water management scenarios (15, 45, 46).

Cool farming tool does not rely on either ideological classifications or brand identities of inputs to farming but rather on nutrient flows and management intensity as the core drivers of the model. Hence, GHG emissions are reflective of the amounts of synthetic fertilisers, organic amendments, residue handling practices, tillage intensity and fuel use (20). This feature allows the tool to be very attractive for simple comparisons of conventional and organic production systems, where the different levels of nutrient inputs are explicitly quantified, but it presents methodological challenges when evaluating natural farming systems.

Often, inputs such as Jeevamrit, Beejamrit and Panchagavya may be used in natural farming, which are indeed characterised by very low concentrations of macronutrients and mainly operate through stimulation of the soil microbial community and nutrient mineralisation rather than by a direct supply of N, P, or K. Since CFT operates on the basis that emissions are a function of the nutrients delivered to the soil and their subsequent transformations by the soil N microbial community, it would be methodologically incorrect and potentially misleading to include such products as fertilisers when reporting emissions. Hence, it is consistent with the rationale behind previous CFT applications in low-input and organic systems that natural farming inputs should rather be represented through the indirect use of management proxies than via explicit fertiliser entries (20, 45).

When CFT was used on rice- and cereal-based crop systems, the emissions were found to be the most dependent on the levels of synthetic N applied, the way that residues are managed, how the crop is irrigated and the use of energy, particularly in flooded areas where CH_4 emissions are greatly enhanced (46). In the CFT framework, residue management variables were entered based on

field-specific practices, including residue retention, residue incorporation, or residue removal after harvest. Tillage operations were recorded whether there is change in tillage processes. These management parameters were incorporated into the model along with irrigation and energy-use data to estimate farm-level GHG emissions. Similarly, an analysis of maize-wheat systems revealed that most GHG emissions decrease significantly when the level of N fertiliser decreases, which occurs mainly through the reduction in soil N₂O fluxes and emissions related to the manufacturing of fertilisers (15). Such evidence serves to theoretically justify the interpretation of natural farming systems in CFT by taking zero synthetic fertiliser inputs while the effects of the system are being captured through residue retention, decreased tillage and lower energy consumption.

On the other hand, the greatest drawback of CFT is that it does not have the ability to explicitly represent microbial inoculants, biostimulants, or biological improvements in nutrient cycling, which are the essence of natural farming systems. Although CFT can affect soil carbon stocks and N emissions, it is incapable of capturing, for example, the improved microbial efficiency, altered microbial community structure, or increased nutrient use efficiency associated with the addition of biostimulants. Therefore, the GHG emission results obtained for natural farming systems from the use of CFT should be seen as a conservative estimate, with the likely longer-term benefits of soil carbon stabilisation and biological regulation of N being overlooked (20, 46).

Despite these limitations, CFT remains a scientifically defensible tool for the comparative assessment of farming systems when its assumptions are transparently stated and when the results are interpreted in relative rather than absolute terms. Previous studies applying CFT across contrasting nutrient management scenarios have demonstrated that the tool is most robust when it is used to evaluate emission trends and system-level differences rather than precise emission magnitudes (15, 45). When combined with independent measurements of soil biological indicators such as SOC, microbial biomass and respiration, CFT-based assessments can provide a balanced and integrated evaluation of the climate implications of natural farming systems.

Conclusion

Greenhouse gas emissions (GHGs) were compared from conventional, organic and natural farming in rice-wheat systems. Natural had the lowest emissions, reducing emissions by approximately 62 % in rice and 80 % in wheat compared to conventional methods. Organic farming achieved reductions of 51 % and 69 %, respectively. The differences observed among the farming systems were largely attributable to variations in synthetic fertiliser use, soil management practices and energy consumption. Rice produced more emissions than wheat, primarily due to flooded conditions. The study noted yield-emission trade-offs; conventional farms had the highest yields but high environmental costs, while organic and natural methods, though lower in productivity, offered better sustainability. To enhance sustainability, strategies like improved residue management and water-efficient practices are necessary. Policymakers can promote climate-smart farming through financial incentives and training. Future research should focus on long-term strategies to balance productivity and emission reductions in these systems.

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Authors' contributions

NK was responsible for data collection, formal analysis, preparation of the original draft and compilation of the manuscript. DG supervised the study, designed the methodology, contributed to manuscript writing and provided critical inputs to enhance the work. AKM contributed to the conceptualisation of the study and the final editing of the manuscript. MRS assisted with data interpretation. All authors read and approved the final manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for minor language refinement and improvement of sentence structure. Additionally, Grammarly software was used to grammar-correction and language editing purposes. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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