

FINAL PROJECT REPORT

On

**Popularization of direct seeded rice technology for climate change adaptation
by reducing Greenhouse Gases (GHGs) emission and acquiring carbon credit**

Submitted by

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to

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Preface

I take this opportunity to express my deep sense of gratitude to Dr. Ajai Rana, CEO & Managing Director, Savannah Seeds Private Ltd., Gurugram, Haryana, India, for generously providing the funds necessary for the conduct of this project study. I am equally thankful to Dr. Vinod Verma, Seed Quality Lead, for his continued monitoring, interaction, and valuable guidance during the project period. In addition, I am grateful to the worthy Directors of Research, CSKHPKV, Palampur, for their constant encouragement and support throughout the course of this work.

I am sincerely indebted to Dr. N.K. Sankhyan, presently serving as Registrar, Central University of Himachal Pradesh (CUHP) and former Head, Department of Soil Science cum Co-Principal Investigator of the project, for his sustained guidance and encouragement during the study period. Without his support, such a study at Palampur would not have been possible. I also extend my gratitude to Dr. R.P. Sharma, present Head of the Department of Soil Science, for his valuable guidance and for providing the necessary facilities during the course of this work. My sincere thanks are due to Dr. Anil Kumar, Principal Scientist (Agronomy), for his continuous guidance and support throughout the project period.

I am further thankful to the Associate Directors of Research, HAREC, Dhaulakuan, and the Programme Coordinator, KVK, Una (H.P.), for their continued support during the study. I am deeply thankful to Dr. Janardhan Singh, Head, Department of Natural Farming and Organic Agriculture, for kindly permitting the use of the Gas Chromatography Machine for greenhouse gas sample analysis during the experimental period.

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In addition, I gratefully acknowledge the contributions of the Senior Research Fellows associated with the project during the study period, particularly Dr. Rushali Katoch, and my Ph.D. student Mr. Hansraj, for compiling the final project report. I am also thankful to all the field workers from Palampur, Una, and Dhaulakuan who worked diligently on the project and whose efforts were vital to its successful execution.

Finally, I express my sincere thanks to all those who contributed, directly or indirectly, to the successful completion of this project.



Dr. Dhanbir Singh
Principal Investigator of the Project

Introduction:

Rice (*Oryza sativa* L.) is a staple food for nearly half of the global population and plays a pivotal role in ensuring nutritional and livelihood security across Asia. In India, it constitutes the backbone of the agricultural economy, supporting millions of farming households. However, meeting the rising demand of an ever-increasing population from the existing cultivated area must be achieved without imposing adverse environmental impacts, particularly those associated with greenhouse gases (GHGs) emissions from paddy fields.

The conventional puddled transplanted rice (PTR) system has long been recognized as the dominant method of rice establishment in India due to its early yield advantage and effective weed control. However, this system is increasingly criticized for its unsustainable resource use and environmental consequences. This is because repeated puddling operations require large quantities of irrigation water, disrupt soil structure by breaking aggregates and capillary pores, and create a compact hardpan that hinders the establishment and growth of succeeding crops. Such structural degradation reduces water productivity and adversely affects soil fertility, thereby compromising the long-term productivity and sustainability of rice-based cropping systems.

Furthermore, the continuous anaerobic conditions under PTR favour methanogenesis, leading to substantial GHG emissions and an elevated global warming potential (GWP), while simultaneously reducing carbon credit potential. In addition, intensive fertilizer inputs and higher labour requirements further increase the carbon footprint of this production system.

Addressing these challenges requires improved agricultural management practices that improves the soil structure and mitigate emissions of the three major GHGs viz., CO₂, CH₄, and N₂O with GWPs of 1, 28, and 265, respectively. Ensuring the sustainability of rice ecosystems while meeting growing food demand remains a critical challenge. The emphasis, therefore, is on developing resource-efficient and climate-resilient rice genotypes and to validate alternate production systems that sustain high productivity while reducing GHG emissions, thereby contributing to long-term food and environmental security.

In this context, the present study was conducted by the Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya (CSK HPKV), Palampur, in collaboration with Savannah Seeds Pvt. Ltd., Gurugram, Haryana, India, across

two agro-climatic zones and three locations of Himachal Pradesh with the following objectives:

Objectives:

The study was designed to analyze and compare the performance of different rice genotypes under direct seeding methods of rice (DSR) with that of popular genotypes cultivated under the conventional puddled transplanted rice (CT-PTR) system. The specific objectives were:

1. To evaluate the effects of different rice management practices on greenhouse gas (GHG) emissions, grain yield, and water productivity, and
2. to assess changes in soil physico-chemical and microbiological properties under contrasting establishment methods.

The quantifiable reductions in GHG emissions obtained from this study will be utilized for the estimation of carbon credits.

Study overview:

The proposed research was conducted by the Department of Soil Science, CSK HPKV, Palampur, in collaboration with Savannah Seeds Pvt. Ltd., Gurugram, India, to evaluate the effects of different rice genotypes established under direct seeding methods of rice (DSR) on greenhouse gas (GHG) emissions, soil health, water productivity, and carbon credit potential, in comparison with popular genotypes cultivated under the conventional puddled transplanted rice (CT-PTR) system. The study was undertaken during the *kharif* seasons of 2023 and 2024 across two agro-climatic zones and three locations in Himachal Pradesh.

Technical details:

The proposed research was conducted in two major rice-growing agro-climatic zones of Himachal Pradesh:

- Zone I: Una and Dhaulakuan
- Zone II: Palampur

The field experiments were laid out in a randomized block design (RBD) across these zones to ensure robust evaluation of treatment effects. Each trial comprised six treatments (T₁–T₆) with four replications, thereby facilitating precise and reliable comparisons.

Experimental details & crop management:

- **Rice hybrid/varieties:**

A diverse set of rice hybrids and varieties was evaluated to assess their adaptability and performance under different establishment methods and across varying agro-ecological situations.

- **Treatment details:**

The field experiments on rice crop were conducted during the *kharif* seasons of 2023 and 2024 at the research farm of the Department of Soil Science at CSK HPKV Palampur, KVK Una and at HAREC, Dhaulakuan. The trials were laid out in a randomized block design (RBD) with six treatments and four replications. The details of the treatments are presented below:

Detail of Treatments

Sr. No.	Treatment
T ₁	Conventional puddled-transplanted rice popular variety <i>PR-126</i>
T ₂	Conventional puddled-transplanted rice <i>SAVAH-134</i>
T ₃	Direct seeded rice-popular variety <i>PR-126</i>
T ₄	Direct seeded rice <i>SAVAH-134</i>
T ₅	Direct seeded rice <i>SAVAH-134</i> HT Full Page hybrid
T ₆	Direct seeded rice <i>SAVAH-134</i> HT Full Page hybrid with alternate flooding and drying

Number of Treatments : 6

Replications : 4

Total number of plots : 24

Plot size : 4m × 4m at Palampur
4m × 3m at Una and Dhaulakuan

Design : Randomized Block Design (RBD)

General recommended dose : 90:40:40 kg ha⁻¹ (N: P₂O₅: K₂O)

Varieties : *PR-126*, *SAVAH-134*, *SAVAH-134* HT Full Page hybrid

Seed rate for Direct seeded rice : 25 kg ha⁻¹

Seed rate for Transplanted rice : 12.5 kg ha⁻¹

Layout of the experiments

The experiment comprised six treatments arranged in a randomized block design with four replications. The layout plans of the experiment at Palampur, Una, and Dhaulakuan are presented in Fig. 1, Fig. 2, and Fig. 3, respectively.

Direct-seeded rice varieties *PR-126*, *SAVAH-134*, and *SAVAH-134* HT Full Page hybrid were sown between 5–6 June in 2023 and between 5–7 June in 2024 at the experimental farms of the Department of Soil Science CSK HPKV Palampur, KVK Una, and HAREC Dhaulakuan. Similarly, nurseries for transplanted rice varieties *PR-126* and *SAVAH-134* were established on 5th June during both years.

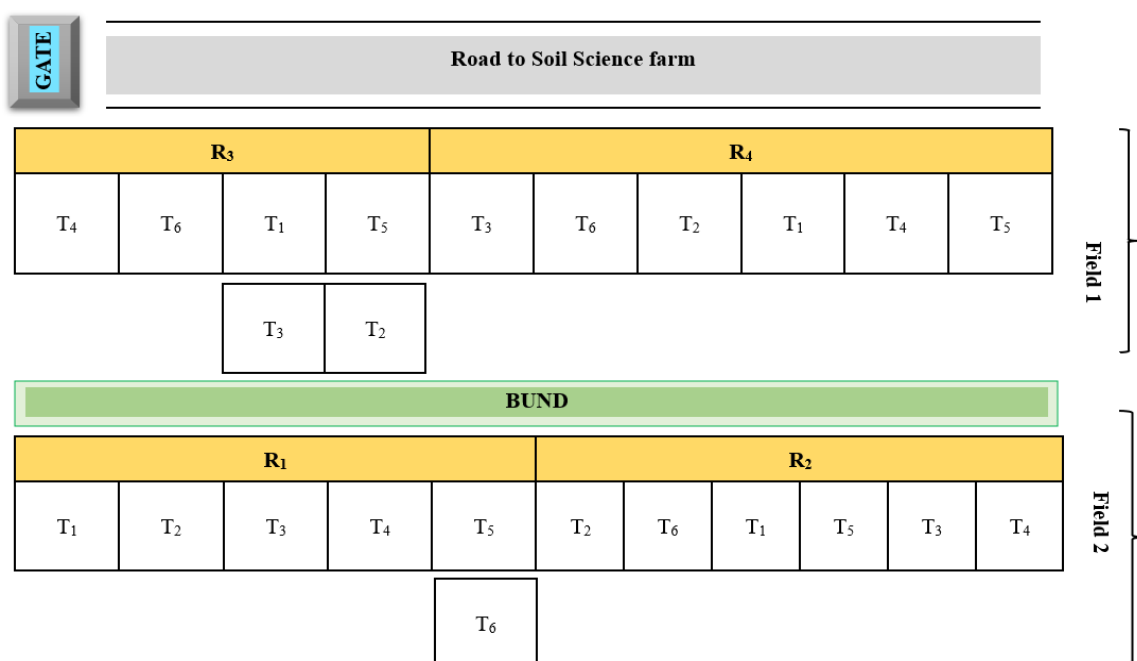


Fig. 1: Layout plan of the experiment at Palampur

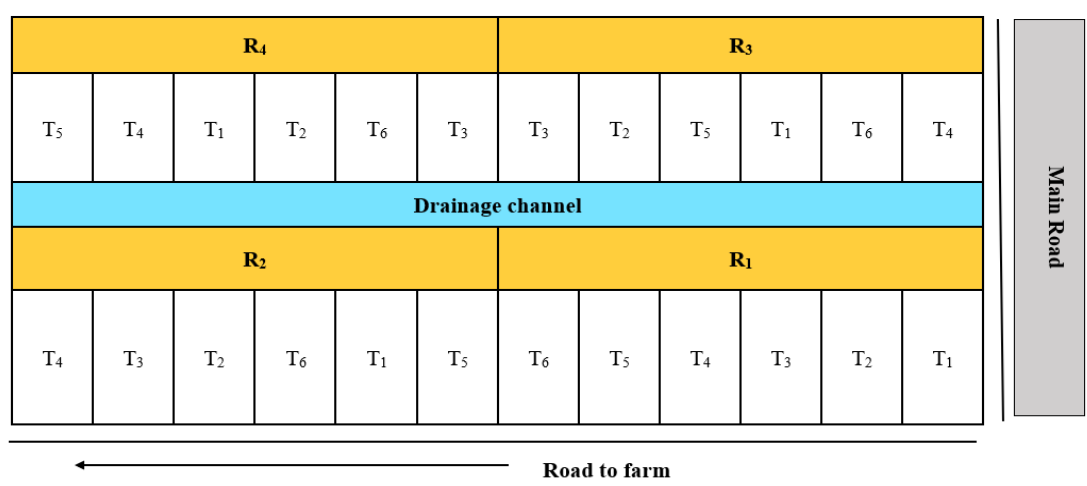


Fig. 2: Layout plan of the experiment at KVK, Una

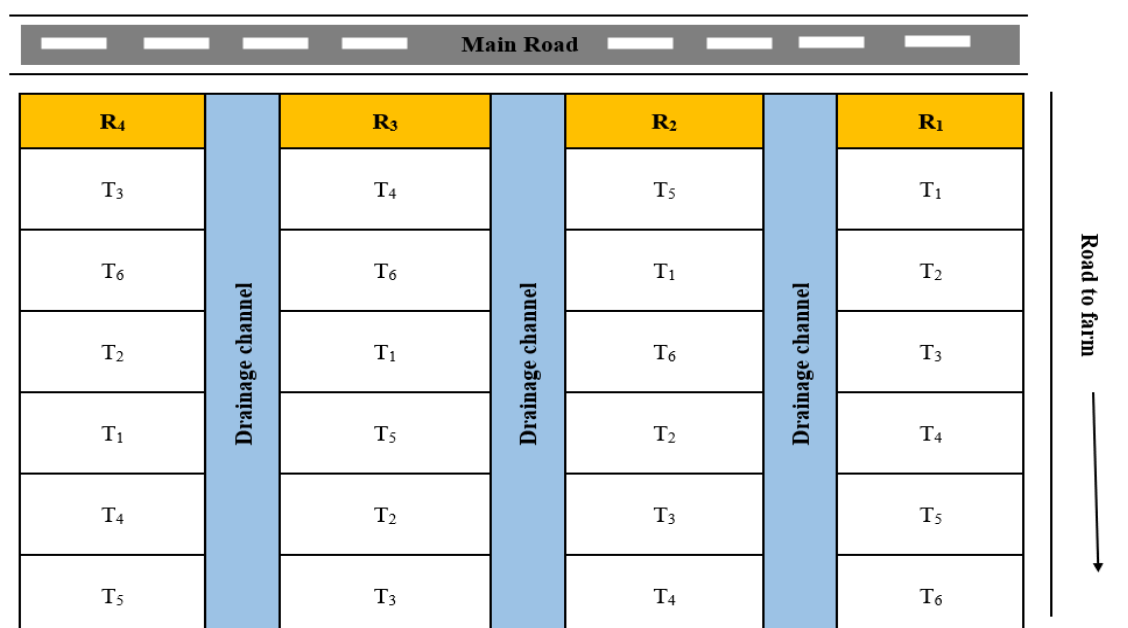


Fig. 3: Layout plan of the experiment at HAREC, Dhaulakuan

Field Preparation and Crop Establishment

For direct-seeded rice (DSR) plots, the field was prepared by carrying out two dry ploughings using a disc plough and cultivator, followed by land levelling. In puddled transplanted rice (PTR) plots, the field was prepared with two dry ploughings, after which

irrigation was applied and puddling was carried out using a power tiller. Transplanting of rice seedlings was done 2–3 days after puddling.

Nursery Management for PTR

Seedlings were raised in nursery beds measuring 2 m × 1 m. Approximately 12.5 kg seed per hectare was used for nursery sowing under the puddled transplanted rice (PTR) method for different hybrids. Moisture in the nursery beds was maintained by daily irrigation using a watering can. To protect the crop from pest infestation, Cartap was applied at 1 kg ha⁻¹ seven days prior to seedling uprooting.

Direct Seeding

Paddy seeds were treated with Thiram at 2 g kg⁻¹ of seed. The treated seeds were sown at the rate of 25 kg ha⁻¹ using a seed drill, maintaining a row spacing of 20 cm.

Transplanting of Seedlings

Approximately 28-day-old rice seedlings were transplanted into puddled plots at a spacing of 25 cm × 20 cm, with 2–3 seedlings placed in each hill.

Fertilizer Application and Crop Management

A uniform dose of 90 kg N, 40 kg P₂O₅, and 40 kg K₂O ha⁻¹ was applied through urea (46% N), single superphosphate (SSP; 16% P₂O₅), and muriate of potash (MOP; 60% K₂O). The entire dose of phosphorus and potassium, along with half of the nitrogen, was applied uniformly as a basal dose at the time of sowing. The remaining half dose of the nitrogen was top-dressed in two equal splits, *i.e.*, at tillering and panicle initiation stages, across all treatments.

The standard package of practices recommended by the university was followed for raising the crop. After attaining physiological maturity, the crop was harvested during the first fortnight of October at KVK Una and HAREC Dhaulakuan, and during the second fortnight of October at Palampur in both years.

Water management

At all locations, in conventional puddled transplanted rice (PTR) plots, markings were made at a height of 10 cm on sticks installed at visible sites within the plots. Irrigation water was applied whenever the water level dropped below the 5 cm mark.

In direct-seeded rice (DSR) under the alternate wetting and drying (AFD) treatment, irrigation water was monitored using PVC tubes of 30 cm length and 15 cm diameter, perforated with 2 mm holes at 2 cm intervals up to a height of 15 cm. The tubes were installed with 15 cm above the soil surface and 15 cm below, with perforations on the subsurface portion. After irrigation, water entered the tube through the perforations and rose to a height of 10 cm, equalizing with the water level outside. Irrigation was applied when the water level inside the tube was completely depleted, and each irrigation was continued until the water level in the test plots reached 10 cm.

In DSR plots, additional need-based irrigations up to 10 cm depth were applied as required, depending on the weekly rainfall pattern at the respective locations.

Greenhouse Gas Sampling and Analysis from rice fields

Greenhouse gases emitted from the rice fields at different crop growth stages were collected using the closed-chamber technique (Hutchinson and Mosier, 1981).

Chambers measuring 50 cm × 30 cm × 100 cm, constructed from 6 mm acrylic sheets, were used for sampling. A metal channel was placed in the field for each chamber, inserted 10 cm into the soil, and filled with water to ensure an air-tight seal. A three-way stopcock (Eastern Medikit Ltd., India) was fitted at the top of each chamber for gas sampling.

Prior to sampling, the chamber air was homogenized by flushing several times with a 50 ml syringe. Gas samples were then drawn using a 20 ml syringe fitted with a 24-gauge hypodermic needle. After sampling, the chambers were sealed with the three-way stopcock. The headspace volume inside each chamber was recorded which was used to calculate fluxes of nitrous oxide (N₂O) and methane (CH₄).

Gas samples were collected at 0, 15, and 30 minutes for CH₄ and N₂O, respectively, and analyzed using a gas chromatograph following the method described by Bhatia et al. (2005). Estimation of total CH₄, CO₂ and N₂O emissions during the crop growth period was carried

out by successive linear interpolation of average emissions on sampling days, assuming a linear trend during unsampled intervals (Bhatia et al., 2011).

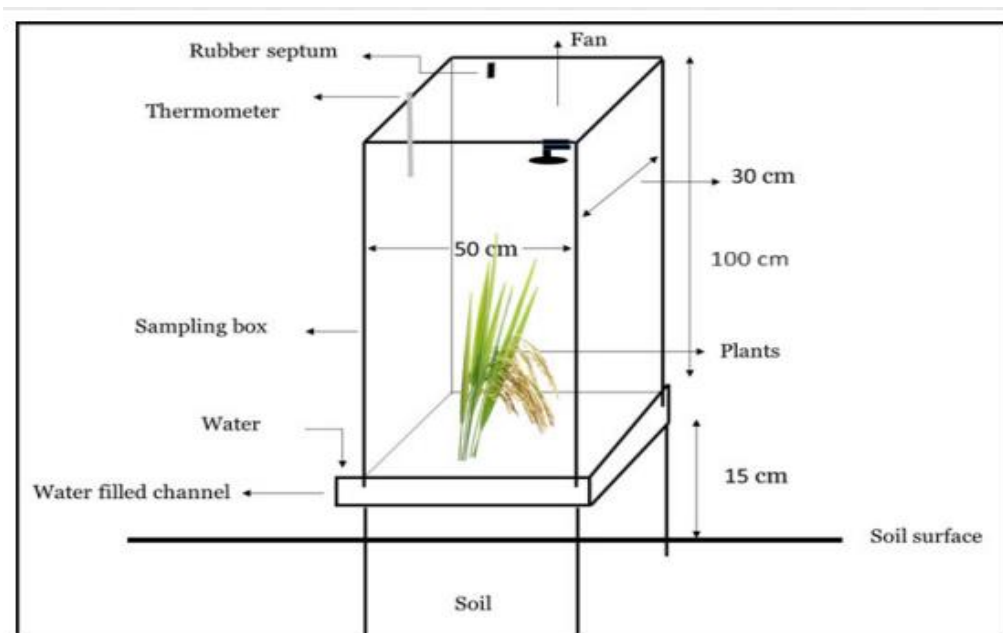


Fig. 4 Closed-chamber used for collection of greenhouse gas samples from field

Analysis of gas samples

The gas samples were analysed by a gas chromatograph equipped with electron capture detector (ECD) and flame ionization detector (FID) for analysing N_2O and CH_4 respectively. CO_2 was reduced to CH_4 with hydrogen in a nickel catalytic mechanizer at $350^\circ C$ and then detected by the FID.

Calculation of flux

The flux of methane and nitrous oxide was calculated using the following equations:

Cross-sectional area of the chamber (m^2) = A

Headspace (m) = H

Volume of headspace (L) = $1000 \times AH$

CH_4 concentration at 0 time ($\mu L L^{-1}$) = C_0

CH_4 concentration after time t ($\mu L L^{-1}$) = C_t

Change in concentration in time t ($\mu\text{L L}^{-1}$) = $(C_t - C_0)$

Volume of CH_4 evolved in time t (μL) = $(C_t - C_0) \times 1000 \text{ AH}$

When t is in hours, then flux ($\text{mL m}^{-2} \text{ h}^{-1}$) = $[(C_t - C_0) \times \text{AH}] / (A \times t)$

Now 22.4 mL of CH_4 is 16 mg at STP

Hence, CH_4 flux = $[(C_t - C_0) / t] \times H \times 16 / 22.4 \times 10000 \times 24 \text{ mg ha}^{-1} \text{ d}^{-1}$

N_2O flux = $[(C_t - C_0) / t] \times H \times 44 / 22.4 \times 10000 \times 24 \text{ mg ha}^{-1} \text{ d}^{-1}$

CO_2 flux = $[(C_t - C_0) / t] \times H \times 44 / 22.4 \times 10000 \times 24 \text{ mg ha}^{-1} \text{ d}^{-1}$

Estimation of Global warming potential (GWP) of CH_4 and N_2O

GWP is an index defined as the cumulative radiative driving between the present and some chosen later time ‘horizon’ caused by a unit mass of gas emitted now. It is used to compare the effectiveness of each GHG to trap heat in the atmosphere relative to some standard gas, by convention CO_2 . The GWP for CH_4 (based on a 100-year time horizon) is 28 and for N_2O is 265, while for CO_2 , the GWP is taken as 1, as per IPCC (2013).

$$\text{GWP} = \text{CO}_2 (\text{kg ha}^{-1}) + \text{N}_2\text{O} (\text{kg ha}^{-1}) \times 265 + \text{CH}_4 (\text{kg ha}^{-1}) \times 28$$

Calculation of Carbon credits

Carbon credits were estimated by quantifying the methane (CH_4) emission reduction achieved under different rice establishment methods, considering transplanted rice (TPR) treatments as the baseline. The methodology followed the IPCC (2006) guidelines with modification for field-specific factors. The calculation involved the following steps:

✓ **Baseline Emission (BE):**

Baseline methane emission factor ($\text{kg CH}_4 \text{ ha}^{-1} \text{ season}^{-1}$) was derived from field trial observations under transplanted rice and subsequently adjusted using scaling factors for water regime during the cultivation period (SFW) and pre-season water regime (SFP) as:

$$BE = EF_{BL} \times SFW \times SFP \quad \text{where,}$$

EF_{BL} = Baseline emission factor for continuously flooded fields ($\text{kg CH}_4 \text{ ha}^{-1} \text{ season}^{-1}$)

SFW = Scaling factor for water management during the cultivation period

SFP = Scaling factor for pre-season water regime

✓ **Project Emission (PE):**

Methane emissions under mitigation practices (direct-seeded rice, alternate wetting and drying, etc.) were similarly estimated using the same scaling factors.

✓ **Conversion to CO₂ equivalent:**

Both baseline and project emissions were converted into carbon dioxide equivalents (tCO₂e) using the global warming potential (GWP) of CH₄ (28).

$$Emissions (tCO_2e) = \frac{CH_4 (kg/ha)}{1000} \times GWP$$

✓ **Net Emission Reduction (NER):**

The difference between baseline and project emissions was considered as net emission reduction.

$$NER = BE - PE$$

✓ **Final Carbon Credits:**

The final carbon credits (tCO₂e ha⁻¹) were equal to the net emission reduction.

Estimation of Carbon Footprints (CF)

The carbon footprint (CF) of rice production was estimated following the methodologies suggested by Gan et al., (2012), Ma et al., (2012) and Singh and Ahlawat (2015). CF was expressed as the greenhouse gas emissions per unit of grain yield (kg CO₂-eq kg⁻¹ grain) and calculated using the equation:

$$CF = \frac{CI}{GY}$$

The total carbon input (CI) was obtained by summing the greenhouse gas emissions from different sources of crop production, including fuel consumption, human labour (man-days), fertilizer application, use of herbicides, fungicides and insecticides, as well as power consumption in rice fields. Emissions from each source were calculated using standard emission factors and converted into CO₂-equivalents using the 100-year global warming potential (GWP) values of respective gases. The grain yield (GY) was recorded from field trials under different rice establishment methods and expressed on a hectare basis.

Calculations of water productivity (WP)

Water productivity (WP) was calculated as the ratio of grain yield to the total amount of irrigation and rainfall water used during the crop growing period and was expressed as kilograms of grain produced per cubic metre of water (kg m^{-3}). The total water input (irrigation + effective rainfall) was estimated using field irrigation records and meteorological data from the experimental site. Water productivity was computed using the following equation:

$$WP = \frac{Y_g}{W_t}$$

where WP is the water productivity (kg m^{-3}), Y_g is the grain yield (kg ha^{-1}) and W_t is the total water input ($\text{m}^3 \text{ ha}^{-1}$) including both irrigation and rainfall received during the crop season. The total water use was determined from the sum of measured irrigation water applied through field channels and effective rainfall estimated using the FAO CROPWAT model.

The field experiments were conducted at three locations in the state, including one set of treatments evaluated at the research farm of the Department of Soil Science, CSK HPKV, Palampur. Data was collected on yield and yield-attributing characteristics of plants under different treatments. Soil samples were taken before the demonstrations were set up and after the crop was harvested. To assess the effects of different treatments on soil health, the collected soil samples were processed in the laboratory and analysed for various physical, chemical, and biological properties.

Collection and analysis of grain and plant samples

At harvest, grain and straw samples were collected from each treatment to determine nitrogen, phosphorus and potassium (NPK) content and uptake. The samples were oven dried at $60 \pm 5^\circ\text{C}$, ground finely and analysed using standard procedures. N content in grain and straw was estimated by the micro-Kjeldahl method (Jackson, 1973). For P and K determination, samples were digested in a di-acid mixture ($\text{HNO}_3\text{:HClO}_4$, 9:4). P was analysed by the vanadomolybdate yellow colour method using a spectrophotometer (Jackson, 1973) and K was measured by flame photometry (Black, 1965). The nutrient uptake (kg ha^{-1}) for N, P and K was computed by multiplying their respective contents in grain and straw with the corresponding dry matter yield and expressed on a per hectare basis.

Collection and analysis of soil samples

Plot-wise composite soil samples (0-15 cm depth) were collected after harvest of rice crop. The soil samples were dried in shade, ground in a wooden pestle and mortar, passed through 2 mm sieve and analysed for its important physical (bulk density, particle density, porosity and water holding capacity) and chemical (pH, electrical conductivity, soil organic carbon) properties along with available N, P and K in soil (Table 1). For the determination of biological properties (microbial biomass carbon, microbial count and dehydrogenase activity), fresh soil samples were collected and analysed using standard methods (Table 1).

Table 1. Standard methods used for analysis of soil samples

S. No.	Parameter	Method	Reference
1.	Bulk density	Core sampler methods	Blake and Hartge (1986)
2.	Particle density	Pycnometer method	Gupta and Dhakshinamoorthy (1980)
3.	Porosity	Empirical method	Gupta and Dhakshinamoorthy (1980)
4.	Water holding capacity	Keen's box	Piper (1950)
5.	Soil pH (1:2.5)	Potentiometric method	Jackson (1973)
6.	Organic carbon	Rapid titration method	Walkley and Black (1934)
7.	Available nitrogen	Alkaline potassium permanganate	Subbiah and Asija (1956)
8.	Available phosphorus	Colorimetric method	Olsen et al., (1954)
9.	Available potassium	Flame photometric method	Black (1965)
10.	Microbial biomass carbon	Fumigation extraction	Vance et al., (1987)
11.	Dehydrogenase activity	2,3,5-TTC reduction technique	Casida et al., (1964)

Statistical analysis

The data obtained from the present study was subjected to statistical analysis using technique of analysis of variance for randomized block design following the procedure as outlined by Gomez and Gomez (1984).

Results

1. Rice Yield

The data depicting the effect of rice establishment methods on grain, straw, and biological yield of rice across different locations and seasons, along with pooled values, are presented in Tables 2–4.

At Palampur (Table 2; Fig. 5), the highest grain yield across both seasons was recorded under T₂ (Conventional puddled-transplanted rice, Savannah hybrid PTR *SAVAH-134*), which produced 63.5 q ha⁻¹ in 2023, 61.3 q ha⁻¹ in 2024, and 62.4 q ha⁻¹ in pooled data. This treatment was statistically at par with T₁ (Conventional puddled-transplanted rice, popular variety PTR *PR-126*), which yielded 60.2 q ha⁻¹ in 2023, 59.7 q ha⁻¹ in 2024, and 60.0 q ha⁻¹ in pooled data. Although statistically similar, T₂ registered yield increases of 5.5, 2.7, and 4.0 per cent over T₁ in 2023, 2024, and pooled data, respectively, highlighting the superior performance of the *SAVAH-134* hybrid over *PR-126*.

These transplanted treatments (T₁ and T₂) were followed by T₅ (Direct-seeded rice, Savannah Full Page hybrid, DSR *SAVAH-134* Full Page), which recorded the highest and significantly superior grain yield among all DSR treatments (57.4 q ha⁻¹ in 2023, 55.3 q ha⁻¹ in 2024, and 56.4 q ha⁻¹ pooled). Compared to T₆ (DSR *SAVAH-134* Full Page hybrid with alternate flooding and drying, AFD), T₄ (DSR *SAVAH-134*), and T₃ (DSR *PR-126*), T₅ showed yield increase of 8.5, 15.1, and 51.9 per cent in 2023; 12.2, 26.0, and 58.0 per cent in 2024; and 10.2, 20.2, and 54.9 per cent on pooled basis, respectively. Between T₃ and T₄, T₄ was statistically superior, recording 31.7, 25.4, and 28.4 per cent higher grain yield in 2023, 2024, and pooled data, respectively. The lowest grain yield was consistently recorded under T₃ (DSR *PR-126*), i.e., 37.8 q ha⁻¹ in 2023, 35.0 q ha⁻¹ in 2024, and 36.4 q ha⁻¹ pooled.

Straw and biological yields followed similar trends. The highest straw yield (82.6, 79.6, and 81.1 q ha⁻¹ in 2023, 2024, and pooled, respectively) and biological yield (146.1, 140.9, and 143.5 q ha⁻¹) were recorded under T₂, which was statistically at par with T₁. In contrast, the lowest straw yield (43.5, 40.3, and 41.9 q ha⁻¹) and biological yield (81.3, 75.3, and 78.3 q ha⁻¹) were recorded under T₃ in 2023, 2024 and pooled data, respectively.

At Una (Table 3; Fig. 6), the highest grain yield was again recorded under T₂ (PTR *SAVAH-134*), with 52.6 q ha⁻¹ in 2023, 52.0 q ha⁻¹ in 2024, and 52.3 q ha⁻¹ pooled. This was statistically

at par with T₁ (PTR *PR-126*), which yielded 52.0, 50.9, and 51.4 q ha⁻¹ in 2023, 2024, and pooled data, respectively. Although statistically similar, T₂ showed marginal yield increases of 1.2, 2.2, and 1.8 per cent over T₁ in 2023, 2024, and pooled basis. These transplanted treatments were followed by T₅ (DSR *SAVAH-134* Full Page hybrid), which recorded significantly superior yields among DSR treatments (48.9, 47.4, and 48.1 q ha⁻¹ in 2023, 2024, and pooled, respectively). Compared to T₆, T₄, and T₃, T₅ registered yield increases of 9.2, 34.0, and 58.3 per cent in 2023; 4.2, 27.2, and 52.4 per cent in 2024; and 4.3, 30.0, and 54.7 per cent in pooled data. Between T₃ and T₄, T₄ was significantly superior, recording 18.1, 20.9, and 19.0 per cent higher yields in 2023, 2024, and pooled data, respectively. The lowest grain yield was recorded under T₃ (30.9, 31.3, and 31.1 q ha⁻¹ in 2023, 2024, and pooled data). Straw and biological yields followed similar patterns, with T₂ recording the highest straw (68.4, 67.7, and 68.1 q ha⁻¹) and biological yields (121.1, 119.7, and 120.4 q ha⁻¹), statistically at par with T₁. The lowest straw (35.6, 35.9, and 35.8 q ha⁻¹) and biological yields (66.5, 67.2, and 66.8 q ha⁻¹) were recorded under T₃.

At HAREC Dhaulakuan (Table 4; Fig. 7), the highest grain yield was recorded under T₂ (PTR *SAVAH-134*), with 58.9 q ha⁻¹ in 2023, 59.1 q ha⁻¹ in 2024, and 59.0 q ha⁻¹ pooled. This was statistically at par with T₁ (PTR *PR-126*), which yielded 57.6, 57.0, and 57.3 q ha⁻¹ in 2023, 2024, and pooled data, respectively. Although statistically similar, T₂ showed yield increases of 2.3, 3.7, and 3.0 per cent over T₁ in 2023, 2024, and pooled basis. These transplanted treatments were followed by T₅ (DSR *SAVAH-134* Full Page hybrid), which recorded the highest and significantly superior yields among DSR treatments (53.8, 52.4, and 53.1 q ha⁻¹ in 2023, 2024, and pooled, respectively). Compared to T₆, T₄, and T₃, T₅ registered yield increases of 5.9, 28.1, and 43.8 per cent in 2023; 3.8, 23.3, and 37.5 per cent in 2024; and 5.1, 25.8, and 40.5 per cent pooled. T₄ was significantly superior to T₃, recording 12.3, 11.5, and 11.6 per cent higher yields in 2023, 2024, and pooled data, respectively. The lowest grain yield was consistently recorded under T₃ (37.4, 38.1, and 37.8 q ha⁻¹ in 2023, 2024, and pooled). Compared to T₂, T₃ showed 36.5, 35.5, and 35.9 per cent lower yield in 2023, 2024, and pooled data, respectively, while reductions over T₁ were 35.0, 33.2, and 34.1 per cent.

Straw and biological yields followed similar patterns. T₂ recorded the highest straw yield (76.6, 76.8, and 76.7 q ha⁻¹) and biological yield (135.6, 135.9, and 135.7 q ha⁻¹), statistically at par with T₁. In contrast, T₃ consistently recorded the lowest straw yield (43.0, 43.9, and 43.4 q ha⁻¹) and biological yield (80.4, 82.0, and 81.2 q ha⁻¹) across both the years and pooled data.

Table 2 – Rice yield (q ha⁻¹) during 2023 & 2024 at Palampur

Treatments	Yield								
	2023			2024			Pooled data		
	Grain	Straw	Biological	Grain	Straw	Biological	Grain	Straw	Biological
T₁	60.2	78.3	138.5	59.7	77.6	137.3	60.0	77.9	137.9
T₂	63.5	82.6	146.1	61.3	79.6	140.9	62.4	81.1	143.5
T₃	37.8	43.5	81.3	35.0	40.3	75.3	36.4	41.9	78.3
T₄	49.9	57.4	107.2	43.9	50.5	94.4	46.9	53.9	100.8
T₅	57.4	66.0	123.5	55.3	63.6	118.9	56.4	64.8	121.2
T₆	52.9	60.9	113.8	49.5	57.0	106.5	51.2	58.9	110.1
CD (p=0.05)	4.2	5.0	9.2	3.0	3.7	6.8	2.6	3.1	5.7

Table 3 – Rice yield (q ha⁻¹) during 2023 & 2024 at Una

Treatments	Yield								
	2023			2024			Pooled data		
	Grain	Straw	Biological	Grain	Straw	Biological	Grain	Straw	Biological
T₁	52.0	67.6	119.6	50.9	66.2	117.1	51.4	66.9	118.3
T₂	52.6	68.4	121.1	52.0	67.7	119.7	52.3	68.1	120.4
T₃	30.9	35.6	66.5	31.3	35.9	67.2	31.1	35.8	66.8
T₄	36.5	42.0	78.5	37.5	43.2	80.7	37.0	42.6	79.6
T₅	48.9	56.3	105.2	47.4	54.5	101.9	48.1	55.4	103.5
T₆	46.8	53.8	100.5	45.5	52.3	97.8	46.1	53.0	99.2
CD (p=0.05)	4.7	5.7	10.4	4.2	4.9	9.0	3.5	4.1	7.6

Table 4 – Rice yield (q ha⁻¹) during 2023 & 2024 at Dhaulakuan

Treatments	Yield								
	2023			2024			Pooled data		
	Grain	Straw	Biological	Grain	Straw	Biological	Grain	Straw	Biological
T₁	57.6	74.9	132.5	57.0	74.1	131.1	57.3	74.5	131.8
T₂	58.9	76.6	135.6	59.1	76.8	135.9	59.0	76.7	135.7
T₃	37.4	43.0	80.4	38.1	43.9	82.0	37.8	43.4	81.2
T₄	42.0	48.3	90.3	42.5	48.9	91.4	42.2	48.6	90.8
T₅	53.8	61.9	115.7	52.4	60.3	112.7	53.1	61.1	114.2
T₆	50.6	58.2	108.7	50.5	58.1	108.6	50.5	58.1	108.7
CD (p=0.05)	4.2	5.1	9.3	4.0	4.8	8.7	3.6	4.4	8.1

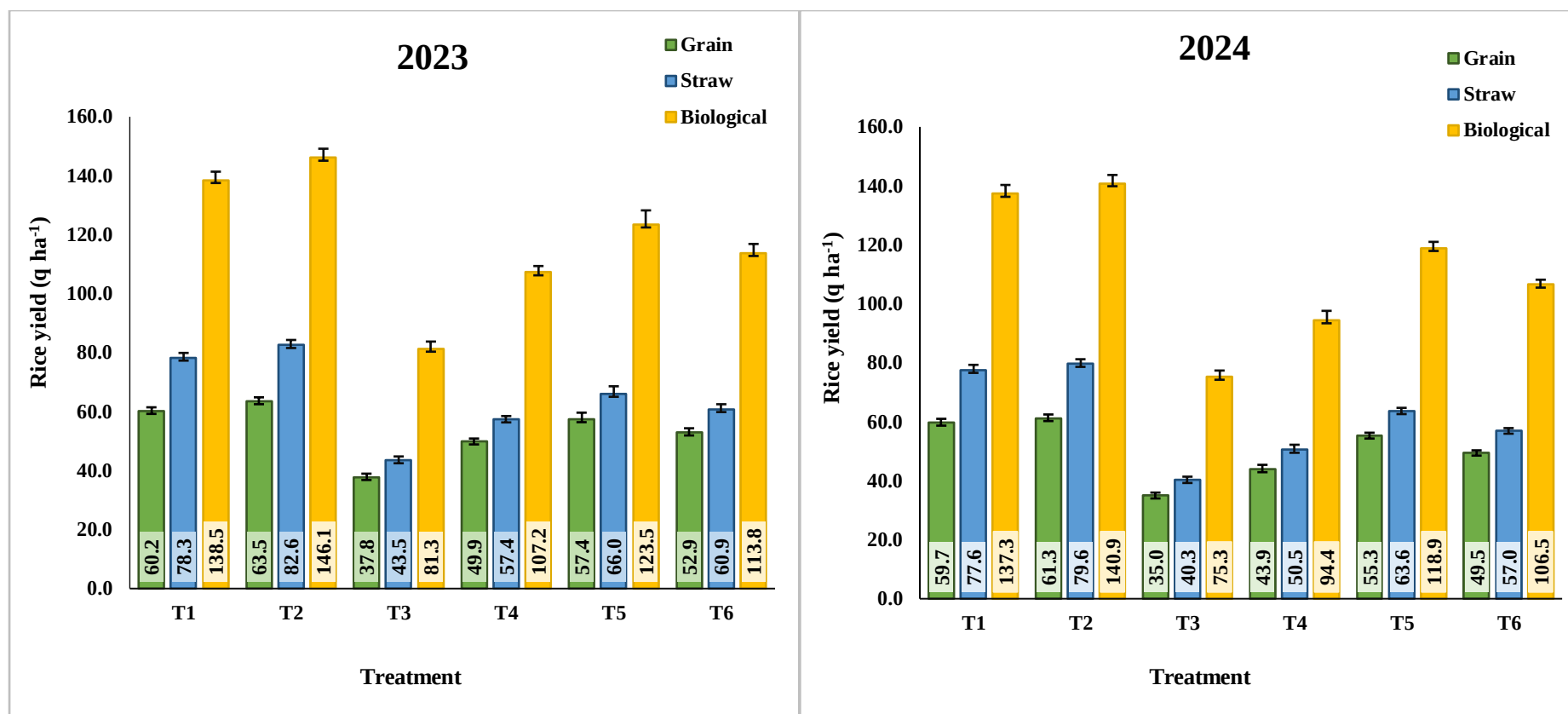


Fig 5. Rice yield (q ha⁻¹) at Palampur during 2023 and 2024

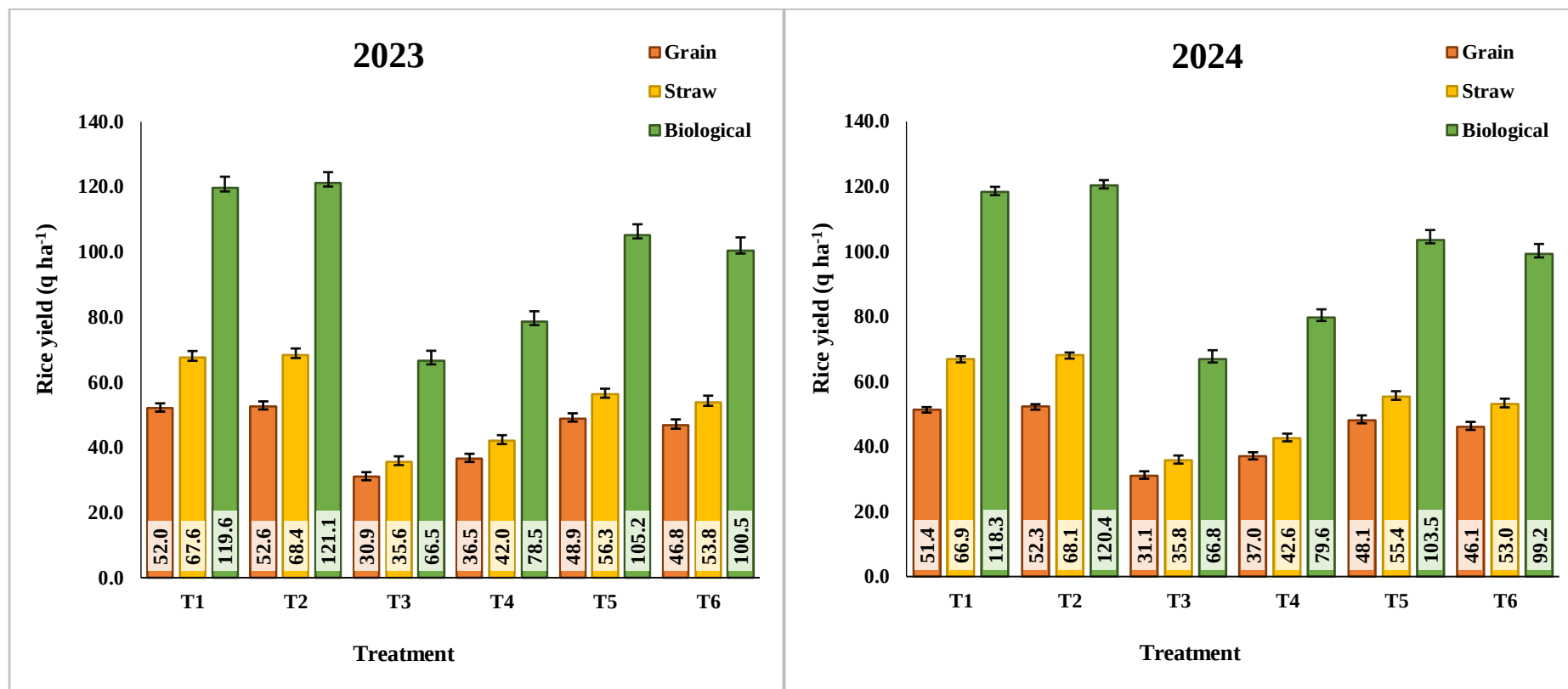


Fig 6. Rice yield (q ha⁻¹) at Una during 2023 and 2024

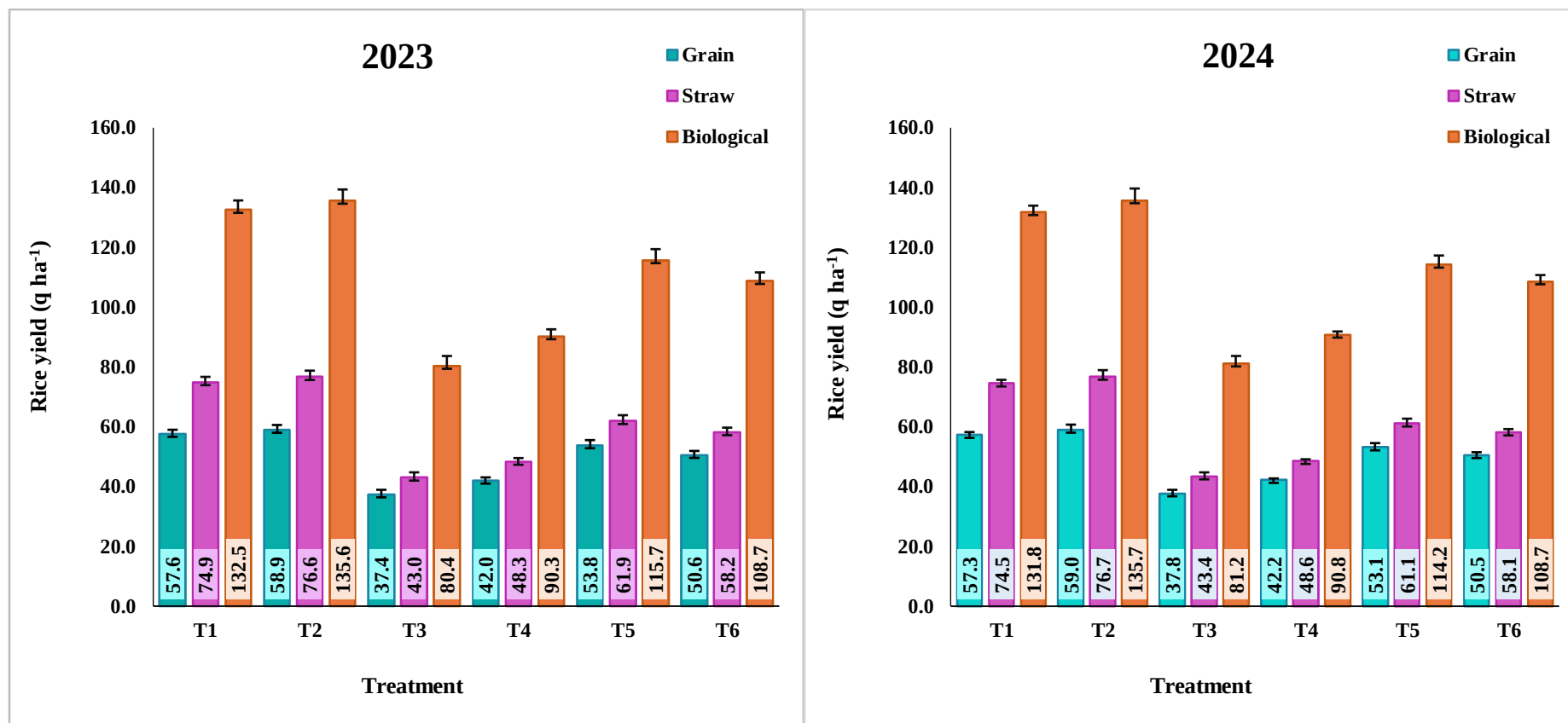


Fig 7. Rice yield (q ha⁻¹) at Dhaulakuan during 2023 and 2024

2. Greenhouse gases emission (GHGs)

A. Methane Emission

Methane (CH₄), a potent greenhouse gas with a global warming potential approximately 28 times greater than that of CO₂, contributes about 15 per cent to total global GHG emissions. Owing to its high warming capacity, even minor fluctuations in its concentrations can substantially influence the climate. Globally, transplanted rice fields represent the second largest anthropogenic source of CH₄ after enteric fermentation, accounting for nearly 9 per cent of total methane emissions.

In the present study, CH₄ emission fluxes varied significantly across rice establishment methods, cropping seasons, and locations (Table 4; Fig. 8). At Palampur, treatment T₁ (PTR *PR-126*) recorded the highest CH₄ emission (43.9 kg ha⁻¹), whereas T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the lowest (4.5 kg ha⁻¹) during 2023. A similar trend was observed in 2024 and in the pooled data across both years. Emissions under T₅ were reduced by 89.7, 89.8, and 89.8 per cent over T₁, and by 89.9, 89.4, and 89.7 per cent over T₂ (PTR *SAVAH-134*) in 2023, 2024, and pooled data, respectively. Besides the treatments T₁ and T₂ were statistically at par.

Among the DSR treatments, T₅ recorded significantly lower CH₄ emissions compared to T₆ (DSR *SAVAH-134* Full Page hybrid with AFD). CH₄ flux under T₆ was 7.1, 7.7, and 7.4 kg ha⁻¹ in 2023, 2024, and pooled data, respectively. Relative to T₆, T₅ showed reductions of 36.6, 41.6, and 39.2 per cent, which may be attributed to improved soil aeration in T₅, whereas alternate wetting and drying in T₆ sustained anaerobic conditions for longer period, thereby enhancing CH₄ production. Nevertheless, compared to puddled transplanted treatments (T₁ and T₂), treatment T₆ demonstrated substantial decline in CH₄ emissions, with reductions of 83.8, 82.5, and 83.1 per cent over T₁, and 84.0, 81.9, and 82.9 per cent over T₂ in 2023, 2024, and pooled data, respectively. Furthermore, among DSR treatments, T₅ recorded 11.8, 6.3, and 10.0 per cent lower emission than T₄ (DSR *SAVAH-134*), and 16.6, 10.0, and 13.5 per cent lower emission than T₃ (DSR *PR-126*) in 2023, 2024, and pooled data, respectively.

Likewise, at KVK Una, T₁ (PTR *PR-126*) recorded the highest CH₄ emission (50.2 kg ha⁻¹) in 2023, while T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the lowest emission (4.2 kg ha⁻¹). Similar results were observed in 2024 and pooled data. Emissions under T₅ were reduced by 91.6, 91.2, and 91.3 per cent over T₁, and by 91.4, 91.4, and 91.3 per cent over T₂ in 2023, 2024, and pooled data, respectively. Also, the treatments T₁ and T₂ were statistically at par.

Among DSR treatments, T₅ exhibited significantly lower emission than T₆ (4.2, 4.3, and 4.3 kg ha⁻¹ in 2023, 2024, and pooled data, respectively). Relative reductions under T₅ compared to T₆ were 31.1, 44.2, and 37.7 per cent. Compared to puddled transplanted treatments, T₆ showed reductions of 87.8, 84.4, and 86.1 per cent over T₁, and 87.6, 84.7, and 86.1 per cent over T₂ in 2023, 2024, and pooled data, respectively. Among DSR treatments, T₅ recorded lower emissions than T₄ by 8.7, 15.7, and 12.2 per cent, while T₄ exhibited reductions of 2.2, 7.8, and 4.1 per cent compared to T₃ in 2023, 2024, and pooled data, respectively.

Similarly, at HAREC, Dhaulakuan, T₁ (PTR *PR-126*) recorded the highest CH₄ emission (51.0 kg ha⁻¹) in 2023, whereas T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the lowest emission (4.8 kg ha⁻¹). A similar trend was observed in 2024 and pooled data. Emissions under T₅ were reduced by 90.6, 89.1, and 89.7 per cent compared to T₁, and by 90.7, 89.0, and 89.8 per cent compared to T₂ in 2023, 2024, and pooled data, respectively. Both the treatments T₁ and T₂ were statistically at par. Among DSR treatments, T₅ recorded significantly lower emissions (4.8, 5.5, and 5.2 kg ha⁻¹) compared to T₆ (6.9, 7.8, and 7.4 kg ha⁻¹) in 2023, 2024, and pooled data, respectively. Relative reductions under T₅ compared to T₆ were 30.4, 29.5, and 29.7 per cent. Compared to puddled transplanted treatments, T₆ showed reductions of 86.5, 84.5, and 85.4 per cent over T₁, and 86.6, 84.5, and 85.5 per cent over T₂ in 2023, 2024, and pooled data, respectively. Among DSR treatments, T₅ recorded lower emissions than T₄ by 3.9, 1.8, and 1.9 per cent, while T₄ exhibited reductions of 3.8, 3.4, and 5.4 per cent compared to T₃ in 2023, 2024, and pooled data, respectively.

Based on pooled CH₄ flux across the three locations (Table 5), both T₁ (PTR *PR-126*) and T₂ (PTR *SAVAH-134*) recorded the highest emissions (48.1 kg ha⁻¹), and were statistically at par. In contrast, T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the lowest emission (4.6 kg ha⁻¹), showing reductions of 90.4 per cent compared to both T₁ and T₂. Among DSR treatments, T₅ significantly outperformed T₆ (7.2 kg ha⁻¹), with a 36.1 per cent reduction. Additionally, T₅ recorded 9.8 per cent lower emissions than T₄, while T₄ showed a 3.9 per cent reduction compared to T₃.

Table 4 – CH₄ flux (kg ha⁻¹) under different rice establishment methods at Palampur, Una and Dhaulakuan

CH ₄ flux (kg ha ⁻¹)									
Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	43.9	44.0	43.9	50.2	49.3	49.7	51.0	50.4	50.7
T ₂	44.4	42.6	43.5	49.2	50.2	49.7	51.7	50.2	51.0
T ₃	5.4	5.0	5.2	4.7	5.5	5.1	5.3	5.8	5.6
T ₄	5.1	4.8	5.0	4.6	5.1	4.9	5.1	5.6	5.3
T ₅	4.5	4.5	4.5	4.2	4.3	4.3	4.8	5.5	5.2
T ₆	7.1	7.7	7.4	6.1	7.7	6.9	6.9	7.8	7.4
CD (p=0.05)	2.1	2.0	2.1	2.4	2.4	2.4	2.5	2.5	2.4

Table 5 – Pooled CH₄ flux (kg ha⁻¹) across three locations under different rice establishment methods

CH ₄ flux (kg ha ⁻¹)			
Treatments	2023	2024	Pooled
T ₁	48.3	47.9	48.1
T ₂	48.4	47.7	48.1
T ₃	5.1	5.4	5.3
T ₄	5.0	5.2	5.1
T ₅	4.5	4.8	4.6
T ₆	6.7	7.7	7.2
CD (p=0.05)	2.4	2.3	2.3

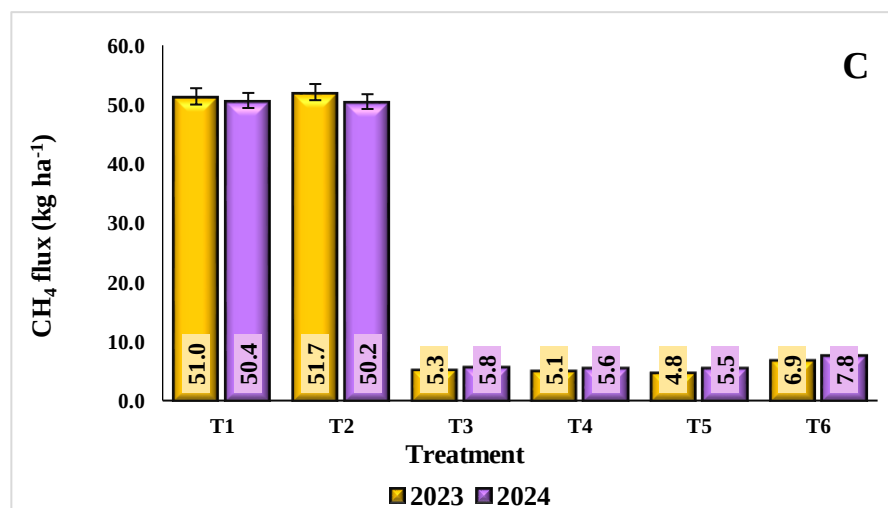
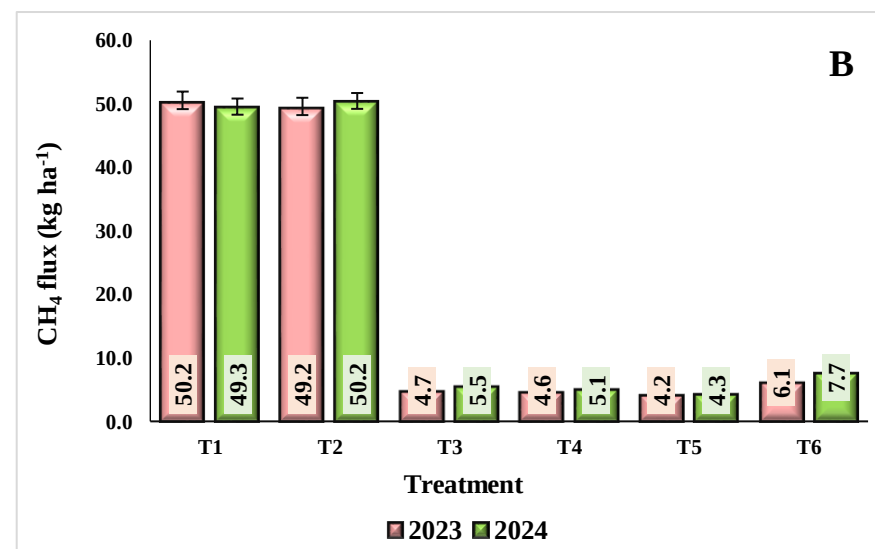
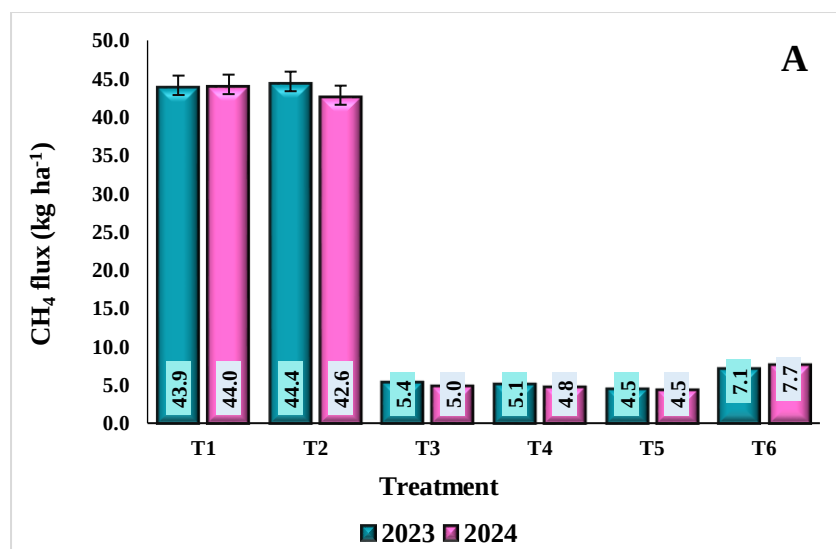


Fig 8. CH₄ flux (kg ha⁻¹) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

B. Carbon dioxide (CO₂)

Carbon dioxide (CO₂) is the most prevalent greenhouse gas, accounting for over 60 per cent of global GHG emissions and serving as the primary driver of climate change. Although its global warming potential is lower than that of CH₄, its higher atmospheric concentration and longer residence time make it highly impactful. In agriculture, CO₂ emissions primarily arise from soil respiration, organic matter decomposition, and fossil fuel use. In the present study, CO₂ fluxes varied considerably across rice establishment methods, cropping seasons, and locations (Table 6; Fig. 9).

At Palampur, T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded the highest CO₂ flux among all treatments, with values of 1039.3 kg ha⁻¹ in 2023, 1031.2 kg ha⁻¹ in 2024, and 1035.2 kg ha⁻¹ in pooled data. T₆ was followed by T₃ (DSR *PR-126*), T₄ (DSR *SAVAH-134*), and T₅ (DSR *SAVAH-134* Full Page hybrid), though T₆ remained significantly superior to these treatments. Among DSR treatments, T₄ showed marginal reductions of 3.4, 2.0, and 2.7 per cent, while T₅ recorded 3.4, 2.7, and 3.0 per cent lower fluxes compared to T₆. Similarly, T₃ showed reductions of 2.8, 1.7, and 2.3 per cent relative to T₆ in the respective years. In contrast, T₂ (PTR *SAVAH-134*) exhibited the lowest CO₂ emissions (704.0, 711.8, and 707.9 kg ha⁻¹), and was statistically at par with T₁ (PTR *PR-126*), which recorded 714.0, 719.3, and 716.6 kg ha⁻¹ in 2023, 2024, and pooled data, respectively. Compared to T₆, T₂ showed reductions of 32.3, 31.0, and 31.6 per cent, while T₁ recorded 31.3, 30.2, and 30.8 per cent lower emissions in the corresponding periods.

Correspondingly, at Una, T₆ again registered the highest CO₂ flux (1127.6, 1131.3, and 1129.5 kg ha⁻¹ in 2023, 2024, and pooled data, respectively), and was statistically superior to all other treatments. Among DSR treatments, T₃ and T₄ each showed reductions of 3.0, 3.1, and 3.1%, while T₅ exhibited 3.3, 4.0, and 3.6% lower fluxes compared to T₆. These were followed by T₂ (PTR *SAVAH-134*), which recorded 777.7, 781.0, and 779.3 kg ha⁻¹ in 2023, 2024, and pooled data, corresponding to reductions of 31.0% compared to T₆. The lowest flux was recorded in T₁ (PTR *PR-126*), *i.e.*, 771.0, 772.7, and 771.8 kg ha⁻¹, which was statistically at par with T₂. Compared to T₆, T₁ showed reductions of 31.6, 31.7, and 31.7 per cent in 2023, 2024, and pooled data, respectively.

Similarly, at Dhaulakuan, T₆ again recorded the highest CO₂ flux (1105.3, 1095.3, and 1100.3 kg ha⁻¹ in 2023, 2024, and pooled data, respectively). T₆ was followed by DSR treatments (T₃, T₄, and T₅), which were significantly at par with each other. T₃ registered

reductions of 4.6, 2.9, and 3.8 per cent, while T₄ recorded 4.7, 3.1, and 4.0 per cent lower emissions compared to T₆. Likewise, T₅ showed reduction of 5.3, 3.4, and 4.3 per cent relative to T₆ in 2023, 2024, and pooled data, respectively. These DSR treatments were followed by T₂ (PTR *SAVAH-134*), which recorded 745.0, 764.9, and 755.0 kg ha⁻¹ in 2023, 2024, and pooled data, corresponding to reductions of 32.6, 30.2, and 31.4 per cent compared to T₆. The lowest flux was observed in T₁ (PTR *PR-126*), i.e., 746.9, 761.7, and 754.3 kg ha⁻¹, which was statistically at par with T₂. Compared to T₆, T₁ showed reductions of 32.4, 30.5, and 31.4 per cent in 2023, 2024, and pooled data, respectively.

Table 6 – CO₂ flux (kg ha⁻¹) under different rice establishment methods at Palampur, Una and Dhaulakuan

CO ₂ flux (kg ha ⁻¹)									
Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	714.0	719.3	716.6	771.0	772.7	771.8	746.9	761.7	754.3
T ₂	704.0	711.8	707.9	777.7	781.0	779.3	745.0	764.9	755.0
T ₃	1009.9	1013.2	1011.6	1094.0	1096.2	1095.1	1053.9	1063.0	1058.5
T ₄	1004.5	1010.7	1007.6	1093.3	1095.8	1094.5	1052.3	1061.5	1056.9
T ₅	1003.7	1003.9	1003.8	1090.9	1087.2	1089.1	1047.1	1058.0	1052.6
T ₆	1039.3	1031.2	1035.2	1127.6	1131.3	1129.5	1105.3	1095.3	1100.3
CD (p=0.05)	21.0	20.5	20.7	22.5	22.4	22.4	23.9	21.0	22.5

Table 7 – Pooled CO₂ flux (kg ha⁻¹) across three locations under different rice establishment methods

CO ₂ flux (kg ha ⁻¹)			
Treatments	2023	2024	Pooled
T ₁	743.9	751.2	747.6
T ₂	742.2	752.6	747.4
T ₃	1052.6	1057.5	1055.1
T ₄	1050.0	1056.0	1053.0
T ₅	1047.2	1049.7	1048.5
T ₆	1090.7	1085.9	1088.3
CD (p=0.05)	22.4	21.3	21.8

Across pooled means of all locations and years (Table 7), T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) registered the highest CO₂ flux (1088.3 kg ha⁻¹). This was followed by T₃, T₄, and T₅, which recorded pooled means of 1055.1, 1053.0, and 1048.5 kg ha⁻¹, corresponding to reductions of 3.1, 3.2, and 3.7 per cent, respectively, compared to T₆. In contrast, significantly lower pooled emissions were observed under transplanted conditions, with T₂ and T₁ recording 747.4 and 747.6 kg ha⁻¹, corresponding to reductions of 31.2 and 31.3 per cent relative to T₆.

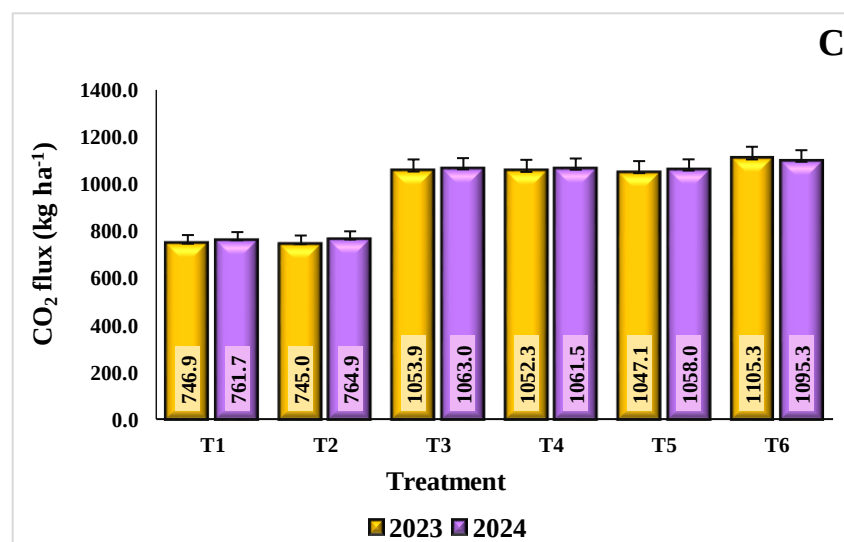
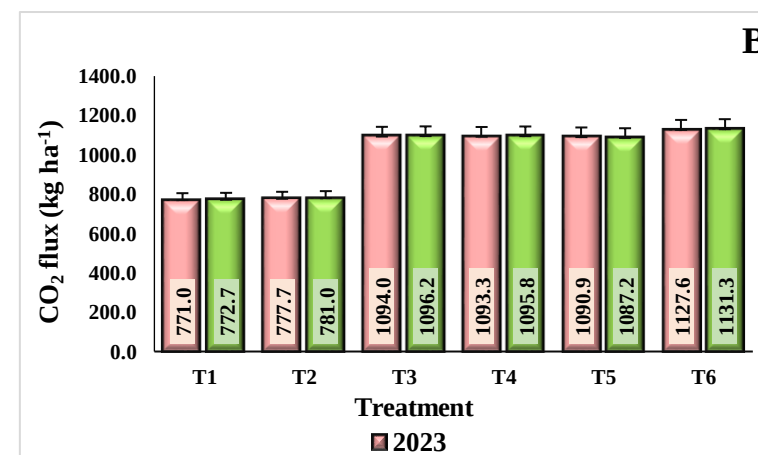
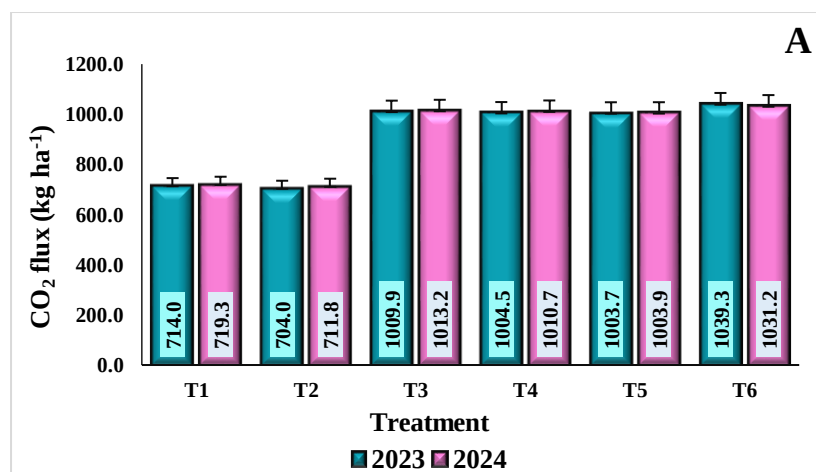


Fig 9. CO₂ flux (kg ha⁻¹) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

C. Nitrous oxide (N₂O)

Nitrous oxide (N₂O), though present in lower atmospheric concentrations than carbon dioxide (CO₂) and methane (CH₄), possesses a global warming potential nearly 265 times greater than CO₂ over a 100-year time horizon. In agricultural soils, N₂O emissions primarily arise from microbial processes such as nitrification and denitrification, particularly under conditions of intermittent moisture and high nitrogen availability. Rice-based systems, especially those employing intermittent irrigation, create aerobic–anaerobic transitions that intensify N₂O emissions.

In the present study, N₂O fluxes varied significantly with establishment methods and cropping seasons across three locations (Table 8; Fig. 10).

At Palampur, treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded the highest N₂O flux of 820.2 g ha⁻¹ on a pooled basis, with annual values of 817.7 g ha⁻¹ in 2023 and 822.8 g ha⁻¹ in 2024. This was followed by transplanted treatments (T₁ and T₂). T₁ (PTR *PR-126*) recorded fluxes of 742.8, 747.7, and 745.3 g ha⁻¹ in 2023, 2024, and pooled data, respectively, corresponding to reduction of 9.1 per cent in each case compared with T₆. Similarly, T₂ (PTR *SAVAH-134*) emitted 748.9, 744.2, and 746.6 g ha⁻¹, reflecting reductions of 8.4, 9.6, and 9.0 per cent over T₆. Although T₁ and T₂ were statistically at par, T₁ exhibited a marginally lower pooled flux (0.2% reduction compared to T₂). Within the DSR system, markedly lower N₂O emissions were observed. T₅ (DSR *SAVAH-134* Full Page hybrid) consistently recorded the lowest fluxes of 705.9, 707.1, and 706.5 g ha⁻¹ in 2023, 2024, and pooled data, respectively, representing reductions of 13.7, 14.1, and 13.9 per cent relative to T₆. T₅ also outperformed other DSR treatments, recording lower emissions than T₄ (DSR *SAVAH-134*) by 1.0, 0.4, and 0.7 per cent in 2023, 2024, and pooled values, respectively. Compared with T₃ (DSR *PR-126*), reductions were more pronounced at 1.9, 1.4, and 1.7 per cent in the corresponding years.

Similar trend was also observed at KVK, Una where treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded the highest emissions of 877.2, 870.2, and 873.7 g ha⁻¹ in 2023, 2024, and pooled data, respectively. Among transplanted treatments, T₁ (PTR *PR-126*) emitted 775.5, 778.0, and 776.8 g ha⁻¹, corresponding to reductions of 11.6, 10.6, and 11.1 per cent compared with T₆. T₂ (PTR *SAVAH-134*) recorded fluxes of 772.2, 781.1, and 776.7 g ha⁻¹, reflecting reductions of 12.0, 10.2, and 11.1 per cent over T₆. Within the DSR system, T₅ (DSR

SAVAH-134 Full Page hybrid) again proved most effective, with emissions of 714.6, 726.9, and 720.8 g ha⁻¹, translating to reductions of 18.5, 16.5, and 17.5 per cent relative to T₆. T₄ (DSR *SAVAH-134*) emitted 721.6, 733.1, and 727.3 g ha⁻¹, while T₃ (DSR *PR-126*) recorded 723.6, 736.6, and 730.1 g ha⁻¹. Thus, T₅ reduced emissions compared with T₄ by 1.0, 0.8, and 0.9 per cent, and compared with T₃ by 1.2, 1.4, and 1.3 per cent in 2023, 2024, and pooled data, respectively.

At HAREC, Dhaulakuan, also treatment T₆ again recorded the highest fluxes of 828.9, 832.3, and 830.6 g ha⁻¹ in 2023, 2024, and pooled data, respectively. T₁ (PTR *PR-126*) followed, with emissions of 752.1, 770.1, and 761.1 g ha⁻¹, corresponding to reductions of 9.3, 7.5, and 8.4 per cent over T₆. Likewise, treatment T₂ (PTR *SAVAH-134*) emitted 755.3, 764.3, and 759.8 g ha⁻¹, reflecting reductions of 8.9, 8.2, and 8.5 per cent in comparison to T₆. Among DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) again emerged as the most effective, with emissions of 719.5, 727.1, and 723.3 g ha⁻¹, corresponding to reductions of 13.2, 12.6, and 12.9 per cent over T₆. T₄ (DSR *SAVAH-134*) recorded 720.2, 732.8, and 726.5 g ha⁻¹, while T₃ (DSR *PR-126*) emitted 722.9, 740.8, and 731.9 g ha⁻¹. Consequently, T₅ reduced emissions compared with T₄ by 0.1, 0.8, and 0.4 per cent, and compared with T₃ by 0.5, 1.9, and 1.2 per cent in 2023, 2024, and pooled data, respectively.

Table 8 – N₂O flux (g ha⁻¹) under different rice establishment methods at Palampur, Una and Dhaulakuan

N ₂ O flux (g ha ⁻¹)									
Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	742.8	747.7	745.3	775.5	778.0	776.8	752.1	770.1	761.1
T ₂	748.9	744.2	746.6	772.2	781.1	776.7	755.3	764.3	759.8
T ₃	720.0	716.8	718.4	723.6	736.6	730.1	722.9	740.8	731.9
T ₄	712.5	710.3	711.4	721.6	733.1	727.3	720.2	732.8	726.5
T ₅	705.9	707.1	706.5	714.6	726.9	720.8	719.5	727.1	723.3
T ₆	817.7	822.8	820.2	877.2	870.2	873.7	828.9	832.3	830.6
CD (<i>p</i> =0.05)	14.4	12.1	12.9	10.8	15.0	12.6	14.7	13.6	14.0

Table 9 – Pooled N₂O flux (g ha⁻¹) across three locations under different rice establishment methods

N ₂ O flux (g ha ⁻¹)			
Treatments	2023	2024	Pooled
T ₁	756.8	765.3	761.0
T ₂	758.8	763.2	761.0
T ₃	722.2	731.4	726.8
T ₄	718.1	725.4	721.7
T ₅	713.4	720.4	716.9
T ₆	841.3	841.8	841.5
CD (<i>p</i> =0.05)	21.9	15.0	6.7

Pooled mean data of all the locations and years (Table 9) revealed that treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded the highest N₂O flux at 841.5 g ha⁻¹. This was followed by transplanted treatments T₁ (PTR *PR-126*) and T₂ (PTR *SAVAH-134*), both registering pooled fluxes of 761.0 g ha⁻¹, corresponding to reductions of 9.6% compared with T₆. Among DSR treatments, T₃, T₄, and T₅ recorded further lower emissions of 726.8, 721.7, and 716.9 g ha⁻¹, representing reductions of 13.6, 14.2, and 14.8 per cent, respectively, relative to T₆.

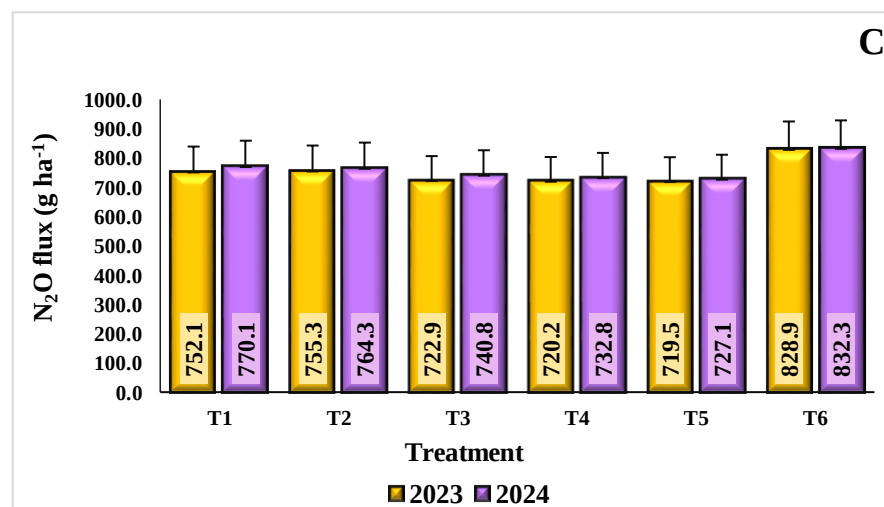
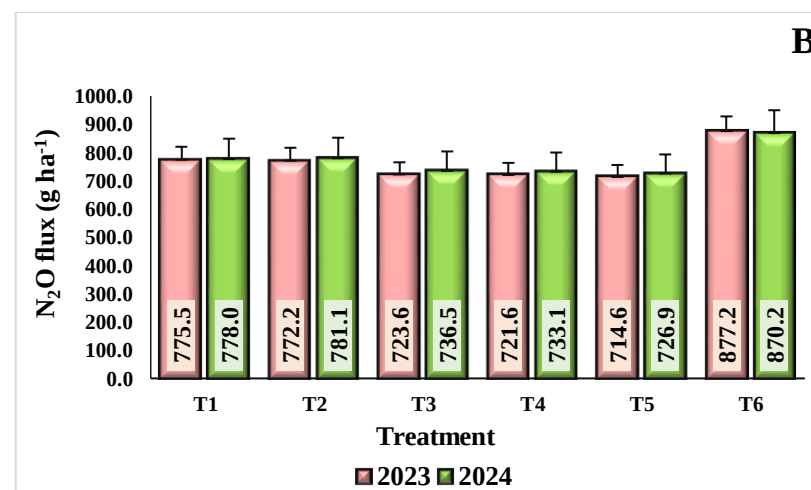
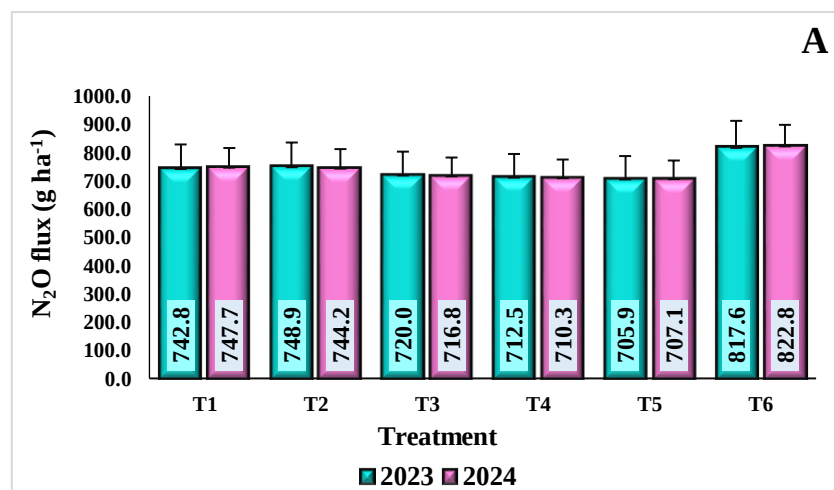


Fig 10. N₂O flux (kg ha⁻¹) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

3. Carbon footprints (kg CO₂ equivalent kg⁻¹ grain)

Carbon footprint is a unified metric that expresses the cumulative impact of all greenhouse gases (GHGs) in terms of their global warming potential relative to CO₂. This approach enables the aggregation of diverse emissions such as CH₄ and N₂O into a single, comparable unit. Expressing emissions per unit of grain yield reflects the emission intensity of different establishment methods, thereby providing a realistic measure of environmental efficiency. In the present study, carbon footprints expressed as CO₂ equivalents varied significantly across rice establishment methods, seasons, and locations, as presented in Table 10 and Fig. 11.

At Palampur, treatment T₃ (DSR *PR-126*) exhibited the highest carbon footprints of 0.24, 0.26, and 0.25 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively. T₃ was followed by T₁ (PTR *PR-126*), which recorded 0.20 kg CO₂ eq. kg⁻¹ grain across both years and pooled data. T₁ was further followed by T₂ (PTR *SAVAH-134*), with carbon footprints of 0.19 kg CO₂ eq. kg⁻¹ grain across both years and pooled data. Although PTR systems are generally associated with higher emissions, the carbon footprints under T₁ and T₂ were lower than those of T₃ (DSR *PR-126*) due to comparatively higher grain yields in transplanted treatments, which reduced emission intensity when expressed on a per-unit-yield basis. The lowest carbon footprints were recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), *i.e.*, 0.16, 0.17, and 0.17 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively. This corresponded to reductions of 20.0, 15.0, and 15.0 per cent over T₁ (PTR *PR-126*) and 15.8, 10.5, and 10.5 per cent over T₂ (PTR *SAVAH-134*) during the respective years and pooled data. Notably, both DSR *SAVAH-134* and DSR *SAVAH-134* Full Page hybrid recorded lower carbon footprints than PTR *SAVAH-134*, confirming that direct-seeded systems can be more climate-efficient when yield performance is sustained.

In the same manner, at KVK Una, the highest carbon footprints were recorded with T₃ (DSR *PR-126*), with values of 0.31 kg CO₂ eq. kg⁻¹ grain across both years and pooled data. Treatment T₃ was followed by T₄ (DSR *SAVAH-134*), which recorded 0.26, 0.25, and 0.26 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively. T₄ was then followed by both transplanted treatments, *i.e.*, T₁ (PTR *PR-126*) with 0.24, 0.25, and 0.24 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively, and T₂ (PTR *SAVAH-134*) with 0.24 kg CO₂ eq. kg⁻¹ grain across both years and pooled data. However, T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded lower carbon footprints (0.22 kg CO₂ eq. kg⁻¹ grain across both years and pooled

data) than both transplanted treatments, corresponding to reductions of 8.3, 12.0, and 8.3 per cent over T₁ and 8.3, 8.3, and 8.3 per cent over T₂ in the respective years and pooled data. In contrast, the lowest carbon footprints (0.20, 0.21, and 0.20 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively) were recorded with T₅ (DSR *SAVAH-134* Full Page hybrid). This treatment (T₅) resulted in reductions of 16.7, 16.0, and 16.7 per cent over T₁ (PTR *PR-126*) and 16.7, 12.5, and 16.7 per cent over T₂ (PTR *SAVAH-134*) during 2023, 2024, and pooled data, respectively.

Likewise, at HAREC, Dhaulakuan, the highest carbon footprints were recorded under T₃ (DSR *PR-126*), with values of 0.26, 0.25, and 0.25 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively. This treatment was followed by T₄ (DSR *SAVAH-134*), which recorded 0.23, 0.22, and 0.23 kg CO₂ eq. kg⁻¹ grain across the respective years and pooled data. The treatments T₃ and T₄ were followed by T₁ (PTR *PR-126*), showing 0.22, 0.22, and 0.22 kg CO₂ eq. kg⁻¹ grain and T₂ (PTR *SAVAH-134*), showing 0.21, 0.21, and 0.21 kg CO₂ eq. kg⁻¹ grain in 2023, 2024, and pooled data, respectively. The DSR *SAVAH-134* Full Page hybrid with AFD treatment (T₆) registered carbon footprints of 0.20 kg CO₂ eq. kg⁻¹ grain across the respective years and pooled data, consistently lower than the transplanted treatments, with reductions of about 9.1% over T₁ and 4.8% over T₂. In contrast, the lowest carbon footprints were observed under treatment T₅ (DSR *SAVAH-134* Full Page hybrid), *i.e.*, 0.18, 0.19, and 0.18 kg CO₂ eq. kg⁻¹ grain, corresponding to reductions of 18.2, 13.6, and 18.2 per cent over T₁ and 14.3, 9.5, and 14.3 per cent over T₂ in 2023, 2024, and pooled data, respectively.

Table 10 – Carbon footprints (kg CO₂ equivalent kg⁻¹ grain) under different rice establishment methods at Palampur, Una and Dhaulakuan

Carbon footprints (kg CO ₂ equivalent kg ⁻¹ grain)									
Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	0.20	0.20	0.20	0.24	0.25	0.24	0.22	0.22	0.22
T ₂	0.19	0.19	0.19	0.24	0.24	0.24	0.21	0.21	0.21
T ₃	0.24	0.26	0.25	0.31	0.31	0.31	0.26	0.25	0.25
T ₄	0.18	0.21	0.20	0.26	0.25	0.26	0.23	0.22	0.23
T ₅	0.16	0.17	0.17	0.20	0.21	0.20	0.18	0.19	0.18
T ₆	0.18	0.20	0.19	0.22	0.22	0.22	0.20	0.20	0.20
CD (<i>p</i> =0.05)	0.02	0.01	0.01	0.03	0.03	0.02	0.02	0.02	0.02

Table 11 – Pooled carbon footprints (kg CO₂ equivalent kg⁻¹ grain) across three locations under different rice establishment methods

Carbon footprints (kg CO₂ equivalent kg⁻¹ grain)			
Treatments	2023	2024	Pooled
T₁	0.22	0.22	0.22
T₂	0.21	0.22	0.21
T₃	0.27	0.27	0.27
T₄	0.22	0.23	0.23
T₅	0.18	0.19	0.19
T₆	0.20	0.21	0.20
CD (<i>p</i>=0.05)	0.01	0.01	0.01

The pooled means data of all the locations presented in the (Table 11), depicted that treatment T₃ (DSR *PR-126*) recorded the highest pooled carbon footprint of 0.27 kg CO₂ eq. kg⁻¹ grain. This was followed by T₄ (DSR *SAVAH-134*), with a pooled carbon footprint of 0.23 kg CO₂ eq. kg⁻¹ grain, which was followed by both transplanted treatments, *i.e.*, T₁ (PTR *PR-126*) and T₂ (PTR *SAVAH-134*), with pooled carbon footprints of 0.22 and 0.21 kg CO₂ eq. kg⁻¹ grain, respectively. Treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) recorded slightly lower pooled carbon footprints of 0.20 kg CO₂ eq. kg⁻¹ grain compared to both T₁ and T₂. The lowest pooled carbon footprint of 0.19 kg CO₂ eq. kg⁻¹ grain across all treatments was recorded in treatment T₅ (DSR *SAVAH-134* Full Page hybrid), corresponding to reductions of 13.6 per cent over T₁ and 9.5 per cent over T₂, respectively.

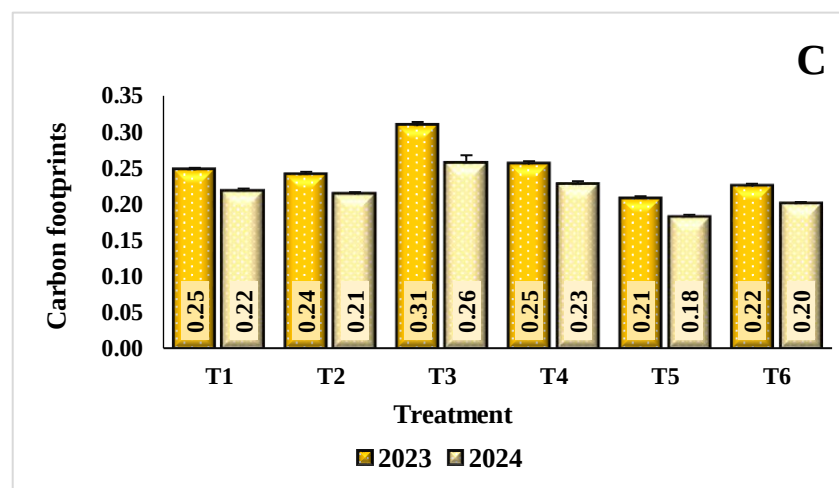
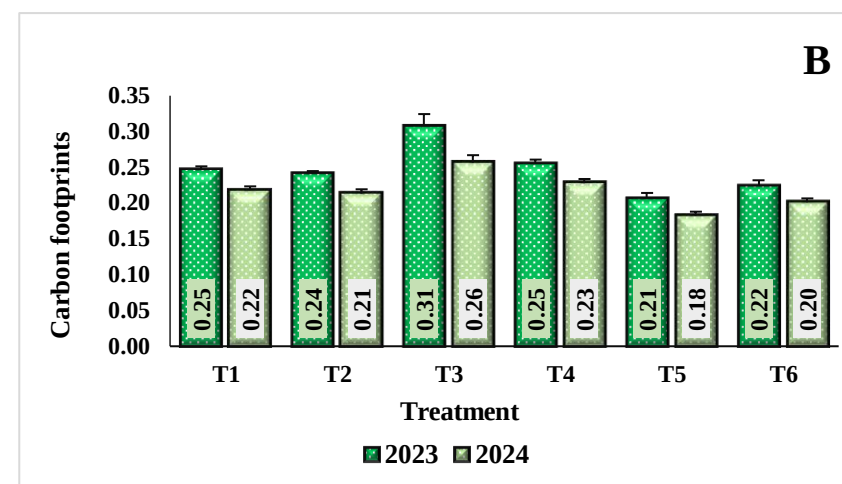
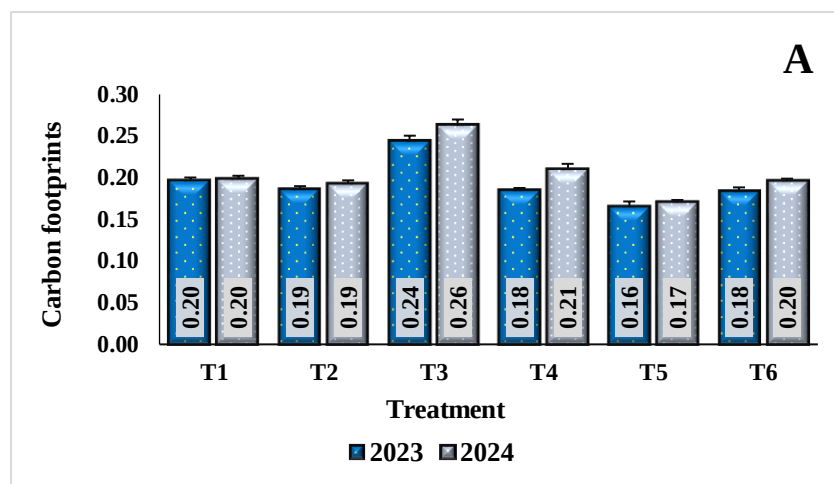


Fig 11. Carbon footprints (kg CO₂ equivalent kg⁻¹ grain) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

4. Global warming potential (GWP)

Global Warming Potential (GWP) reflects the cumulative warming effect of greenhouse gases emitted, expressed as kg CO₂ equivalents ha⁻¹, thereby enabling comparison of their climate impact across treatments and environments. In the present study, GWP values varied significantly across rice establishment methods, locations, and years (Table 12; Fig. 12).

At Palampur, the highest GWP was recorded under transplanted rice establishment. Treatment T₁ (PTR *PR-126*) registered 2138.9, 2148.8, and 2143.9 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, respectively. This was closely followed by T₂ (PTR *SAVAH-134*), which recorded 2144.5, 2101.5, and 2123.0 kg CO₂ eq. ha⁻¹. Although T₂ showed a slight increase in 2023, whereas, reduction of 2.2 per cent and 1.0 per cent were observed relative to T₁ in 2024 and pooled data, respectively; however, both transplanted treatments were statistically at par. These were followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which exhibited comparatively lower values of 1456.1, 1464.0, and 1460.0 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, corresponding to decreases of 31.9 per cent compared to T₁ and 32.1, 30.3, and 31.2 per cent compared to T₂ across the respective years and pooled data. Among DSR treatments, T₃ (DSR *PR-126*) showed higher GWP (1351.0, 1342.4, and 1346.7 kg CO₂ eq. ha⁻¹), followed by T₄ (DSR *SAVAH-134*) with 1336.7, 1334.3, and 1335.5 kg CO₂ eq. ha⁻¹, representing reductions of 1.1, 0.6, and 0.8 per cent relative to T₃. The lowest GWP was recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), with 1316.4, 1316.6, and 1316.5 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, resulting in reductions of 9.6, 10.1, and 9.8 per cent compared to T₆. Furthermore, T₅ consistently showed marked declines relative to transplanted treatments: reductions of 38.5, 38.7, and 38.6 per cent compared to T₁, and 38.6, 37.4, and 38.0 per cent compared to T₂ in 2023, 2024, and pooled data, respectively.

In the same way, at KVK Una, the highest GWP was also associated with transplanted rice. Treatment T₁ (PTR *PR-126*) registered 2381.0, 2358.7, and 2369.8 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, respectively. Likewise, treatment T₂ (PTR *SAVAH-134*) recorded 2360.5, 2393.6, and 2377.0 kg CO₂ eq. ha⁻¹, showing a 0.9% reduction relative to T₁ in 2023 but slightly higher values in 2024 and pooled data; both transplanted treatments were statistically at par. These were followed by treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which exhibited 1530.8, 1576.5, and 1553.7 kg CO₂ eq. ha⁻¹, corresponding to declines of 35.7, 33.2, and 34.4 per cent compared to T₁ across the respective years and pooled data. Among DSR treatments, T₃ (DSR *PR-126*) showed higher GWP (1418.1, 1445.5, and 1431.8 kg CO₂ eq. ha⁻¹), followed by T₄ (DSR *SAVAH-134*) at 1413.5, 1432.9, and 1423.2 kg

CO₂ eq. ha⁻¹, representing reductions of 0.3, 0.9, and 0.6 per cent relative to T₃. The lowest GWP was recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), with 1397.9, 1400.2, and 1399.1 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, reflecting reductions of 8.7, 11.2, and 10.0 per cent compared to T₆. Relative to transplanted treatments, T₅ consistently exhibited reductions of 41.3, 40.6, and 41.0 per cent compared to T₁, and 40.8, 41.5, and 41.1 per cent compared to T₂ in 2023, 2024, and pooled data, respectively.

Likewise, at HAREC Dhaulakuan, transplanted treatments again resulted in the highest GWP. Treatment T₁ (PTR *PR-126*) recorded 2373.9, 2377.3, and 2375.6 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, respectively. T₂ (PTR *SAVAH-134*) registered 2393.6, 2374.1, and 2383.9 kg CO₂ eq. ha⁻¹, which were 0.8 per cent higher than T₁ in 2023, marginally 0.1 per cent lower in 2024, and 0.3 per cent higher in pooled data; both transplanted treatments were statistically at par. These were followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which showed 1518.8, 1533.7, and 1526.2 kg CO₂ eq. ha⁻¹, corresponding to reductions of 36.0, 35.5, and 35.8 per cent compared to T₁ in 2023, 2024, and pooled data, respectively. Among DSR treatments, T₃ (DSR *PR-126*) exhibited higher GWP (1395.0, 1421.2, and 1408.1 kg CO₂ eq. ha⁻¹), while T₄ (DSR *SAVAH-134*) recorded slightly lower values of 1386.8, 1411.2, and 1399.0 kg CO₂ eq. ha⁻¹, representing reductions of 0.6, 0.7, and 0.6 per cent relative to T₃. The lowest GWP was observed under T₅ (DSR *SAVAH-134* Full Page hybrid), with 1373.5, 1406.0, and 1389.7 kg CO₂ eq. ha⁻¹, reflecting reductions of 9.6, 8.3, and 8.9 per cent compared to T₆. Relative to transplanted treatments, T₅ consistently recorded reductions of 42.1, 40.8, and 41.5 per cent compared to T₁, and 42.6, 40.8, and 41.7 per cent compared to T₂ in 2023, 2024, and pooled data, respectively.

Table 12 – GWP (kg CO₂ equivalent ha⁻¹) under different rice establishment methods at Palampur, Una and Dhaulakuan

GWP (kg CO ₂ equivalent ha ⁻¹)									
Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	2138.9	2148.8	2143.9	2381.0	2358.7	2369.8	2373.9	2377.3	2375.6
T ₂	2144.5	2101.5	2123.0	2360.5	2393.6	2377.0	2393.6	2374.1	2383.9
T ₃	1351.0	1342.4	1346.7	1418.1	1445.5	1431.8	1395.0	1421.2	1408.1
T ₄	1336.7	1334.3	1335.5	1413.5	1432.9	1423.2	1386.8	1411.2	1399.0
T ₅	1316.4	1316.6	1316.5	1397.9	1400.2	1399.1	1373.5	1406.0	1389.7
T ₆	1456.1	1464.6	1460.4	1530.8	1576.5	1553.7	1518.8	1533.7	1526.2
CD (p=0.05)	44.0	42.9	43.4	51.8	51.3	51.6	53.3	50.4	48.7

Table 13 – Pooled GWP (kg CO₂ equivalent ha⁻¹) across three locations under different rice establishment methods

Pooled GWP (kg CO₂ equivalent ha⁻¹)			
Treatments	2023	2024	Pooled
T₁	2297.9	2294.9	2296.4
T₂	2299.5	2289.7	2294.6
T₃	1388.0	1403.0	1395.5
T₄	1379.0	1392.8	1385.9
T₅	1362.6	1374.3	1368.4
T₆	1501.9	1524.9	1513.4
CD (<i>p</i>=0.05)	49.7	45.7	47.3

Across pooled means of all locations (Table 13), the maximum GWP was observed under transplanted treatments. T₁ (PTR *PR-126*) recorded 2297.9, 2294.9, and 2296.4 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, respectively. T₂ (PTR *SAVAH-134*) registered 2299.5, 2289.7, and 2294.6 kg CO₂ eq. ha⁻¹, and both the transplanted treatments statistically at par. These were followed by treatment T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which recorded 1501.9, 1524.9, and 1513.4 kg CO₂ eq. ha⁻¹ in 2023, 2024, and pooled data, reflecting reductions of 34.6, 33.6, and 34.1 per cent compared to T₁, and 34.7, 33.4, and 34.0 per cent compared to T₂. Significantly lower GWP was recorded under DSR treatments, wherein T₃ (DSR *PR-126*) and T₄ (DSR *SAVAH-134*) registered pooled values of 1395.5 and 1385.9 kg CO₂ eq. ha⁻¹, corresponding to reduction of 39.2 and 39.6 per cent compared to T₁, respectively. The lowest pooled GWP was observed under T₅ (DSR *SAVAH-134* Full Page hybrid), with 1362.6, 1374.3, and 1368.4 kg CO₂ eq. ha⁻¹, resulting in reductions of 40.7, 40.1, and 40.4 per cent compared to T₁.

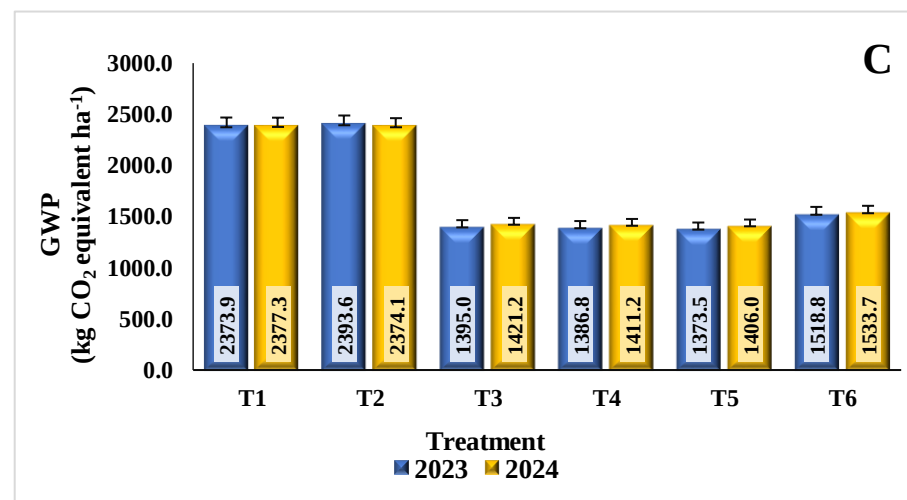
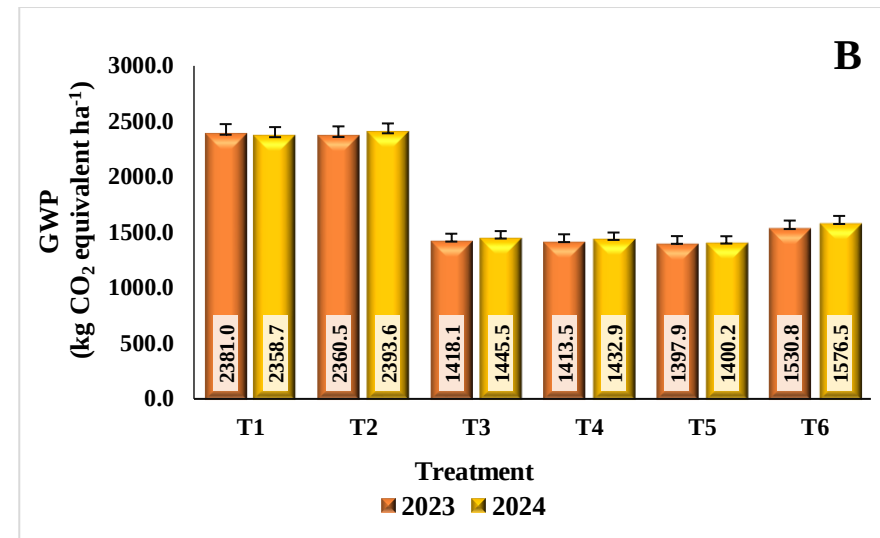
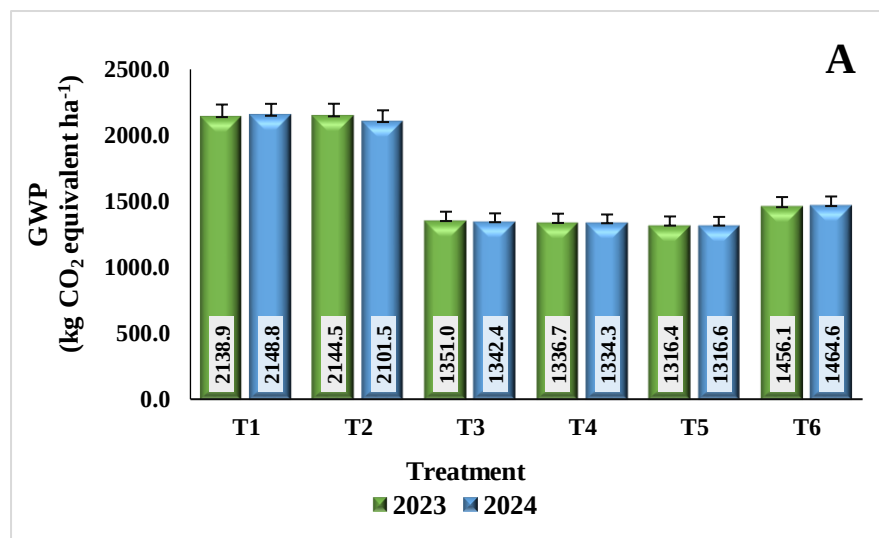


Fig 12. GWP (kg CO₂ equivalent ha⁻¹) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

5. Carbon credits (tCO₂e ha⁻¹)

Carbon credits represent the mitigation potential achieved through reduced greenhouse gas (GHG) emissions, expressed as tonnes of CO₂ equivalent per hectare (tCO₂e ha⁻¹), thereby enabling direct comparison of mitigation benefits across locations and management practices. In the present study, carbon credit values varied considerably across rice establishment methods, locations, and years. Across all three locations, the maximum carbon credit savings were consistently recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), which outperformed all other DSR and DSR-AFD treatments (Table 14). Taking T₁ (PTR *PR-126*) as a baseline, the carbon credits earned under different rice establishment methods clearly demonstrated the advantage of DSR hybrids in reducing GHG emissions.

At Palampur, the highest carbon credits (1.45 and 1.46 tCO₂e ha⁻¹ in 2023 and 2024, respectively) were recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), whereas the lowest credits (1.36 and 1.34 t CO₂e ha⁻¹ in 2023 and 2024, respectively) were obtained under T₆ (DSR *SAVAH-134* Full Page hybrid with AFD). Relative to T₅, reductions in carbon credits were 1.4% and 0.7% in T₄, 2.1% and 1.4% in T₃, and 6.6% and 9.0% in T₆ during 2023 and 2024, respectively.

Similarly, at KVK Una, treatment T₅ again achieved the maximum carbon credits (1.70 and 1.66 t CO₂e ha⁻¹ in 2023 and 2024, respectively), followed closely by T₄ (1.68 and 1.63 t CO₂e ha⁻¹) and T₃ (1.68 and 1.62 t CO₂e ha⁻¹). The lowest credits were recorded under T₆ (1.63 and 1.47 t CO₂e ha⁻¹ in 2023 and 2024, respectively). Compared to T₅, reductions were 1.2 and 1.8 per cent in T₄, 1.2 and 2.5 per cent in T₃, and 4.3 and 12.9 per cent in T₆ during 2023 and 2024, respectively.

Comparable trends were observed at HAREC Dhaulakuan, where the maximum carbon credits were again registered under T₅ (1.70 and 1.66 t CO₂e ha⁻¹ in 2023 and 2024, respectively), whereas T₆ recorded the lowest (1.63 and 1.57 t CO₂e ha⁻¹). Relative to T₅, reductions were 0.6 per cent in T₄ during both years, 0.6 and 1.2 per cent in T₃, and 4.3 and 5.7 per cent in T₆ during 2023 and 2024, respectively.

When treatment T₂ (PTR *SAVAH-134* hybrid) was taken as the baseline, the comparative assessment again highlighted the mitigation advantage of DSR hybrids. At Palampur, treatment T₅ recorded the highest carbon credits (1.47 and 1.41 t CO₂e ha⁻¹ in 2023 and 2024, respectively), whereas T₆ registered the lowest (1.38 and 1.23 t CO₂e ha⁻¹). Relative to T₅,

reductions were 1.2 and 1.8 per cent in T₄, 1.2 and 2.4 per cent in T₃, and 15.9 and 15.7 per cent in T₆ during 2023 and 2024, respectively.

Likewise, at KVK Una, the highest carbon credits were again observed under T₅ (1.66 and 1.69 t CO₂ e ha⁻¹ in 2023 and 2024, respectively), followed closely by T₄ (1.64 and 1.66 t CO₂ e ha⁻¹) and T₃ (1.64 and 1.65 t CO₂e ha⁻¹). The lowest credits were recorded under T₆ (1.59 and 1.57 t CO₂e ha⁻¹). Compared to T₅, reductions were 1.2 and 1.8 per cent in T₄, 1.2 and 2.4 per cent in T₃, and 4.2 and 7.1 per cent in T₆ during 2023 and 2024, respectively.

In the similar way at HAREC Dhaulakuan, treatment T₅ recorded the highest carbon credits (1.73 and 1.65 t CO₂ e ha⁻¹ in 2023 and 2024, respectively), while T₆ exhibited the lowest (1.65 and 1.56 tCO₂e ha⁻¹). Relative to T₅, reductions were 0.6 per cent in T₄, 0.6 and 1.2 per cent in T₃, and 4.6 and 5.5 per cent in T₆ during 2023 and 2024, respectively.

Table 14 – Carbon credits (tCO₂e ha⁻¹) under hybrid DSR and DSR-AFD in comparison to transplanted rice hybrids during 2023 & 2024

Treatment	Carbon credits (tCO ₂ e ha ⁻¹) over transplanted treatments					
	Palampur		Una		Dhaulakuan	
	2023	2024	2023	2024	2023	2024
	Over transplanted treatment T ₁					
T ₃	1.42	1.44	1.68	1.62	1.69	1.64
T ₄	1.43	1.45	1.68	1.63	1.69	1.65
T ₅	1.45	1.46	1.70	1.66	1.70	1.66
T ₆	1.36	1.34	1.63	1.47	1.63	1.57
Over transplanted treatment T ₂						
T ₃	1.44	1.39	1.64	1.65	1.71	1.64
T ₄	1.45	1.39	1.64	1.66	1.72	1.64
T ₅	1.47	1.41	1.66	1.69	1.73	1.65
T ₆	1.38	1.23	1.59	1.57	1.65	1.56

6. Water productivity (kg m^{-3})

Water productivity, defined as the amount of crop yield obtained per unit volume of water used (kg m^{-3}), provides a coherent metric to evaluate both yield performance and water-use efficiency across production systems and environments. Although crop response to water availability varies with location and management practices, expressing output in terms of yield per unit water enables a comprehensive appraisal of resource-use efficiency.

In the present study, water productivity exhibited significant variation across rice establishment methods, seasons, and locations (Table 15; Fig. 13).

At Palampur, values ranged from 0.43 to 0.66 kg m^{-3} in 2023, 0.40 to 0.63 kg m^{-3} in 2024, and 0.42 to 0.65 kg m^{-3} in the pooled data. The significantly highest productivity was recorded under treatment T₅ (DSR *SAVAH-134* Full Page hybrid), with values of 0.66, 0.63, and 0.65 kg m^{-3} in 2023, 2024, and pooled data, respectively. This treatment was followed by T₂ (PTR *SAVAH-134*), which remained statistically at par with T₄, T₆, and T₁ across the years. The lowest water productivity was consistently observed under T₃ (DSR *PR-126*), with values of 0.43, 0.40, and 0.42 kg m^{-3} in 2023, 2024, and pooled data, respectively.

Similarly, at KVK Una also, the highest water productivity was obtained under T₅ (DSR *SAVAH-134* Full Page hybrid), with values of 0.62, 0.72, and 0.67 kg m^{-3} in 2023, 2024, and pooled data, respectively. In 2023, T₅ was followed by T₆ (0.55 kg m^{-3}), which was statistically at par with T₁ (0.49 kg m^{-3}), T₂ (0.48 kg m^{-3}), and T₄ (0.49 kg m^{-3}). In 2024, T₅ maintained superiority (0.72 kg m^{-3}), followed by T₄ (0.57 kg m^{-3}), which was statistically similar to T₆ (0.56 kg m^{-3}), T₁ (0.53 kg m^{-3}), and T₂ (0.54 kg m^{-3}). In the pooled data, T₅ remained superior (0.67 kg m^{-3}), followed by T₆ (0.55 kg m^{-3}), while T₄ (0.53 kg m^{-3}), T₂ (0.51 kg m^{-3}), and T₁ (0.51 kg m^{-3}) were statistically at par.

In the similar manner at HAREC Dhaulakuan also, water productivity ranged from 0.47 to 0.68 kg m^{-3} in 2023, 0.50 to 0.69 kg m^{-3} in 2024, and 0.49 to 0.69 kg m^{-3} in the pooled data. The highest values were consistently recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), with 0.68, 0.69, and 0.69 kg m^{-3} in 2023, 2024, and pooled data, respectively. In 2023, T₅ was followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which recorded 0.57 kg m^{-3} and was statistically at par with T₂, T₁, and T₄. In 2024, T₅ was followed by T₄ and T₂, which remained statistically at par with T₆ and T₁. A similar pattern was observed in the pooled data, wherein T₅ was followed by T₆, both statistically at par with T₁, T₂, and T₄. The lowest water productivity in 2023, 2024 and pooled data was consistently recorded under T₃ (DSR *PR-126*), with values of 0.47, 0.50, and 0.49 kg m^{-3} , respectively.

Table 15 – Water productivity (kg m⁻³) during 2023 & 2024 across all the three locations

Location	Palampur			Una			Dhaulakuan		
Treatments	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	0.56	0.56	0.56	0.49	0.53	0.51	0.53	0.54	0.53
T ₂	0.59	0.57	0.58	0.48	0.54	0.51	0.54	0.56	0.55
T ₃	0.43	0.40	0.42	0.41	0.51	0.46	0.47	0.50	0.49
T ₄	0.57	0.53	0.55	0.49	0.57	0.53	0.53	0.56	0.55
T ₅	0.66	0.63	0.65	0.62	0.72	0.67	0.68	0.69	0.69
T ₆	0.57	0.54	0.56	0.55	0.56	0.55	0.57	0.55	0.56
CD (p=0.05)	0.05	0.05	0.04	0.06	0.05	0.05	0.05	0.05	0.04

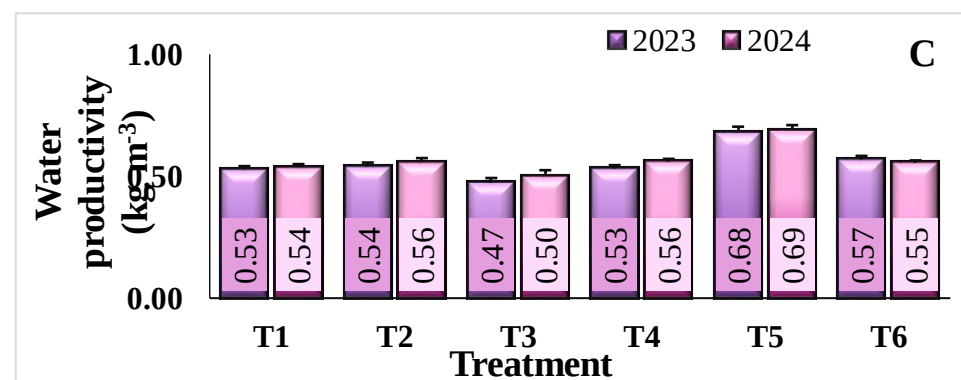
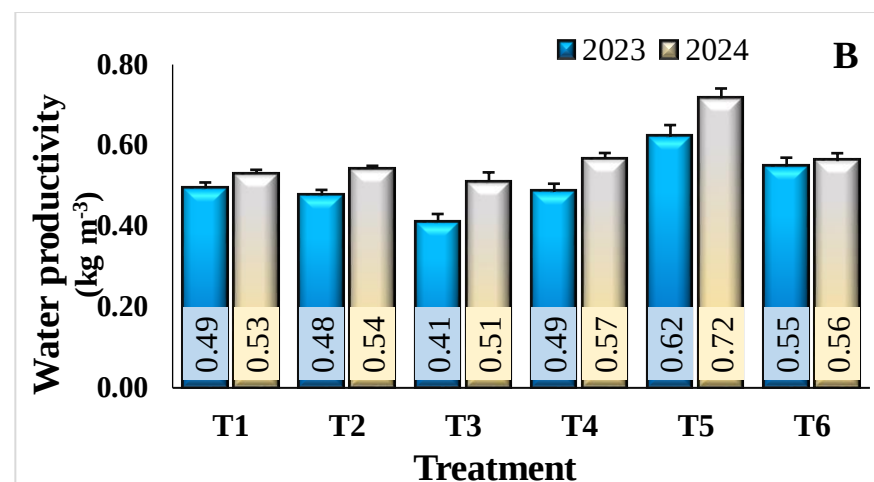
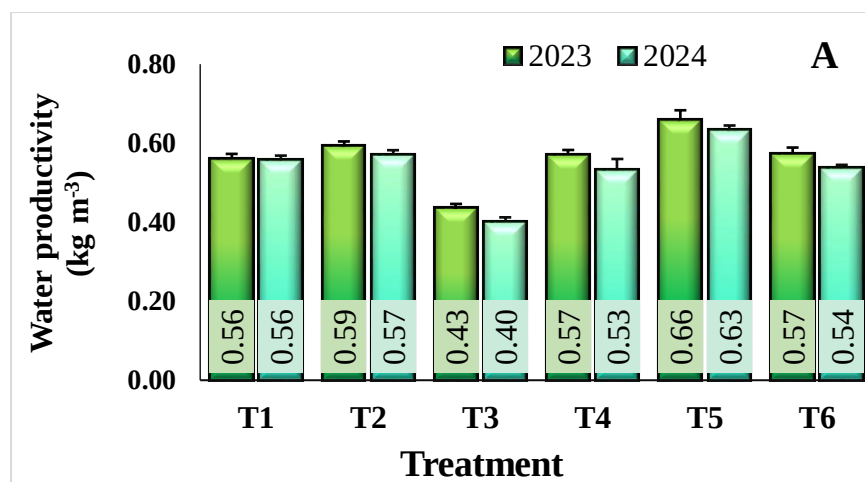


Fig 13. Water productivity (kg m⁻³) at Palampur (A), Una (B) and Dhaulakuan (C) during 2023 and 2024

7. Nutrient Uptake

Nutrient uptake represents the amount of nutrients absorbed by the crop per unit area (kg ha^{-1}), providing a direct measure of crop performance and soil fertility utilization across systems and environments. In the present study, nitrogen (N), phosphorus (P), and potassium (K) uptake varied significantly with rice establishment methods, seasons, and locations, as presented in Tables 16–24 and Figures 14–22.

i. Nitrogen Uptake (kg ha^{-1})

At Palampur, grain N uptake ranged from 41.1 to 86.7, 37.8 to 82.1, and 39.5 to 84.4 kg ha^{-1} in 2023, 2024, and pooled data, respectively (Table 16; Fig. 14). Straw N uptake varied from 22.0 to 44.0, 18.9 to 43.1, and 20.5 to 43.6 kg ha^{-1} in 2023, 2024, and pooled data, respectively. Consequently, total N uptake ranged from 63.2 to 130.7, 56.7 to 125.1, and 60.0 to 127.9 kg ha^{-1} in 2023, 2024, and pooled data, respectively.

Significantly highest grain, straw and total N uptake was recorded under T_2 (PTR *SAVAH-134*) viz., 86.7, 44.0 and 130.7 kg ha^{-1} during 2023, 82.1, 43.1 and 125.1 kg ha^{-1} during 2024 and 84.4, 43.6 and 127.9 kg ha^{-1} in pooled data, respectively, while the lowest was observed under T_3 (DSR *PR-126*) viz., 41.1, 22.0 and 63.2 kg ha^{-1} during 2023; 37.8, 18.9 and 56.7 kg ha^{-1} during 2024 and 39.5, 20.5 and 60.0 kg ha^{-1} in pooled data, respectively. Treatment T_2 was followed by T_1 (PTR *PR-126*), and both transplanted treatments consistently outperformed direct-seeded rice (DSR) treatments. Among DSR treatments, T_5 (DSR *SAVAH-134* Full Page hybrid) recorded the highest grain, straw and total N uptake i.e., 74.1, 34.7 and 108.8 kg ha^{-1} during 2023, 69.8, 33.6 and 103.4 kg ha^{-1} during 2024 and 71.9, 34.1 and 106.1 kg ha^{-1} in pooled data, respectively, followed by T_6 (DSR *SAVAH-134* Full Page hybrid with AFD), T_4 (DSR *SAVAH-134*), and T_3 (DSR *PR-126*).

At KVK Una also, grain N uptake ranged from 27.8 to 64.8, 33.8 to 69.5, and 30.8 to 67.2 kg ha^{-1} in 2023, 2024, and pooled data, respectively (Table 17; Fig. 15). Straw N uptake varied from 18.0 to 36.6, 16.9 to 36.6, and 17.4 to 36.6 kg ha^{-1} in 2023, 2024, and pooled data, respectively. Total N uptake ranged from 45.8 to 101.4, 50.7 to 106.1, and 48.2 to 103.8 kg ha^{-1} in 2023, 2024, and pooled data, respectively.

Similar to Palampur, significantly highest grain (64.8 kg ha^{-1} in 2023, 69.5 kg ha^{-1} in 2024 and 67.2 kg ha^{-1} in pooled data), straw (36.6 kg ha^{-1} in 2023, 2024 and in pooled data), and total N uptake (101.4 kg ha^{-1} in 2023, 106.1 kg ha^{-1} in 2024 and 103.8 kg ha^{-1} in pooled data) was recorded under T_2 (PTR *SAVAH-134*), followed by T_1 (PTR *PR-126*). Both transplanted treatments exhibited higher uptake compared to DSR treatments. Among DSR treatments, T_5

(DSR *SAVAH-134* Full Page hybrid) recorded the highest uptake, followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*) and T₃ (DSR *PR-126*).

At Dhaulakuan, grain N uptake ranged from 37.3 to 70.8, 37.6 to 67.4, and 37.5 to 69.1 kg ha⁻¹ in 2023, 2024, and pooled data, respectively (Table 18; Fig. 16). Straw N uptake varied from 21.5 to 39.6, 21.3 to 39.6, and 21.4 to 39.6 kg ha⁻¹ in 2023, 2024, and pooled data, respectively. Total N uptake ranged from 58.8 to 109.3, 59.0 to 107.0, and 58.9 to 108.1 kg ha⁻¹ in 2023, 2024, and pooled data, respectively.

As observed at other locations, significantly highest grain (70.8 kg ha⁻¹ in 2023, 67.4 kg ha⁻¹ in 2024 and 69.1 kg ha⁻¹ in pooled data), straw (39.6 kg ha⁻¹ in 2023, 2024 and in pooled data), and total N uptake (109.3 kg ha⁻¹ in 2023, 107.0 kg ha⁻¹ in 2024 and 108.1 kg ha⁻¹ in pooled data), followed by T₁ (PTR *PR-126*). Both transplanted treatments consistently outperformed DSR treatments. Among DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the highest uptake, followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*) and T₃ (DSR *PR-126*).

Table 16 – Grain, straw and total nitrogen uptake (kg ha⁻¹) by rice during 2023 & 2024 at Palampur

Treatments	N uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	78.0	40.5	118.4	73.8	40.1	113.9	75.9	40.3	112.7
T ₂	86.7	44.0	130.7	82.1	43.1	125.1	84.4	43.6	127.9
T ₃	41.1	22.0	63.2	37.8	18.9	56.7	39.5	20.5	60.0
T ₄	59.0	29.1	88.1	50.8	25.4	76.2	54.9	27.3	82.2
T ₅	74.1	34.7	108.8	69.8	33.6	103.4	71.9	34.1	106.1
T ₆	65.0	31.6	96.6	57.5	29.2	86.7	62.6	30.4	93.0
CD (p=0.05)	8.3	2.3	9.6	6.3	2.2	7.6	3.0	2.0	5.0

Table 17 – Grain, straw and total nitrogen uptake (kg ha⁻¹) by rice during 2023 & 2024 at Una

Treatments	N uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	58.2	35.0	93.2	63.0	34.2	97.3	60.6	34.6	95.2
T ₂	64.8	36.6	101.4	69.5	36.6	106.1	67.2	36.6	103.8
T ₃	27.8	18.0	45.8	33.8	16.9	50.7	30.8	17.4	48.2
T ₄	37.3	21.3	58.6	43.5	21.7	65.2	40.4	21.5	61.9
T ₅	56.7	29.6	86.3	59.8	28.8	88.6	58.2	29.2	87.4
T ₆	51.5	27.9	79.4	52.9	26.8	79.8	52.2	27.4	79.6
CD (p=0.05)	5.9	3.5	8.4	6.5	2.8	8.6	4.1	2.4	6.2

Table 18 – Grain, straw and total nitrogen uptake (kg ha⁻¹) by rice during 2023 & 2024 at Dhaulakuan

Treatments	N uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T₁	67.1	38.6	105.7	65.5	37.9	103.4	66.3	38.2	104.6
T₂	70.8	39.6	109.3	67.4	39.6	107.0	69.1	39.6	108.1
T₃	37.3	21.5	58.8	37.6	21.3	59.0	37.5	21.4	58.9
T₄	45.9	24.7	70.6	46.4	25.0	71.4	46.2	24.8	71.0
T₅	63.5	33.0	96.5	60.8	32.0	92.8	62.2	32.5	94.6
T₆	56.5	29.8	86.3	57.8	28.4	86.2	57.1	29.1	86.3
CD (<i>p</i>=0.05)	6.4	3.1	8.0	3.4	3.0	5.8	4.0	3.0	6.1

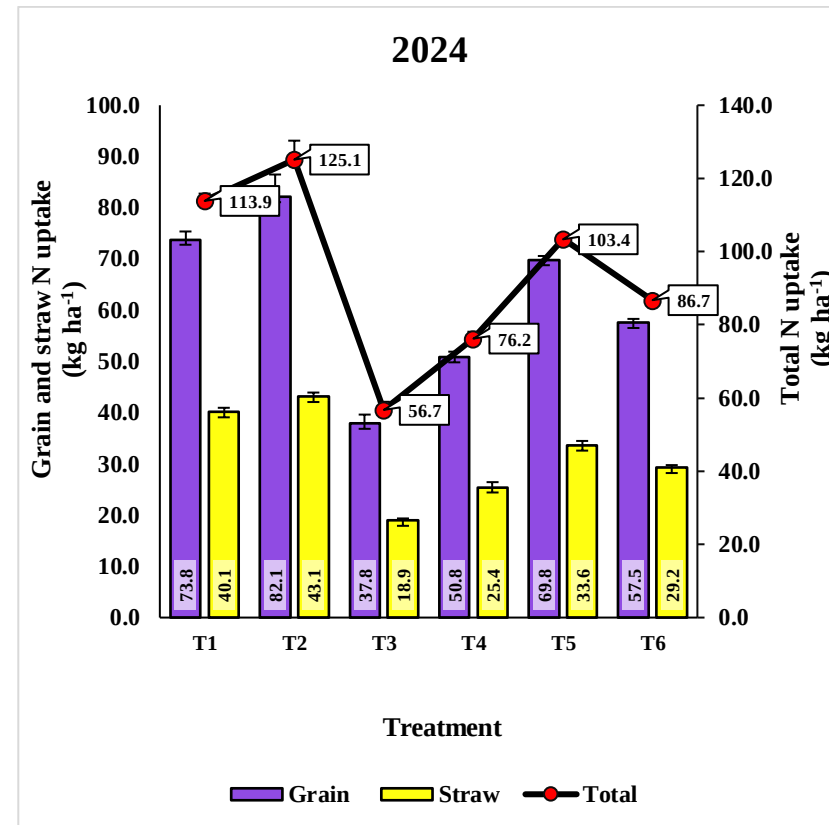
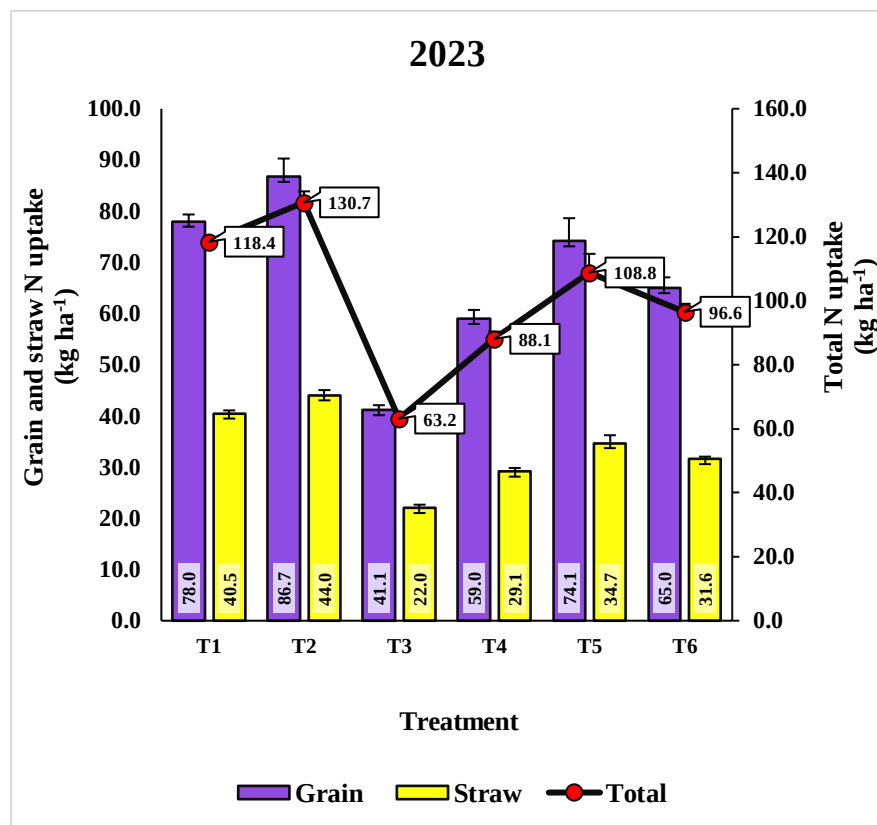


Fig 14. Grain, straw and total N uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Palampur

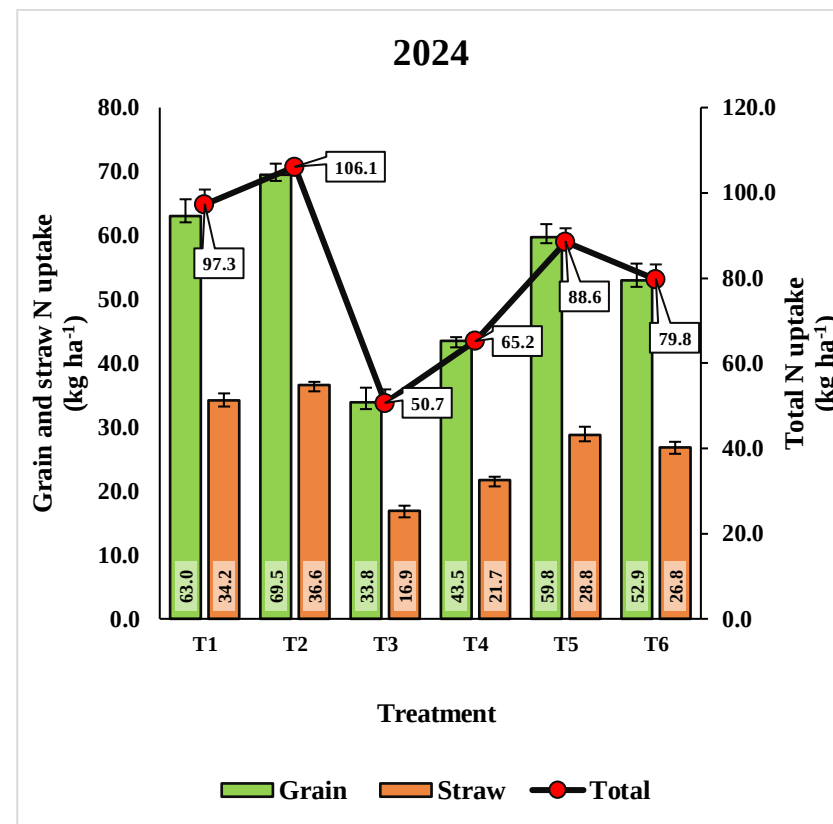
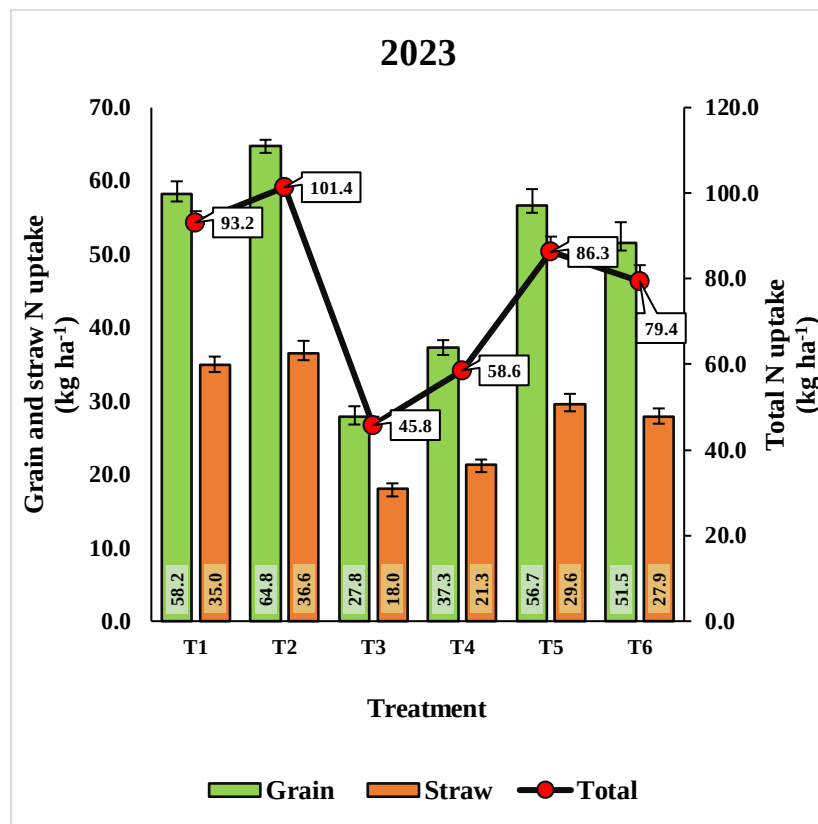


Fig 15. Grain, straw and total N uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Una

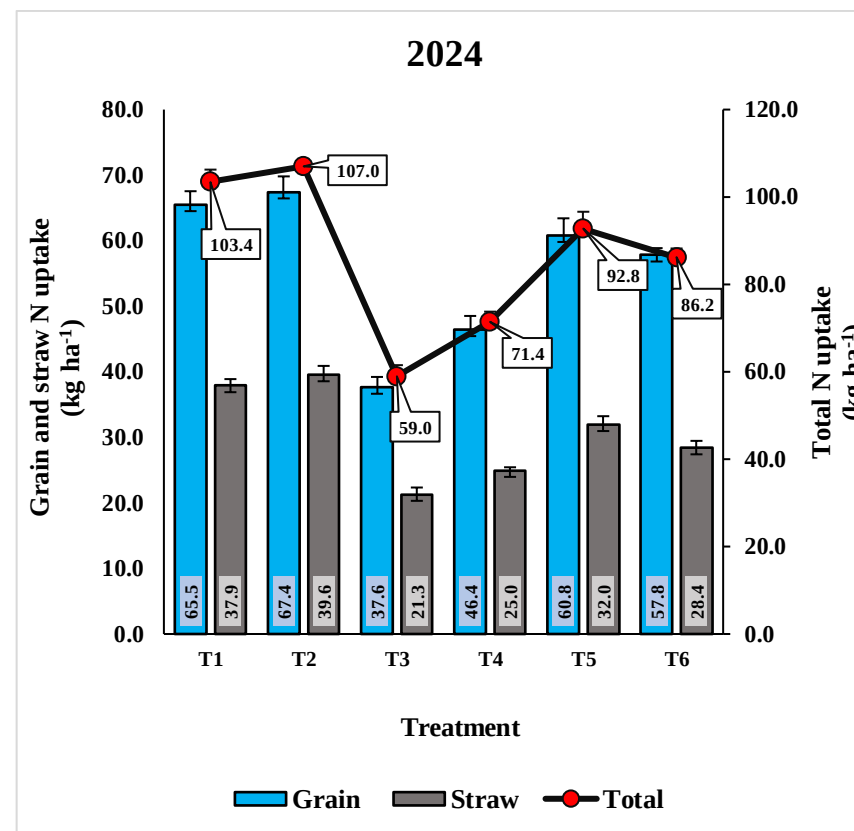
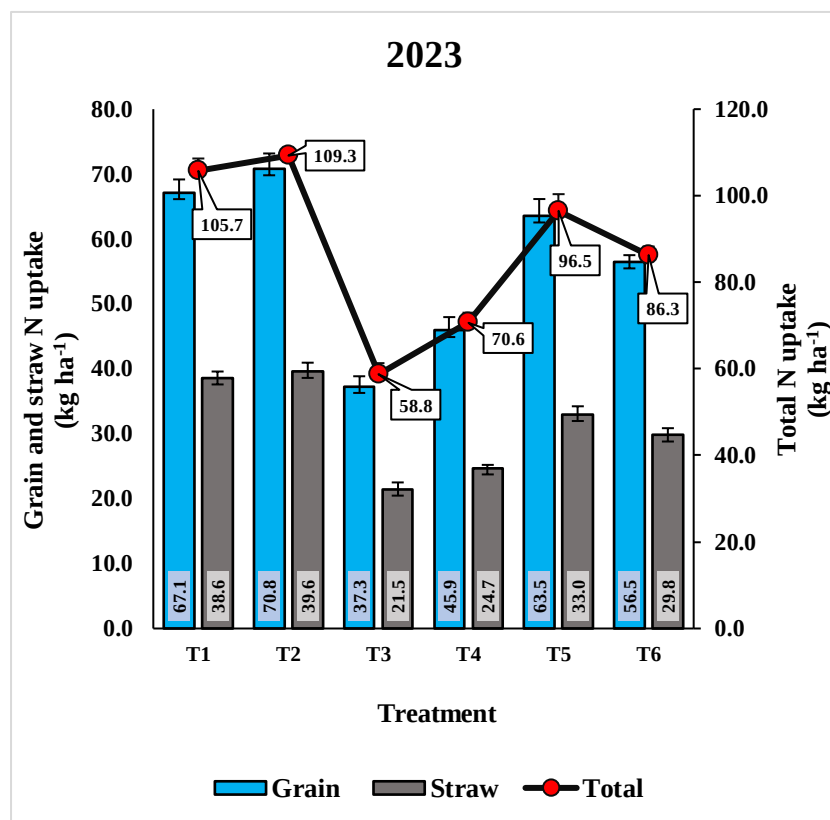


Fig 16. Grain, straw and total N uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

ii. Phosphorus Uptake (kg ha⁻¹)

At Palampur, phosphorus (P) uptake in grain ranged from 11.1 to 21.9, 9.7 to 22.2, and 10.4 to 22.0 kg ha⁻¹ during 2023, 2024, and pooled data, respectively (Table 19; Fig. 17). The P uptake in straw varied from 4.8 to 10.8, 4.3 to 11.1, and 4.5 to 10.0 kg ha⁻¹ in 2023, 2024, and pooled data, respectively. Consequently, the total P uptake ranged from 15.9 to 32.6, 14.0 to 33.3, and 14.9 to 32.9 kg ha⁻¹ in the respective years and pooled data.

Among the transplanted treatments, T₂ (PTR *SAVAH-134*) recorded the highest grain (21.9 kg ha⁻¹ during 2023, 22.2 kg ha⁻¹ during 2024 and 22.0 kg ha⁻¹ in pooled data), straw (10.8 kg ha⁻¹ during 2023, 11.1 kg ha⁻¹ during 2024 and 10.9 kg ha⁻¹ in pooled data), and total P uptake (32.6 kg ha⁻¹ during 2023, 33.3 kg ha⁻¹ during 2024 and 32.9 kg ha⁻¹ in pooled data), closely followed by T₁ (PTR *PR-126*). Within the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) exhibited significantly higher grain, straw, and total P uptake, followed in descending order by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*), and T₃ (DSR *PR-126*) across both years and pooled data.

Table 19 – Grain, straw and total phosphorus uptake (kg ha⁻¹) by rice during 2023 & 2024 at Palampur

Treatments	P uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	20.2	9.6	29.8	20.3	8.6	28.9	20.3	9.1	29.4
T ₂	21.9	10.8	32.6	22.2	11.1	33.3	22.0	10.9	32.9
T ₃	11.1	4.8	15.9	9.7	4.3	14.0	10.4	4.5	14.9
T ₄	16.3	7.7	24.0	14.2	6.5	20.7	15.2	7.1	22.3
T ₅	19.6	9.3	28.9	18.7	8.3	27.0	19.2	8.8	27.9
T ₆	17.4	7.3	24.7	15.4	6.9	22.4	16.4	7.1	23.5
CD (<i>p</i> =0.05)	1.9	0.9	2.0	1.6	1.0	2.4	1.2	0.7	1.7

Table 20 – Grain, straw and total phosphorus uptake (kg ha⁻¹) by rice during 2023 & 2024 at Una

Treatments	P uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	20.2	8.8	29.0	19.7	8.8	28.4	19.9	8.8	28.7
T ₂	22.3	10.5	32.8	21.1	10.2	31.3	21.7	10.4	32.1
T ₃	10.6	4.6	15.3	9.6	4.3	13.9	10.1	4.5	14.6
T ₄	16.1	7.0	23.1	14.1	6.2	20.3	15.1	6.6	21.7
T ₅	19.3	8.7	28.0	18.4	8.4	27.3	18.9	8.5	27.6
T ₆	17.0	7.0	24.0	14.7	6.5	21.3	15.9	6.8	22.6
CD (<i>p</i> =0.05)	1.9	0.9	2.4	1.9	0.9	2.5	1.5	0.8	1.9

Table 21 – Grain, straw and total phosphorus uptake (kg ha⁻¹) by rice during 2023 & 2024 at Dhaulakuan

Treatments	P uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	17.3	8.5	25.8	17.6	8.7	26.3	17.5	8.6	26.1
T ₂	17.6	9.3	26.9	18.2	9.5	27.7	17.9	9.4	27.3
T ₃	10.7	4.0	14.7	11.0	4.0	14.9	10.8	4.0	14.8
T ₄	13.0	4.9	18.0	13.1	5.0	18.1	13.1	5.0	18.0
T ₅	16.6	7.2	24.9	16.4	7.3	24.1	16.5	7.3	23.8
T ₆	15.5	6.2	21.8	14.9	6.3	21.1	15.2	6.2	21.4
CD (<i>p</i> =0.05)	1.3	1.0	2.3	1.3	0.9	1.7	1.1	0.9	1.7

At KVK Una also, grain P uptake ranged from 10.6 to 22.3, 9.6 to 21.1, and 10.1 to 21.7 kg ha⁻¹ during 2023, 2024, and pooled data, respectively (Table 20; Fig. 18). Straw P uptake varied from 4.6 to 10.5, 4.3 to 10.2, and 4.5 to 10.4 kg ha⁻¹ in the respective years and pooled mean. The total P uptake varied from 15.3 to 32.8, 13.9 to 31.3, and 14.6 to 32.1 kg ha⁻¹ in 2023, 2024, and pooled data, respectively.

Among transplanted treatments, T₂ (PTR *SAVAH-134*) consistently recorded the highest grain (22.3 kg ha⁻¹ during 2023, 21.1 kg ha⁻¹ during 2024 and 21.7 kg ha⁻¹ in pooled data), straw (10.5 kg ha⁻¹ during 2023, 10.2 kg ha⁻¹ during 2024 and 10.4 kg ha⁻¹ in pooled data), and total P uptake (32.8 kg ha⁻¹ during 2023, 31.3 kg ha⁻¹ during 2024 and 32.1 kg ha⁻¹ in pooled data), with values statistically comparable but slightly superior to T₁ (PTR *PR-126*). Within DSR methods, maximum P uptake was observed under T₅ (DSR *SAVAH-134* Full Page hybrid), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*), and T₃ (DSR *PR-126*) across both years and pooled data.

Similarly, at HAREC Dhaulakuan also, grain P uptake ranged from 10.7 to 17.6, 11.0 to 18.2, and 10.8 to 17.9 kg ha⁻¹ during 2023, 2024, and pooled data, respectively (Table 21; Fig. 19). Straw P uptake varied between 4.0 and 9.3, 4.0 and 9.5, and 4.0 to 9.4 kg ha⁻¹ in the respective years and pooled data. Accordingly, total P uptake ranged from 14.7 to 26.9, 14.9 to 27.7, and 14.8 to 27.3 kg ha⁻¹ in 2023, 2024, and pooled data, respectively.

Among transplanted methods, T₂ (PTR *SAVAH-134*) consistently exhibited the highest grain (17.6 kg ha⁻¹ during 2023, 18.2 kg ha⁻¹ during 2024 and 17.9 kg ha⁻¹ in pooled data), straw (9.3 kg ha⁻¹ during 2023, 9.5 kg ha⁻¹ during 2024 and 9.4 kg ha⁻¹ in pooled data), and total P uptake (26.9 kg ha⁻¹ during 2023, 27.7 kg ha⁻¹ during 2024 and 27.3 kg ha⁻¹ in pooled data), followed closely by T₁ (PTR *PR-126*). Within DSR establishment, maximum P uptake was recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*), and T₃ (DSR *PR-126*) across both years and pooled data.

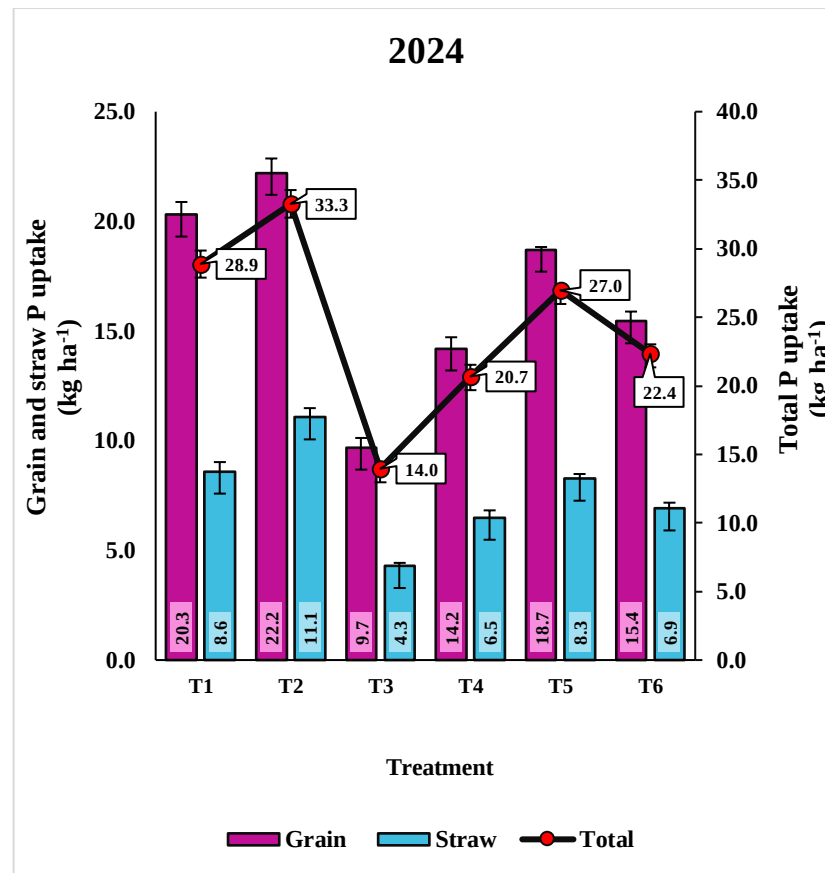
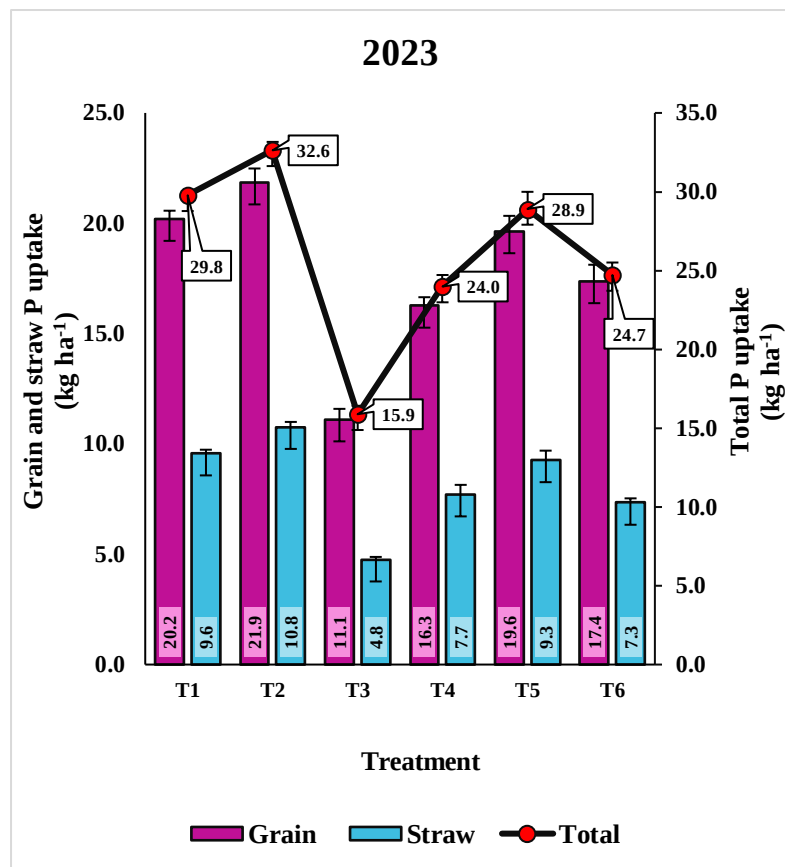


Fig 17. Grain, straw and total P uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Palampur

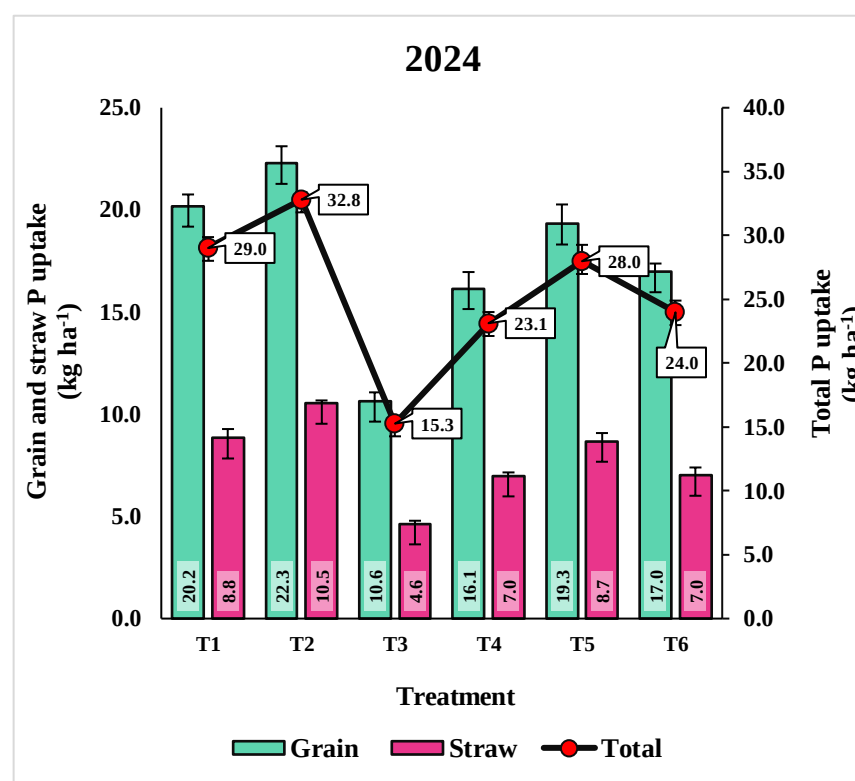
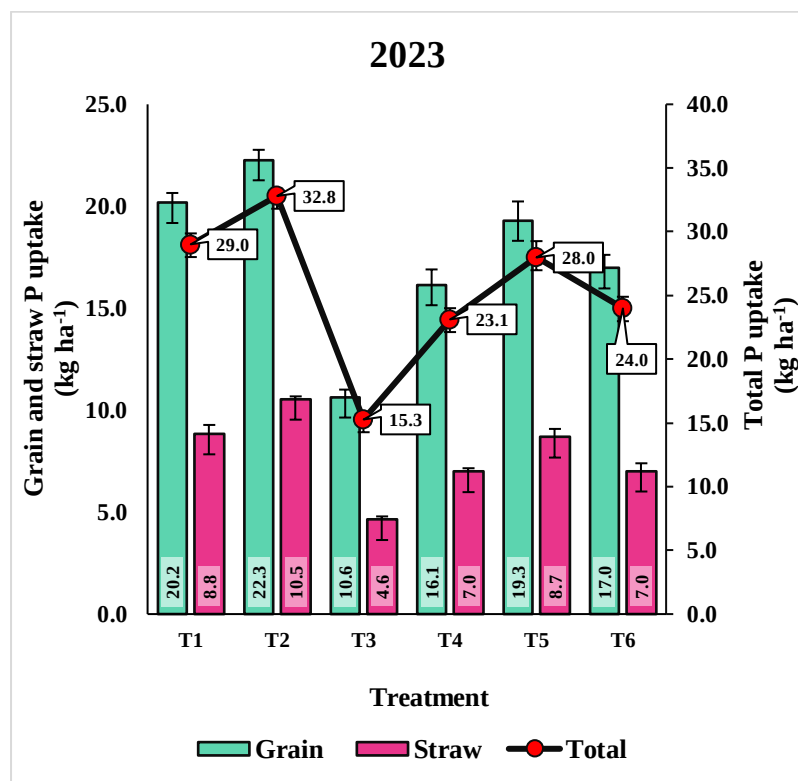


Fig 18. Grain, straw and total P uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Una

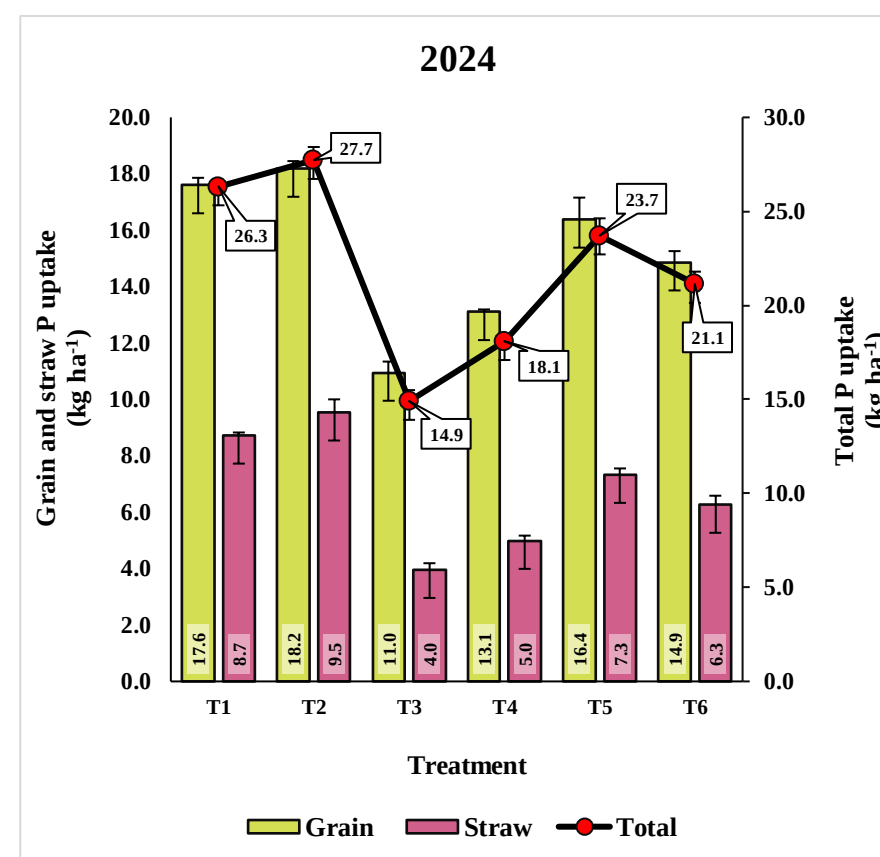
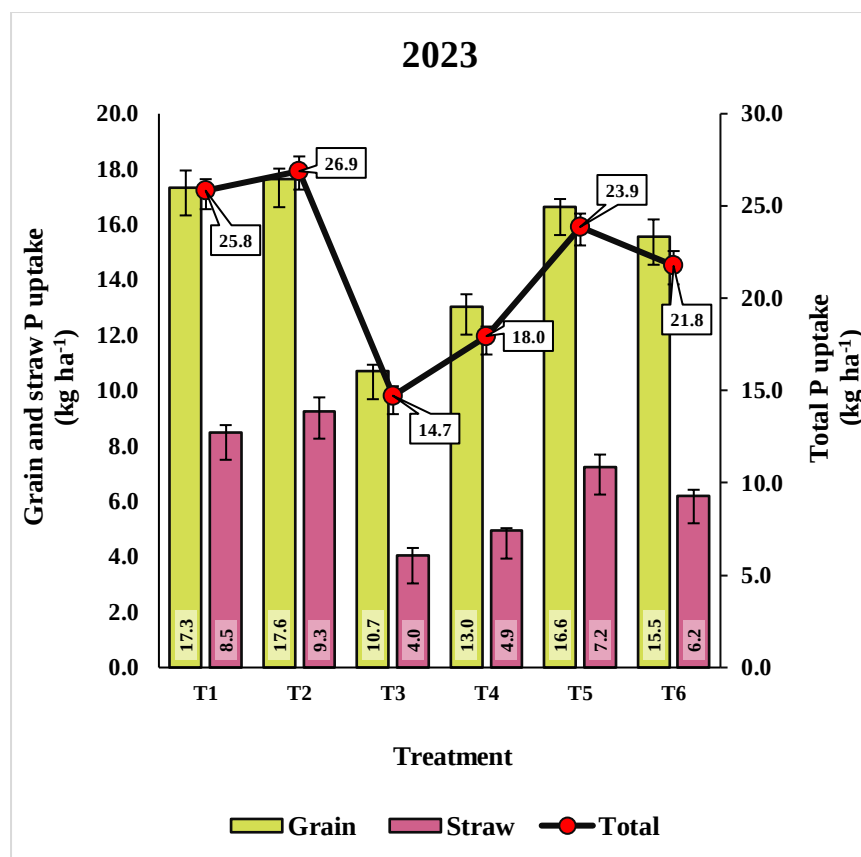


Fig 19. Grain, straw and total P uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

iii. Potassium uptake (kg ha⁻¹)

At Palampur, potassium (K) uptake in grain ranged from 18.8 to 35.8, 17.1 to 34.0, and 18.0 to 34.9 kg ha⁻¹ during 2023, 2024, and pooled data, respectively (Table 22; Fig. 20). The K uptake in straw varied from 64.4 to 137.0, 58.3 to 133.6, and 61.4 to 135.3 kg ha⁻¹ in the corresponding years and pooled data. Consequently, the total K uptake extended from 83.3 to 172.8, 75.4 to 167.7, and 79.3 to 170.2 kg ha⁻¹ during 2023, 2024, and pooled data, respectively.

Table 22 – Grain, straw and total potassium uptake (kg ha⁻¹) by rice during 2023 & 2024 at Palampur

Treatments	K uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	32.4	129.5	161.8	33.3	127.2	160.5	32.8	128.3	161.1
T ₂	35.8	137.0	172.8	34.0	133.6	167.7	34.9	135.3	170.2
T ₃	18.8	64.4	83.3	17.1	58.3	75.4	18.0	61.4	79.3
T ₄	25.1	87.4	112.6	22.8	77.2	99.9	23.9	82.3	106.2
T ₅	31.5	101.3	132.8	29.9	105.7	135.7	30.7	103.5	134.2
T ₆	27.9	93.0	121.0	24.9	89.2	114.1	26.4	91.1	117.5
CD (<i>p</i> =0.05)	3.8	10.5	13.1	2.8	8.3	10.3	2.3	6.5	8.3

Table 23 – Grain, straw and total potassium uptake (kg ha⁻¹) by rice during 2023 & 2024 at Una

Treatments	K uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T ₁	32.3	112.1	144.4	32.7	111.2	143.9	32.5	111.7	144.2
T ₂	34.1	123.2	157.2	34.1	118.8	152.8	34.1	121.0	155.0
T ₃	19.1	59.0	78.2	17.7	54.6	72.3	18.4	56.8	75.3
T ₄	26.1	79.0	105.1	23.1	69.5	92.6	24.6	74.3	98.9
T ₅	31.4	97.7	129.2	30.4	94.2	124.6	30.9	96.0	126.9
T ₆	26.9	88.8	115.7	25.4	83.0	108.5	26.2	85.9	112.1
CD (<i>p</i> =0.05)	2.3	9.7	11.4	2.3	8.1	9.5	1.7	7.6	8.5

Table 24 – Grain, straw and total potassium uptake (kg ha⁻¹) by rice during 2023 & 2024 at Dhaulakuan

Treatments	K uptake (kg ha ⁻¹)								
	2023			2024			Pooled data		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
T₁	28.5	98.0	126.5	28.5	97.5	126.0	28.5	97.8	126.3
T₂	30.6	114.0	144.5	30.2	114.1	144.2	30.4	114.0	144.4
T₃	18.1	54.3	72.4	18.8	54.9	73.7	18.4	54.6	73.0
T₄	21.8	57.8	79.6	21.9	58.2	80.1	21.8	58.0	79.9
T₅	28.0	82.9	110.9	28.8	79.7	108.5	28.4	81.3	109.7
T₆	25.2	76.3	101.5	25.7	76.2	102.0	25.5	76.2	101.7
CD (<i>p</i>=0.05)	2.7	11.2	13.6	1.9	9.5	11.2	2.2	10.2	12.1

Among transplanted treatments, the highest grain (35.8 kg ha⁻¹ during 2023, 34.0 kg ha⁻¹ during 2024 and 34.9 kg ha⁻¹ in pooled data), straw (137.0 kg ha⁻¹ during 2023, 133.6 kg ha⁻¹ during 2024 and 135.3 kg ha⁻¹ in pooled data), and total P uptake (172.8 kg ha⁻¹ during 2023, 167.7 kg ha⁻¹ during 2024 and 170.2 kg ha⁻¹ in pooled data) was consistently observed under T₂ (PTR *SAVAH-134*), closely followed by T₁ (PTR *PR-126*), with both being statistically at par. In contrast, direct-seeded rice (DSR) treatments recorded considerably lower K uptake compared to transplanted methods. Among DSR establishment methods, T₅ (DSR *SAVAH-134* Full Page hybrid) exhibited the maximum K uptake, followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*) and T₃ (DSR *PR-126*).

Similarly, at KVK Una, a similar trend was observed. Grain K uptake ranged between 19.1 and 34.1, 17.7 and 34.1, and 18.4 to 34.1 kg ha⁻¹ in 2023, 2024, and pooled data, respectively (Table 23; Fig. 21). Straw K uptake varied from 59.0 to 123.2, 54.6 to 118.8, and 56.8 to 121.0 kg ha⁻¹ across the respective years and pooled data. Correspondingly, total K uptake ranged between 78.2 and 157.2, 72.3 and 152.8, and 75.3 to 155.0 kg ha⁻¹ in 2023, 2024, and pooled data, respectively. Among transplanted treatments, T₂ (PTR *SAVAH-134*) again recorded the highest grain (34.1 kg ha⁻¹ during 2023, 2024 and in pooled data), straw (123.2 kg ha⁻¹ during 2023, 118.8 kg ha⁻¹ during 2024 and 121.0 kg ha⁻¹ in pooled data), and total K uptake (157.2 kg ha⁻¹ during 2023, 152.8 kg ha⁻¹ during 2024 and 155.0 kg ha⁻¹ in pooled data), marginally surpassing T₁ (PTR *PR-126*), though both were statistically at par and significantly superior to DSR methods. Within the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) consistently recorded maximum grain, straw, and total K uptake, followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*) and T₃ (DSR *PR-126*).

Correspondingly, at HAREC Dhaulakuan also, grain K uptake varied from 18.1 to 30.6, 18.8 to 30.2, and 18.4 to 30.4 kg ha⁻¹ in 2023, 2024, and pooled data, respectively (Table 24; Fig. 22). Straw K uptake ranged between 54.3 and 114.0, 54.9 and 114.1, and 54.6 to 114.0 kg ha⁻¹ across the respective years and pooled mean. Consequently, total K uptake varied from 72.4 to 144.5, 73.7 to 144.2, and 73.0 to 144.4 kg ha⁻¹ during 2023, 2024, and pooled data, respectively. Among transplanted methods, T₂ (PTR *SAVAH-134*) consistently registered the highest grain (30.6 kg ha⁻¹ during 2023, 30.2 kg ha⁻¹ during 2024 and 30.4 kg ha⁻¹ in pooled data), straw (114.0 kg ha⁻¹ during 2023, 114.1 kg ha⁻¹ during 2024 and 114.0 kg ha⁻¹ in pooled data), and total K uptake (144.5 kg ha⁻¹ during 2023, 144.2 kg ha⁻¹ during 2024 and 144.4 kg ha⁻¹ in pooled data), marginally exceeding T₁ (PTR *PR-126*), though both were statistically comparable and significantly superior to DSR treatments. Within the DSR establishment methods, maximum K uptake was recorded under T₅ (DSR *SAVAH-134* Full Page hybrid), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*) and T₃ (DSR *PR-126*) across both years and pooled data.

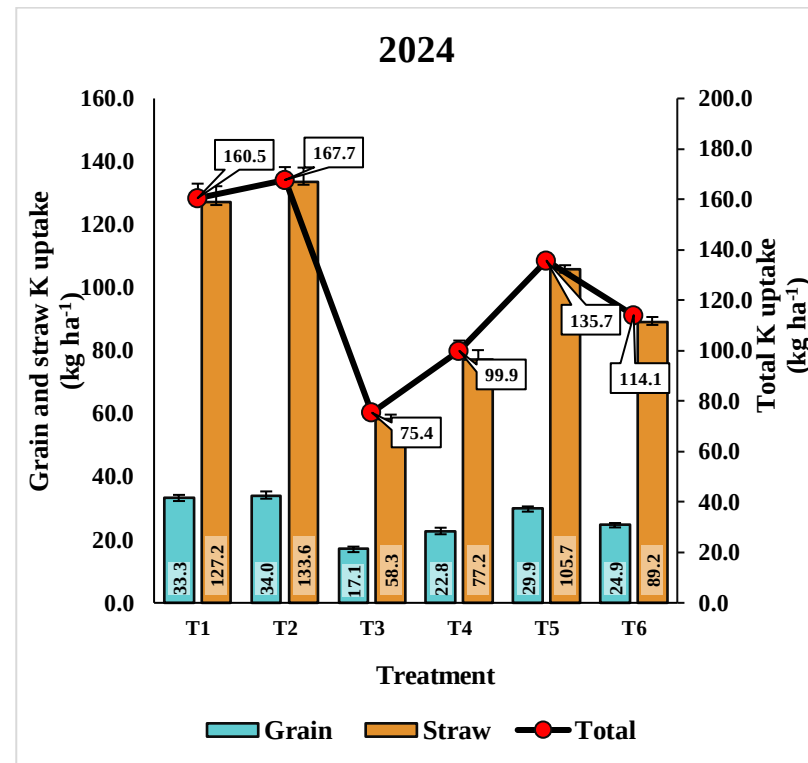
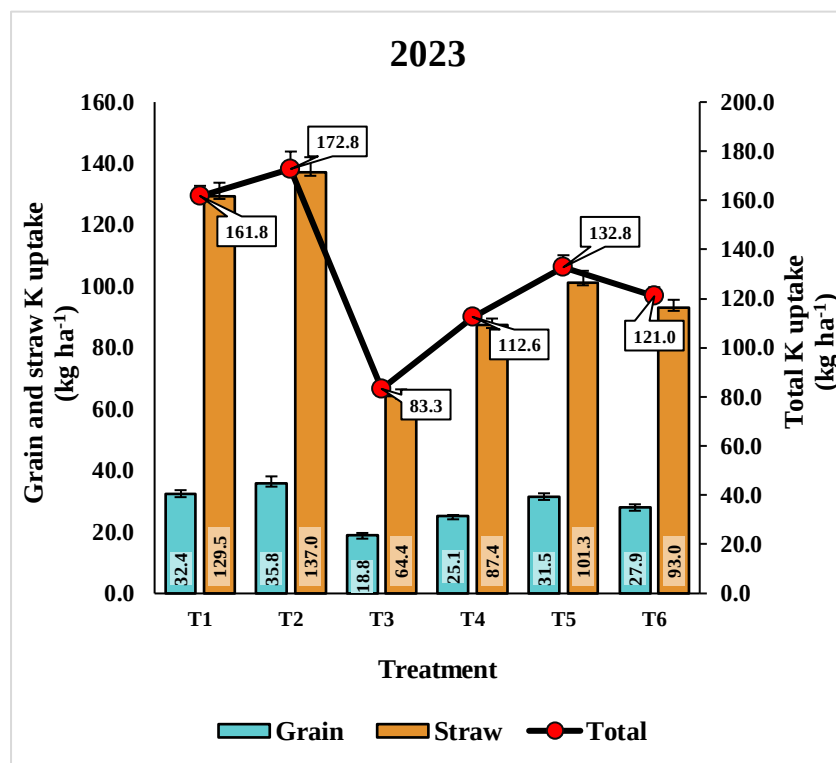


Fig 20. Grain, straw and total K uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Palampur

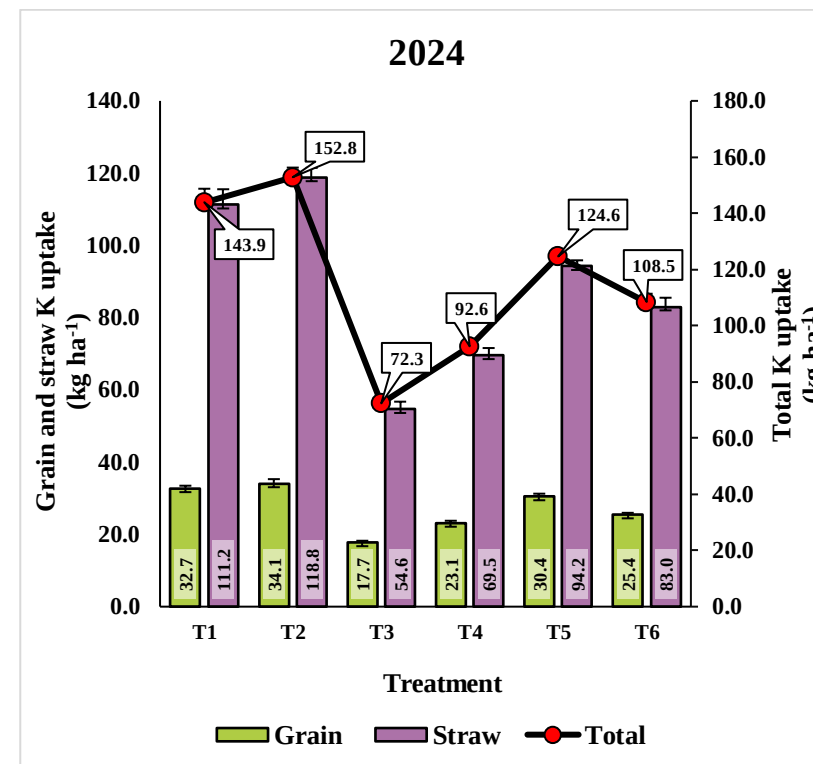
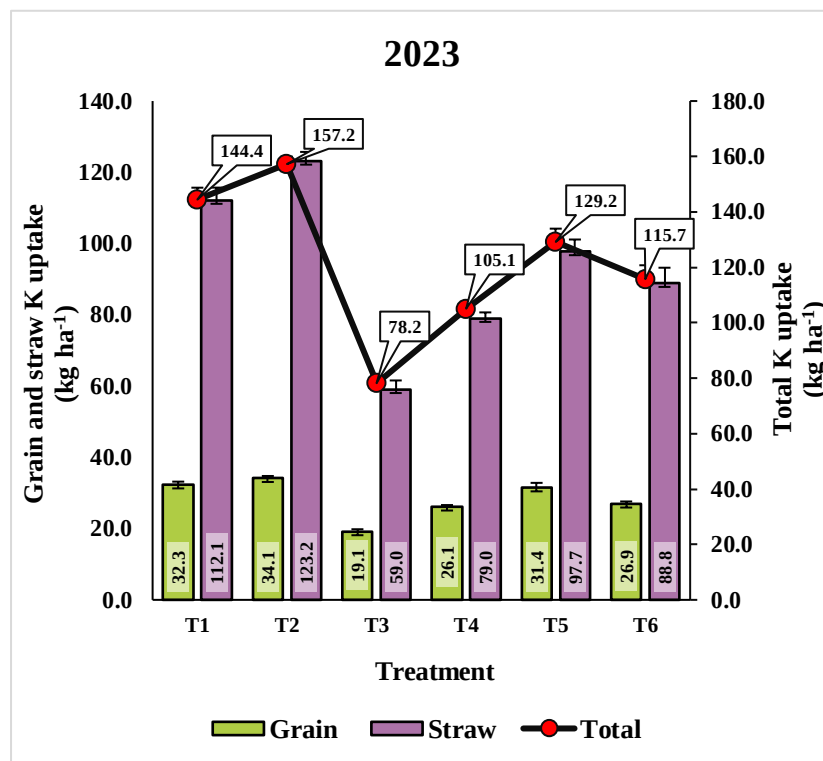


Fig 21. Grain, straw and total K uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Una

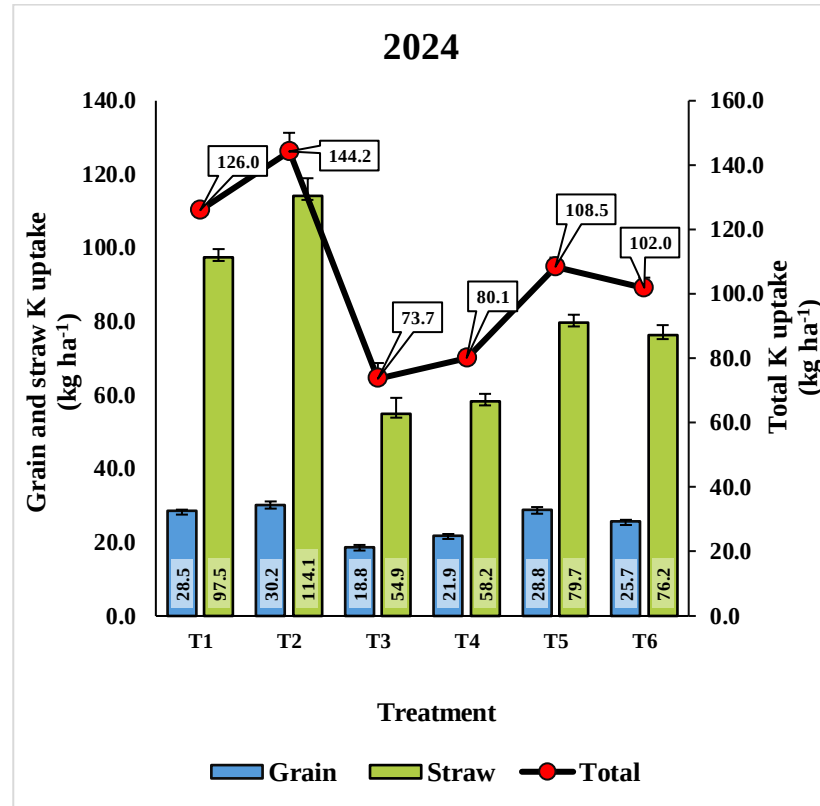
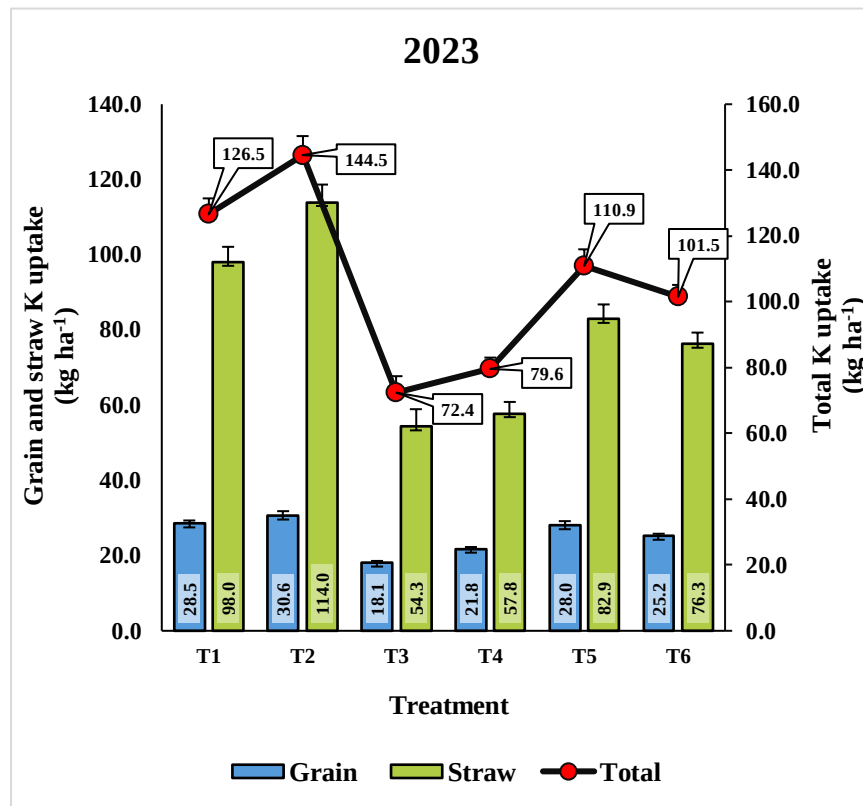


Fig 22. Grain, straw and total K uptake (kg ha⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

8. Soil physical properties

Soil physical properties play a critical role in regulating soil–water dynamics, root growth, and ultimately crop water-use efficiency. In the present study, bulk density and water-holding capacity exhibited significant variation across rice establishment methods, seasons, and locations, whereas particle density and soil porosity remained statistically non-significant.

At Palampur, lower bulk density values were consistently recorded under direct-seeded rice (DSR) establishment methods. Treatment T₅ (DSR SAVAH-134 Full Page hybrid) exhibited the lowest bulk density (1.26 Mg m⁻³) during 2023, 2024, and in pooled data (Table 25; Fig. 23). Treatment T₅ was statistically at par with T₄ and T₃, both registering 1.27 Mg m⁻³ across seasons and pooled data. In contrast, transplanted treatments recorded significantly higher bulk density, with T₁ showing 1.31 Mg m⁻³ in both years and pooled mean, while T₂ registered 1.30 Mg m⁻³ in 2023 and 1.31 Mg m⁻³ in 2024 and in pooled data. With respect to particle density and porosity, numerically lower values were observed under DSR treatments, while transplanted methods recorded relatively higher values. Water-holding capacity was significantly greater under DSR, with T₅ recording 45.9, 46.6, and 46.2 per cent in 2023, 2024, and pooled data, respectively. T₅ was statistically comparable to T₄ and T₃. Conversely, transplanted treatments (T₁ and T₂) exhibited lower water-holding capacity.

At KVK Una (Table 26; Fig. 24), similar trends were observed. Lower bulk density values were recorded under DSR, with T₅ showing the lowest values (1.33 Mg m⁻³ in 2023, 1.32 Mg m⁻³ in 2024, and 1.32 Mg m⁻³ in pooled data). Treatment T₅ was statistically at par with T₄ (1.34 Mg m⁻³ in both years and pooled data) and T₃ (1.34 Mg m⁻³ across seasons and pooled analysis). In contrast, transplanted methods exhibited significantly higher bulk density, with T₁ recording 1.38 Mg m⁻³ in both years and pooled data, followed by T₂ (1.37 Mg m⁻³ across seasons and pooled analysis). Particle density and porosity differences remained statistically non-significant, though slightly lower values tended to occur under DSR and higher values under transplanted methods. Water-holding capacity was significantly higher under DSR, with T₅ recording 43.6, 44.1, and 43.8 per cent in 2023, 2024, and pooled data, respectively. Treatments T₄ and T₃ were statistically comparable. In contrast, transplanted treatments, particularly T₁, recorded lower water-holding capacity (39.8, 40.2, and 40.0 per cent in 2023, 2024, and pooled data, respectively).

At HAREC, Dhaulakuan also (Table 27; Fig. 25), significant differences were observed in bulk density and water-holding capacity across rice establishment methods during both

seasons, while particle density and porosity remained statistically unaffected. DSR methods consistently produced lower bulk density, with T₅ showing the most favourable values (1.36 Mg m⁻³ in 2023, 1.35 Mg m⁻³ in 2024, and 1.36 Mg m⁻³ in pooled data). These values were statistically comparable to T₄ and T₃, which also reflected reduced compaction relative to transplanted methods. In contrast, transplanted treatments exhibited higher bulk density, with T₁ recording 1.42 Mg m⁻³ in both years and pooled analysis, while T₂ maintained 1.41 Mg m⁻³ across seasons. Although particle density and porosity did not differ significantly, a slight trend was evident, with DSR treatments showing marginally higher porosity and transplanted systems recording relatively lower values. Water-holding capacity was markedly improved under DSR, with T₅ recording the highest values (43.9 per cent in 2023, 44.2 per cent in 2024, and 44.1 per cent in pooled data). Treatments T₄ and T₃ followed closely, showing comparable water-holding capacity. In contrast, transplanted methods, particularly T₁, recorded lower values (40.3 per cent in 2023, 40.9 per cent in 2024, and 40.6 per cent pooled data).

Table 25 – Soil physical properties after rice harvest during 2023 & 2024 at Palampur

Treatments	2023				2024				Pooled			
	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)
T₁	1.31	2.53	48.28	43.65	1.31	2.53	48.17	44.16	1.31	2.53	48.23	43.91
T₂	1.30	2.54	48.72	43.93	1.31	2.55	48.80	44.88	1.31	2.55	48.76	44.41
T₃	1.27	2.52	49.73	45.32	1.27	2.52	49.51	45.77	1.27	2.52	49.62	45.55
T₄	1.27	2.52	49.88	45.76	1.27	2.52	49.57	46.31	1.27	2.52	49.72	46.04
T₅	1.26	2.51	49.97	45.92	1.26	2.51	49.89	46.65	1.26	2.51	49.93	46.29
T₆	1.29	2.52	48.74	44.32	1.30	2.54	48.82	45.14	1.30	2.53	48.78	44.73
CD (<i>p</i>=0.05)	0.02	NS	NS	1.34	0.02	NS	NS	1.02	0.02	NS	NS	0.83

Table 26 – Soil physical properties after rice harvest during 2023 & 2024 at Una

Treatments	2023				2024				Pooled			
	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)
T₁	1.38	2.56	46.14	39.80	1.37	2.55	46.17	40.19	1.38	2.55	46.15	40.00
T₂	1.37	2.55	46.42	40.01	1.37	2.55	46.33	40.82	1.37	2.55	46.37	40.42
T₃	1.34	2.53	47.04	42.33	1.33	2.53	47.28	42.67	1.34	2.53	47.16	42.50
T₄	1.34	2.53	47.03	43.17	1.34	2.53	47.18	43.58	1.34	2.53	47.11	43.38
T₅	1.33	2.51	47.24	43.59	1.32	2.52	47.66	44.13	1.32	2.51	47.45	43.86
T₆	1.36	2.54	46.62	41.90	1.36	2.54	46.56	42.28	1.36	2.54	46.59	42.09
CD (<i>p</i>=0.05)	0.03	NS	NS	1.42	0.03	NS	NS	1.06	0.03	NS	NS	0.77

Table 27 – Soil physical properties after rice harvest during 2023 & 2024 at Dhaulakuan

Treatments	2023				2024				Pooled			
	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)	BD (Mg m ⁻³)	PD (Mg m ⁻³)	Porosity (%)	WHC (%)
T₁	1.42	2.61	45.65	40.28	1.42	2.60	45.36	40.91	1.42	2.60	45.50	40.60
T₂	1.41	2.60	45.90	41.09	1.42	2.60	45.63	41.34	1.41	2.60	45.76	41.22
T₃	1.38	2.57	46.27	43.15	1.37	2.57	46.59	43.29	1.38	2.57	46.43	43.22
T₄	1.37	2.56	46.63	43.51	1.36	2.56	46.97	43.77	1.36	2.56	46.80	43.64
T₅	1.36	2.56	46.82	43.97	1.35	2.56	47.07	44.23	1.36	2.56	46.94	44.10
T₆	1.40	2.59	45.97	41.66	1.40	2.58	45.82	42.07	1.40	2.58	45.89	41.87
CD (<i>p</i>=0.05)	0.02	NS	NS	1.31	0.03	NS	NS	1.52	0.02	NS	NS	1.02

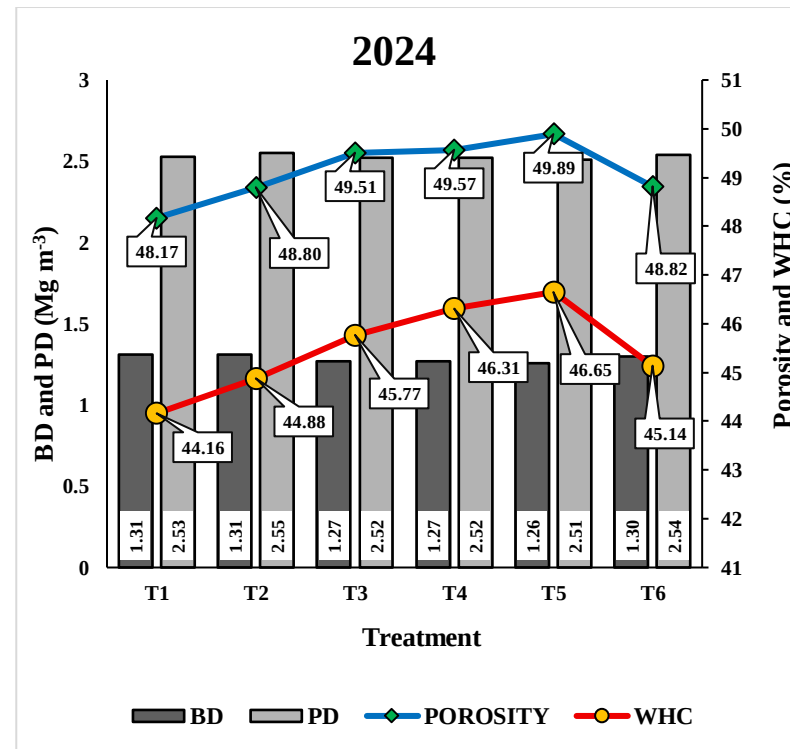
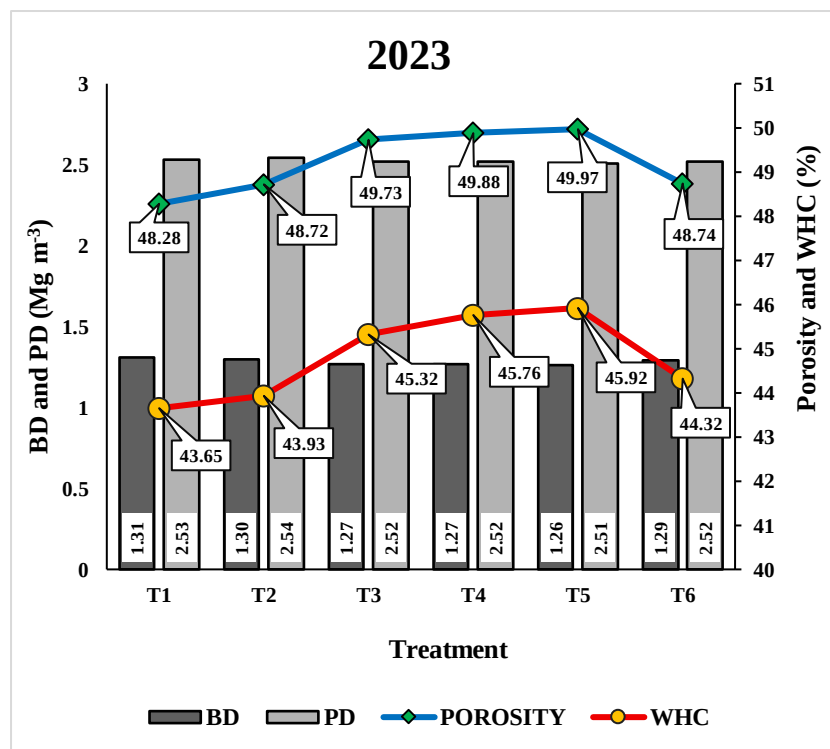


Fig 23. Soil bulk density, particle density (Mg m⁻³), porosity and water holding capacity (%) after rice harvest during 2023 and 2024 at Palampur

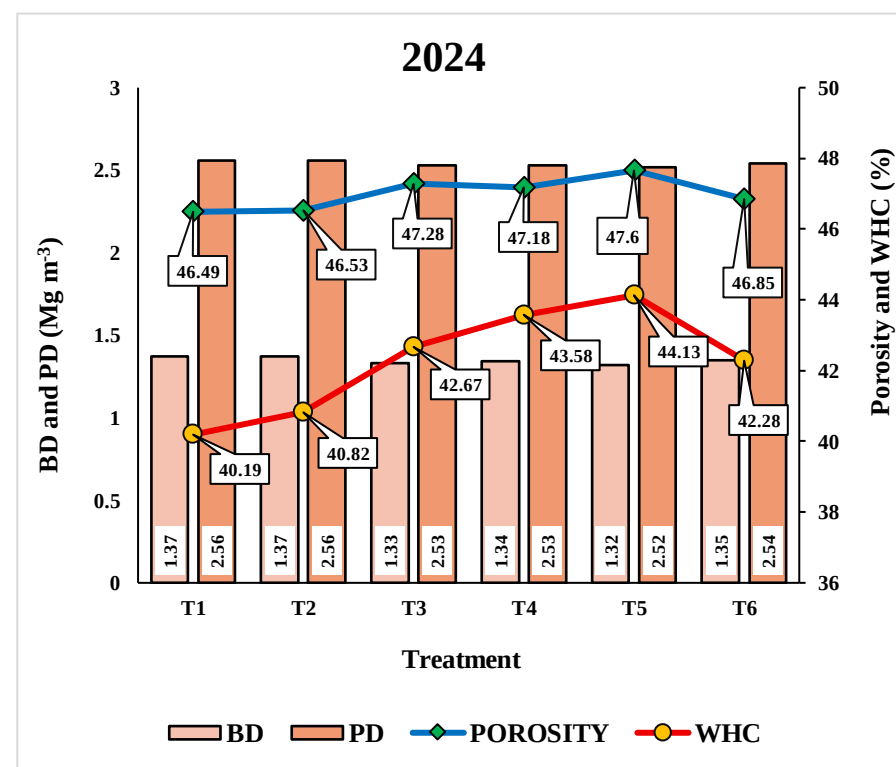
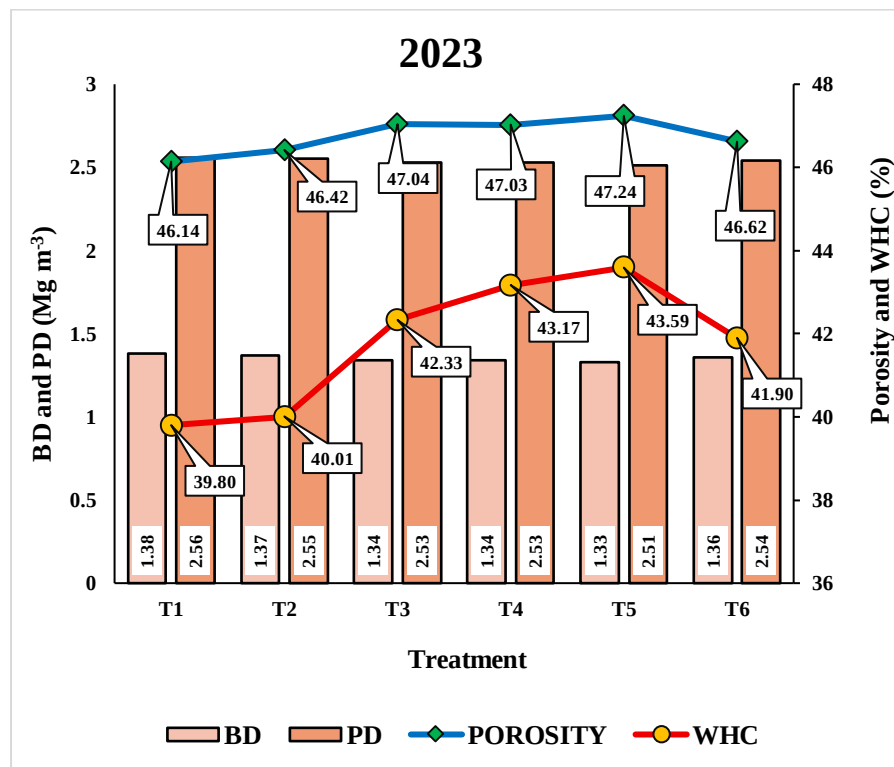


Fig 24. Soil bulk density, particle density (Mg m⁻³), porosity and water holding capacity (%) after rice harvest during 2023 and 2024 at Una

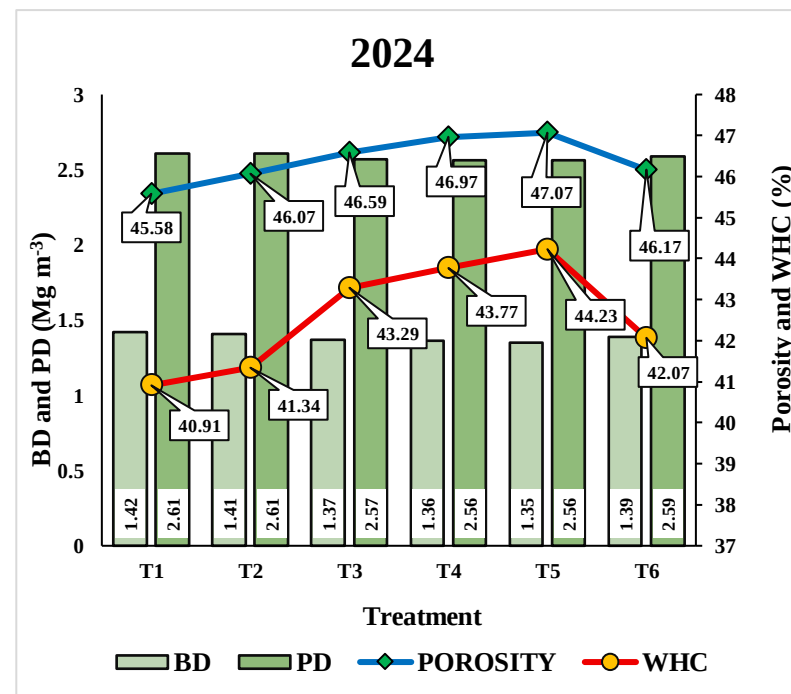
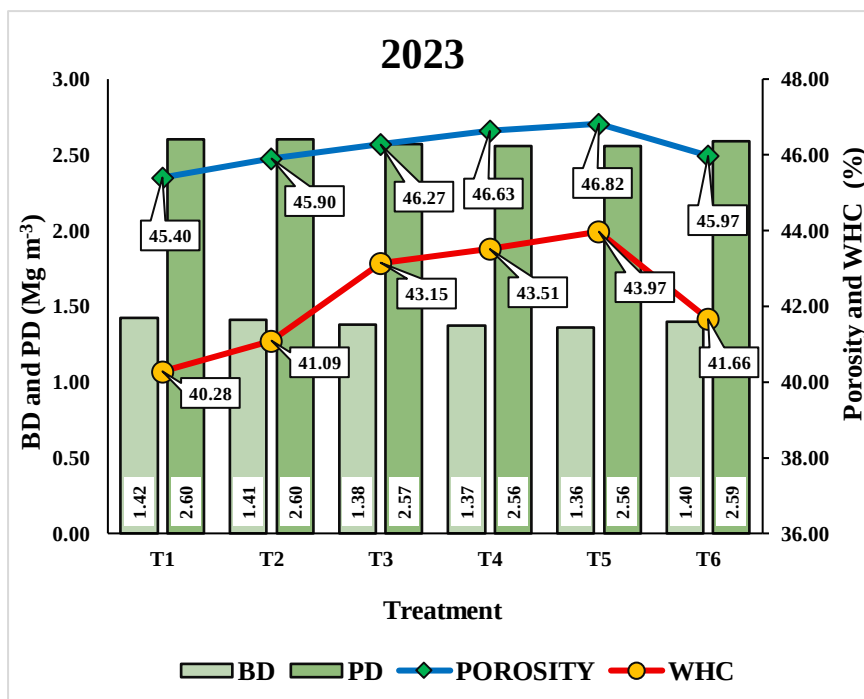


Fig 25. Soil bulk density, particle density (Mg m^{-3}), porosity and water holding capacity (%) after rice harvest during 2023 and 2024 at Dhaulakuan

9. Soil chemical properties

Soil chemical properties, particularly soil pH and soil organic carbon (SOC), exert a strong influence on nutrient availability, microbial activity, and soil–water interactions. In the present study, soil pH exhibited only slight numerical variation, whereas SOC varied significantly across rice establishment methods, seasons, and locations.

At Palampur, transplanted methods recorded comparatively higher soil pH values. Among them, T₂ registered the highest pH, with values of 5.50 in 2023, 5.55 in 2024, and 5.53 in the pooled data (Table 28; Fig. 26). This was followed by T₁, which recorded pH of 5.45, 5.52, and 5.49 during 2023, 2024, and pooled data, respectively. Slightly lower pH was observed in T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), which recorded 5.41, 5.52, and 5.45 across the corresponding seasons. The lowest pH values were associated with DSR methods, particularly with T₃, *i.e.*, 5.31, 5.37, and 5.34 in 2023, 2024, and pooled data, respectively. In contrast, SOC displayed an opposite trend and varied significantly with establishment method and season. The highest SOC was obtained under T₅ (DSR *SAVAH-134* Full Page hybrid), recording 10.47, 10.58, and 10.52 g kg⁻¹ in 2023, 2024, and pooled analysis, and was statistically comparable with other DSR treatments (T₃ and T₄). Conversely, transplanted treatments (T₁ and T₂) showed lower SOC levels, with T₁ recording the lowest values of 8.79, 8.88, and 8.83 g kg⁻¹ during 2023, 2024, and pooled data. Treatment T₆ recorded 9.63, 9.69, and 9.66 g kg⁻¹, which was significantly lower than the DSR methods but higher than the transplanted establishment methods.

At KVK Una, soil pH values showed only numerical variation across rice establishment methods (Table 29; Fig. 27). Among the treatments, T₂ recorded the highest pH, measuring 7.42 in 2023, 7.46 in 2024, and 7.44 in pooled data. This was followed by T₁, which showed pH values of 7.31, 7.37, and 7.34 during 2023, 2024, and pooled analysis, respectively. The DSR treatments exhibited slightly lower pH values, with T₃ recording pH of 7.25, 7.30, and 7.28, while T₄ and T₅ remained close with the pH values, ranging between 7.26–7.33 across seasons. Treatment T₆ also showed intermediate pH values (7.30–7.34). In contrast, SOC varied significantly across treatments and followed an opposite trend to pH. The highest SOC content was recorded under T₅, which measured 8.94, 9.00, and 8.97 g kg⁻¹ during 2023, 2024, and pooled data, respectively. These values were statistically comparable with other DSR-based treatments (T₃ and T₄), which also exhibited higher SOC levels (8.69–8.87 g kg⁻¹). Conversely, transplanted methods (T₁ and T₂) recorded the lowest SOC, with T₁ showing 7.36, 7.41, and

7.38 g kg⁻¹ in 2023, 2024, and pooled data. Treatment T₆, although lower than the DSR treatments, exhibited SOC values (8.15, 8.18, and 8.17 g kg⁻¹) that were still higher than those recorded under transplanted treatments.

At HAREC, Dhaulakuan, soil pH exhibited only marginal numerical differences among rice establishment methods (Table 30; Fig. 28). Among the transplanted treatments, T₂ consistently recorded the highest soil pH, with values of 6.84 in 2023, 6.89 in 2024, and 6.87 in pooled analysis. This was closely followed by T₁, which maintained pH values of 6.81, 6.85, and 6.83 in 2023, 2024, and pooled data, respectively. Slightly lower pH values were associated with the DSR treatments, wherein the lowest values (6.64, 6.67, and 6.66 across the corresponding years and pooled data) were recorded with T₃. Treatments T₄ and T₅ recorded intermediate pH levels among DSR treatments, while T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) exhibited moderately higher values (6.76, 6.79, and 6.79 in 2023, 2024, and pooled data, respectively).

Table 28 – Soil pH and organic carbon after rice harvest during 2023 & 2024 at Palampur

Treatments	2023		2024		Pooled	
	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)
T ₁	5.45	8.79	5.52	8.88	5.49	8.83
T ₂	5.50	8.96	5.55	9.09	5.53	9.03
T ₃	5.31	10.17	5.37	10.24	5.34	10.21
T ₄	5.35	10.27	5.40	10.32	5.38	10.29
T ₅	5.37	10.47	5.44	10.58	5.41	10.52
T ₆	5.41	9.63	5.52	9.69	5.45	9.66
CD (p=0.05)	-	1.09	-	1.12	-	1.08

Table 29 – Soil pH and organic carbon after rice harvest during 2023 & 2024 at Una

Treatments	2023		2024		Pooled	
	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)
T ₁	7.31	7.36	7.37	7.41	7.34	7.38
T ₂	7.42	7.57	7.46	7.61	7.44	7.59
T ₃	7.25	8.69	7.30	8.74	7.28	8.72
T ₄	7.26	8.81	7.31	8.87	7.28	8.84
T ₅	7.29	8.94	7.33	9.00	7.31	8.97
T ₆	7.30	8.15	7.34	8.18	7.32	8.17
CD (p=0.05)	-	0.91	-	0.81	-	0.50

Table 30 – Soil pH and organic carbon after rice harvest during 2023 & 2024 at Dhaulakuan

Treatments	2023		2024		Pooled	
	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)	pH	SOC (g kg ⁻¹)
T₁	6.81	8.08	6.85	8.15	6.83	8.11
T₂	6.84	8.18	6.89	8.25	6.87	8.21
T₃	6.64	9.44	6.67	9.51	6.66	9.48
T₄	6.69	9.61	6.73	9.67	6.71	9.64
T₅	6.74	9.83	6.74	9.89	6.74	9.86
T₆	6.76	8.76	6.79	8.82	6.79	8.79
CD (<i>p</i>=0.05)	-	1.02	-	1.10	-	0.93

In contrast, SOC differed significantly across establishment methods and exhibited an inverse trend relative to soil pH. The highest SOC content was recorded under T₅, which measured 9.83 g kg⁻¹ in 2023, 9.89 g kg⁻¹ in 2024, and 9.86 g kg⁻¹ in pooled data. These values were statistically comparable with those of T₄ and T₃, which also demonstrated elevated SOC levels (9.44–9.67 g kg⁻¹). Conversely, transplanted treatments (T₁ and T₂) registered comparatively lower SOC, with T₁ showing 8.08, 8.15, and 8.11 g kg⁻¹ and T₂ recording 8.18, 8.25, and 8.21 g kg⁻¹ across the respective seasons. Furthermore, T₆ maintained intermediate SOC levels (8.76, 8.82, and 8.79 g kg⁻¹ in 2023, 2024, and pooled data), exceeding those of the transplanted methods but remaining significantly lower than the DSR treatments.

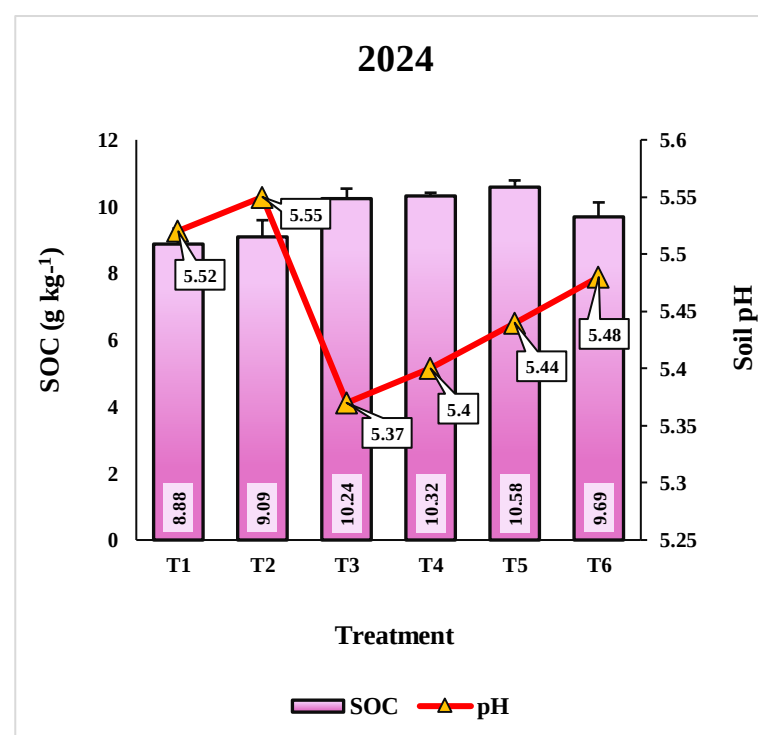
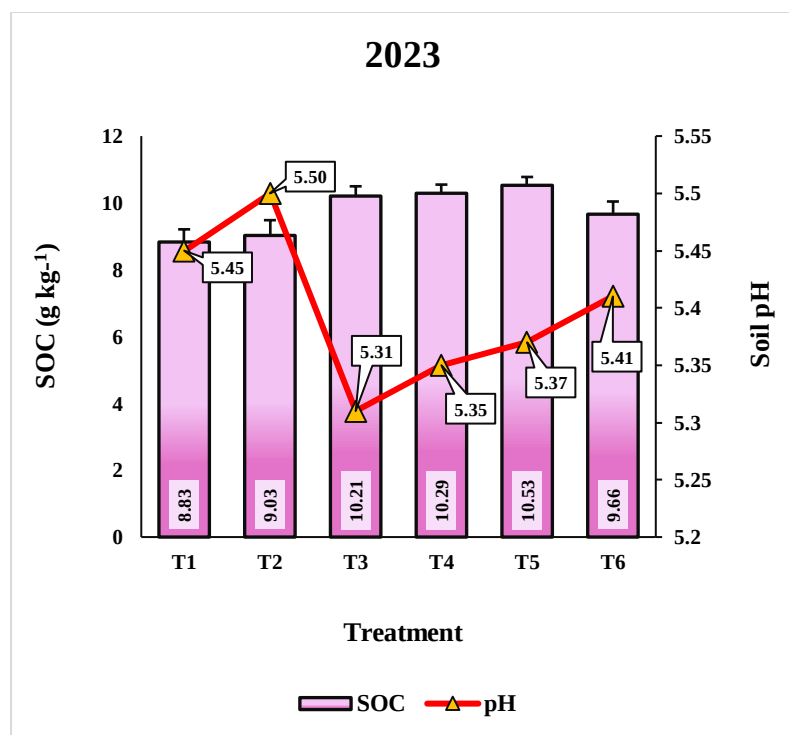


Fig 26. Soil pH and organic carbon (g kg⁻¹) after rice harvest during 2023 and 2024 at Palampur

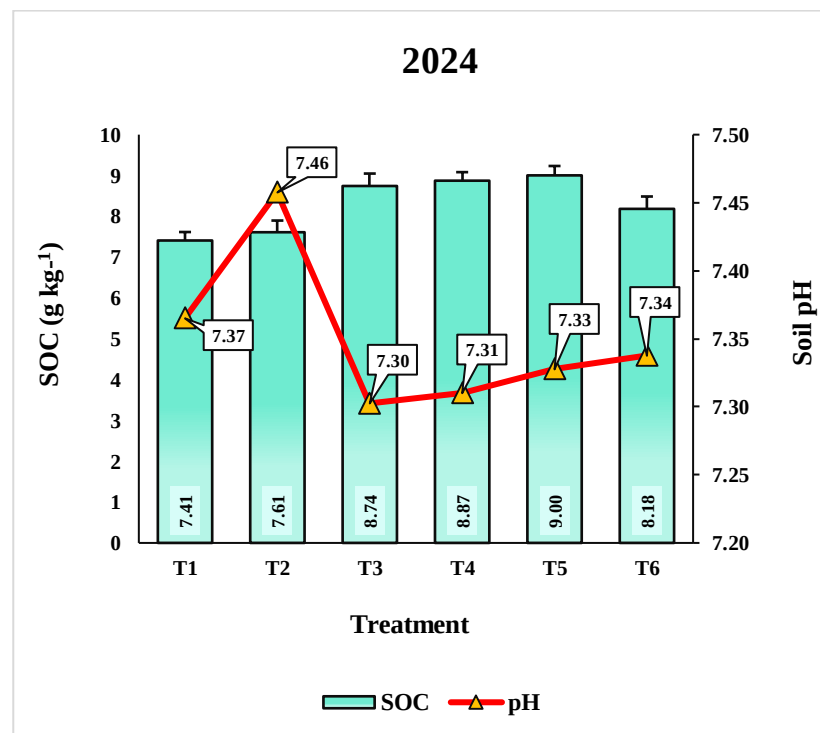
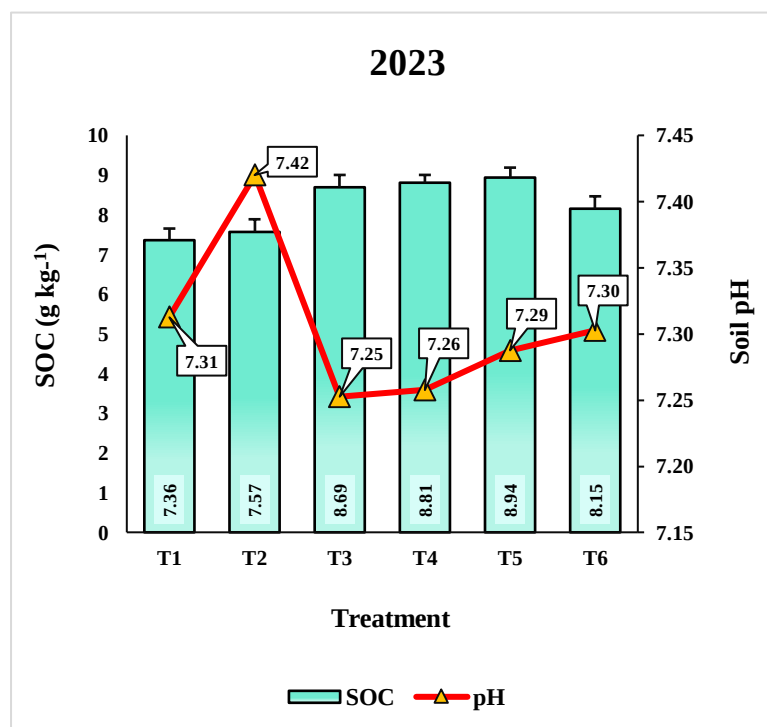


Fig 27. Soil pH and organic carbon (g kg⁻¹) after rice harvest during 2023 and 2024 at Una

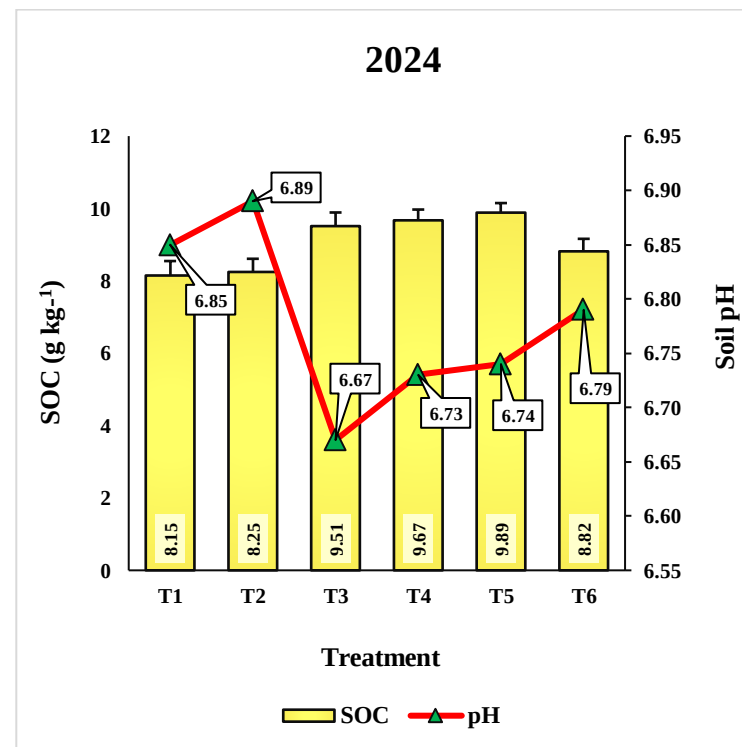
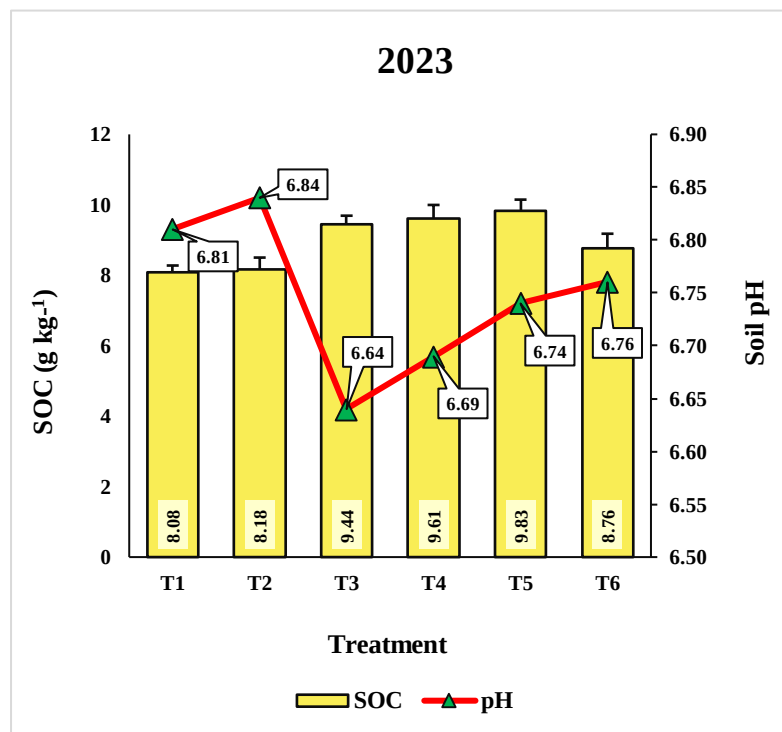


Fig 28. Soil pH and organic carbon (g kg⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

Soil available nutrients

Available nutrients in soil represent the fraction of essential elements readily accessible for plant uptake and are therefore a key indicator of soil fertility and nutrient-supplying capacity. In the present study, the availability of nitrogen (N), phosphorus (P), and potassium (K) varied significantly across rice establishment methods, seasons, and locations.

At Palampur, soil available nitrogen differed significantly among treatments during both years and in pooled analysis. Treatment T₂ (PTR *SAVAH-134*) recorded the highest available nitrogen, with values of 276.1, 278.6, and 277.4 kg ha⁻¹ during 2023, 2024, and pooled data, respectively (Table 31; Fig. 29). Treatment T₁ (PTR *PR-126*) was statistically at par with T₂, registering 275.4, 276.9, and 276.2 kg Nitrogen ha⁻¹ and T₅ (DSR *SAVAH-134* Full Page hybrid) recorded 273.7, 275.3 and 274.5 kg Nitrogen ha⁻¹ during respective years and pooled data. T₅ was followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) that recorded 272.6, 273.9 and 273.3 kg ha⁻¹ of soil available nitrogen during 2023, 2024 and in pooled data, respectively. The lowest nitrogen availability was observed under T₃ (DSR *PR-126*), with values of 269.8, 271.0 and 270.4 kg ha⁻¹ in 2023, 2024 and pooled data, respectively. With respect to availability of phosphorus, no significant difference was found among various treatments. However, transplanted treatments showed numerically highest available phosphorus, wherein T₂ (PTR *SAVAH-134*) recorded 18.1, 18.9 and 18.5 kg ha⁻¹ and T₁ (PTR *PR-126*) recorded 17.8, 18.6 and 18.2 kg ha⁻¹ soil available phosphorus during 2023, 2024, and pooled data, respectively. Among DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) showed higher soil available phosphorus viz., 17.1, 18.4 and 17.7 kg ha⁻¹ during 2023, 2024, and pooled data, respectively, while the lowest availability of phosphorus in soil was recorded with T₃ (DSR *PR-126*), with values of 16.0, 16.8 and 16.4 kg ha⁻¹ in the respective years and pooled data. For potassium, transplanted treatments again showed superiority. T₂ recorded the highest available potassium (217.2, 221.8 and 219.5 kg ha⁻¹), statistically similar to T₁ (215.6, 219.4 and 217.5 kg ha⁻¹). Among DSR treatments, T₅ recorded relatively higher potassium (212.7, 217.2 and 215.0 kg ha⁻¹), which was statistically comparable with T₆ and T₄. The lowest potassium availability was observed under T₃ (207.9, 213.8 and 210.9 kg ha⁻¹).

Similarly, at KVK Una, soil nitrogen availability after rice harvest varied significantly across establishment methods during both years and in pooled analysis (Table 32; Fig. 30). T₂ (PTR *SAVAH-134*) recorded the highest nitrogen availability (265.6, 267.2 and 266.4 kg ha⁻¹ in 2023, 2024, and pooled data, respectively), statistically at par with T₁ (264.2, 265.6 and 264.9 kg ha⁻¹

¹) and T₅ (DSR *SAVAH-134* Full Page hybrid), which recorded 263.0, 264.8 and 263.9 kg ha⁻¹ soil available nitrogen. Treatment T₅ was however, found statistically at par with T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) with nitrogen availability of 262.1, 263.7 and 262.9 kg ha⁻¹) during 2023, 2024 and pooled data, respectively. The lowest nitrogen availability was consistently observed under T₃ (259.7, 260.8 and 260.3 kg ha⁻¹). With respect to soil available phosphorus, no significant differences were observed among the treatments during 2023, 2024, or in the pooled analysis, however, numerical variations were evident. Among the treatments, T₂ (PTR *SAVAH-134*) recorded the highest available phosphorus, with values of 14.1, 14.7 and 14.4 kg ha⁻¹ during 2023, 2024 and in pooled data, respectively. This was closely followed by T₁ (PTR *PR-126*), which registered 13.5, 14.0 and 13.7 kg ha⁻¹ in the respective years and pooled analysis. Among the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) showed relatively higher phosphorus availability (12.9, 13.3 and 13.1 kg ha⁻¹), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) with values of 12.7, 13.0 and 12.8 kg ha⁻¹. The lowest soil available phosphorus was recorded under T₃ (DSR *PR-126*), with 11.8, 12.1 and 12.0 kg ha⁻¹ during 2023, 2024 and pooled data, respectively. For soil available potassium, significant differences among treatments were observed in both years as well as in the pooled analysis. Treatment T₂ (PTR *SAVAH-134*) recorded the highest potassium availability of 149.7, 151.9 and 150.8 kg ha⁻¹ during 2023, 2024 and pooled data, respectively. This was statistically at par with T₁ (PTR *PR-126*), which recorded 147.6, 149.5 and 148.6 kg ha⁻¹ of soil available potassium. Among the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) showed comparatively higher potassium (145.0, 147.5 and 146.3 kg ha⁻¹), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) with 143.8, 145.8 and 144.8 kg ha⁻¹. Treatments T₄ and T₃ recorded lower potassium availability, with T₃ (DSR *PR-126*) showing the lowest available potassium of 139.6, 142.9 and 141.3 kg ha⁻¹ during 2023, 2024 and pooled analysis, respectively.

Likewise, at HAREC Dhaulakuan also, soil available nitrogen after rice harvest differed significantly among treatments during both years and in the pooled analysis (Table 33; Fig. 31). Treatment T₂ (PTR *SAVAH-134*) recorded the highest nitrogen availability of 271.5, 273.8 and 272.6 kg ha⁻¹ during 2023, 2024 and pooled data, respectively. This was statistically at par with T₁ (PTR *PR-126*), which registered 269.9, 271.7 and 270.8 kg ha⁻¹ and with T₅ (DSR *SAVAH-134* Full Page hybrid) that recorded 268.6, 270.1 and 269.4 kg ha⁻¹ soil available nitrogen. T₅ was followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) with nitrogen availability of 267.8, 269.3 and 268.5 kg ha⁻¹ during 2023, 2024 and pooled data, respectively.

The lowest nitrogen availability was observed under T₃ (DSR *PR-126*), which recorded 265.8, 266.9 and 266.4 kg ha⁻¹ in 2023, 2024 and pooled analysis, respectively. With respect to soil available phosphorus, no significant differences were observed among treatments during years or in pooled data, however, numerical differences were observed. Treatment T₂ (PTR *SAVAH-134*) recorded the highest available phosphorus (22.3, 22.7 and 22.5 kg ha⁻¹), followed closely by T₁ (PTR *PR-126*) with 21.8, 22.1 and 21.9 kg ha⁻¹ during 2023, 2024 and pooled data, respectively. Among the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) showed comparatively higher phosphorus availability (21.5, 22.1 and 21.8 kg ha⁻¹), followed by T₆ (DSR *SAVAH-134* Full Page hybrid with AFD) with 21.2, 21.9 and 21.6 kg ha⁻¹. The lowest soil available phosphorus was observed under T₃ (DSR *PR-126*), which recorded 19.6, 20.4 and 20.0 kg ha⁻¹ during 2023, 2024 and pooled analysis, respectively. In the case of soil available potassium, treatment T₂ (PTR *SAVAH-134*) recorded the highest soil available potassium of 187.8, 189.7 and 188.8 kg ha⁻¹ during 2023, 2024 and pooled data, respectively, and was statistically at par with T₁ (PTR *PR-126*), which registered 185.6, 186.9 and 186.3 kg ha⁻¹. Among the DSR treatments, T₅ recorded relatively higher potassium availability (183.2, 185.5 and 184.3 kg ha⁻¹), followed by T₆ (182.7, 184.3 and 183.5 kg ha⁻¹) and T₄ (180.4, 183.7 and 182.0 kg ha⁻¹). The lowest potassium availability was observed under T₃ (DSR *PR-126*), i.e., 179.5, 182.8 and 181.2 kg ha⁻¹ of soil potassium during 2023, 2024 and pooled data, respectively.

Table 31 – Soil available NPK after rice harvest during 2023 & 2024 at Palampur

Treatments	Nitrogen (kg ha ⁻¹)			Phosphorus (kg ha ⁻¹)			Potassium (kg ha ⁻¹)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T ₁	275.4	276.9	276.2	17.8	18.6	18.2	215.6	219.4	217.5
T ₂	276.1	278.6	277.4	18.1	18.9	18.5	217.2	221.8	219.5
T ₃	269.8	271.0	270.4	16.0	16.8	16.4	207.9	213.8	210.9
T ₄	270.7	272.6	271.7	16.3	17.1	16.7	209.5	215.2	212.3
T ₅	273.7	275.3	274.5	17.1	18.4	17.7	212.7	217.2	215.0
T ₆	272.6	273.9	273.3	17.0	17.9	17.5	211.2	216.1	213.6
CD (p=0.05)	3.4	4.3	3.0	NS	NS	NS	4.2	3.8	3.1

Table 32 – Soil available NPK after rice harvest during 2023 & 2024 at Una

Treatments	Nitrogen (kg ha ⁻¹)			Phosphorus (kg ha ⁻¹)			Potassium (kg ha ⁻¹)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T₁	264.2	265.6	264.9	13.5	14.0	13.7	147.6	149.5	148.6
T₂	265.6	267.2	266.4	14.1	14.7	14.4	149.7	151.9	150.8
T₃	259.7	260.8	260.3	11.8	12.1	12.0	139.6	142.9	141.3
T₄	260.1	262.1	261.1	12.1	12.6	12.3	141.5	144.8	143.2
T₅	263.0	264.8	263.9	12.9	13.3	13.1	145.0	147.5	146.3
T₆	262.1	263.7	262.9	12.7	13.0	12.8	143.8	145.8	144.8
CD (p=0.05)	3.1	3.4	3.1	NS	NS	NS	4.4	4.3	3.0

Table 33 – Soil available NPK after rice harvest during 2023 & 2024 at Dhaulakuan

Treatments	Nitrogen (kg ha ⁻¹)			Phosphorus (kg ha ⁻¹)			Potassium (kg ha ⁻¹)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T₁	269.9	271.7	270.8	21.8	22.1	21.9	185.6	186.9	186.3
T₂	271.5	273.8	272.6	22.3	22.7	22.5	187.8	189.7	188.8
T₃	265.8	266.9	266.4	19.6	20.4	20.0	179.5	182.8	181.2
T₄	266.9	267.4	267.2	20.1	20.8	20.4	180.4	183.7	182.0
T₅	268.6	270.1	269.4	21.5	22.1	21.8	183.2	185.5	184.3
T₆	267.8	269.3	268.5	21.2	21.9	21.6	182.7	184.3	183.5
CD (p=0.05)	3.6	4.1	3.8	NS	NS	NS	4.1	3.9	2.6

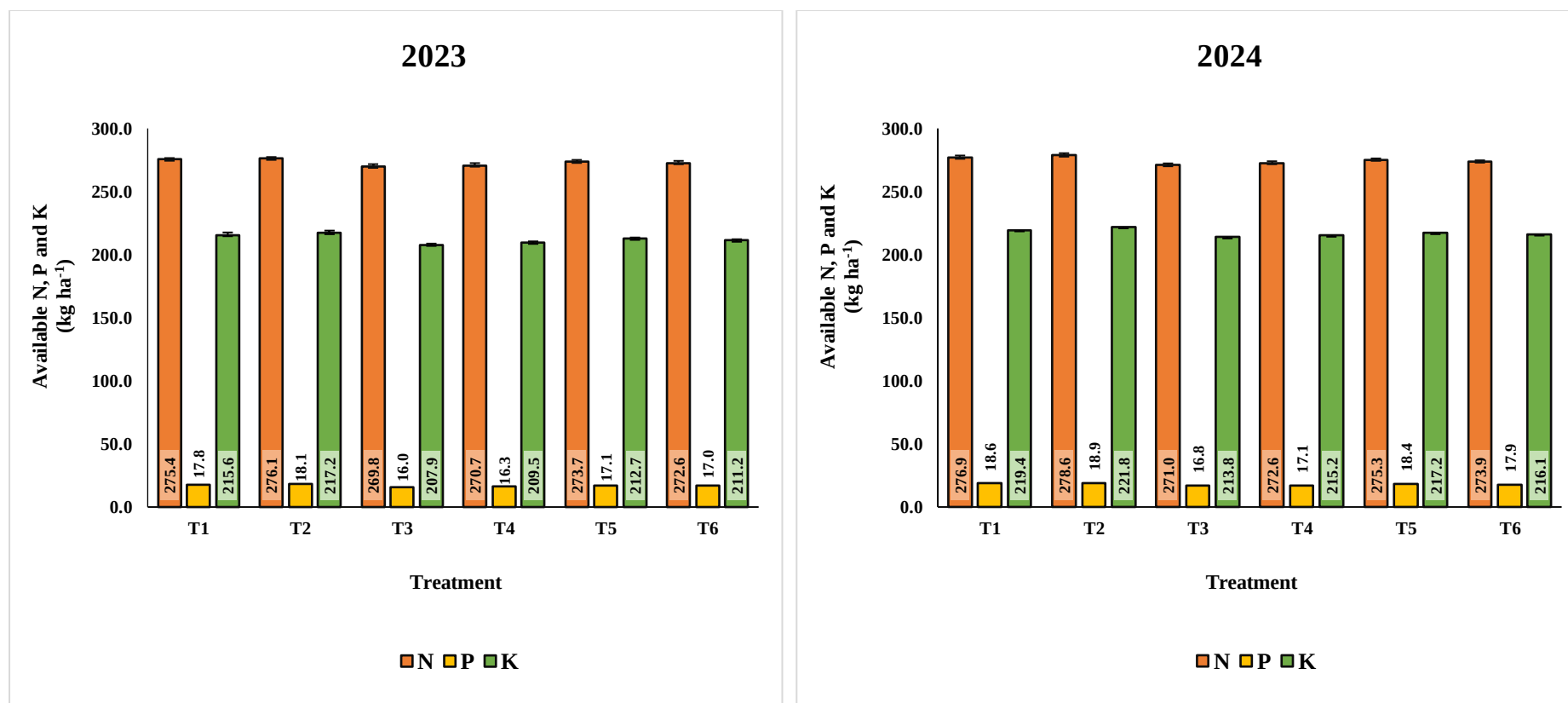


Fig 29. Soil NPK (kg ha⁻¹) after rice harvest during 2023 and 2024 at Palampur

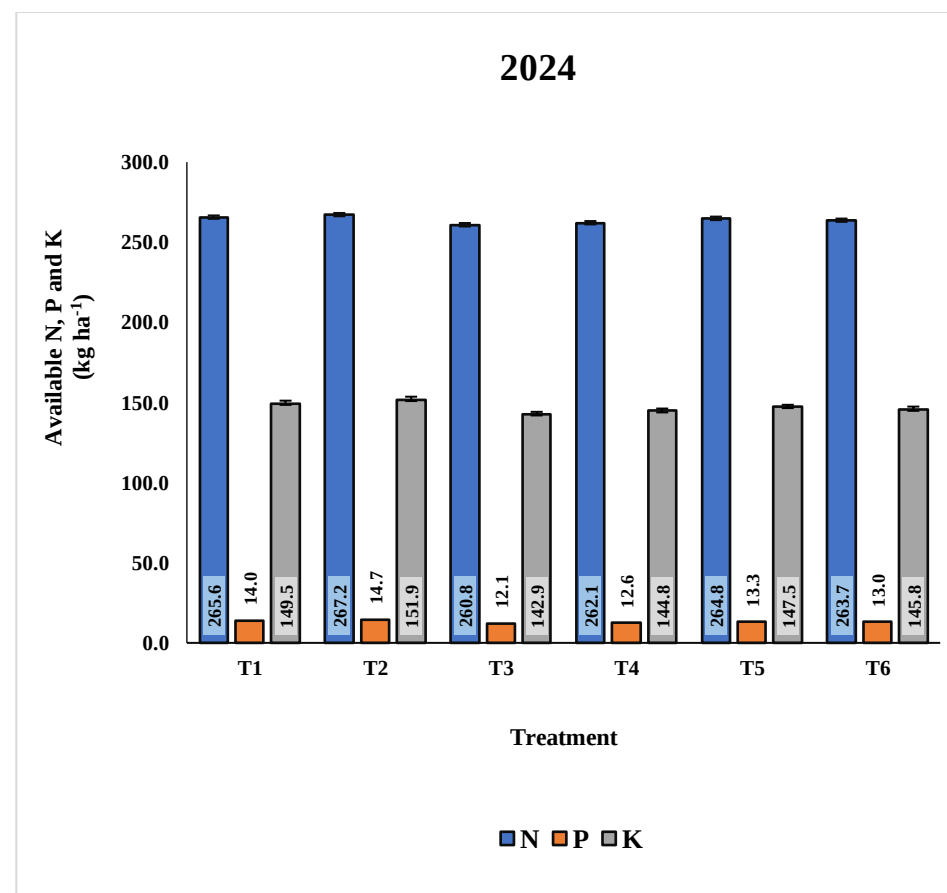
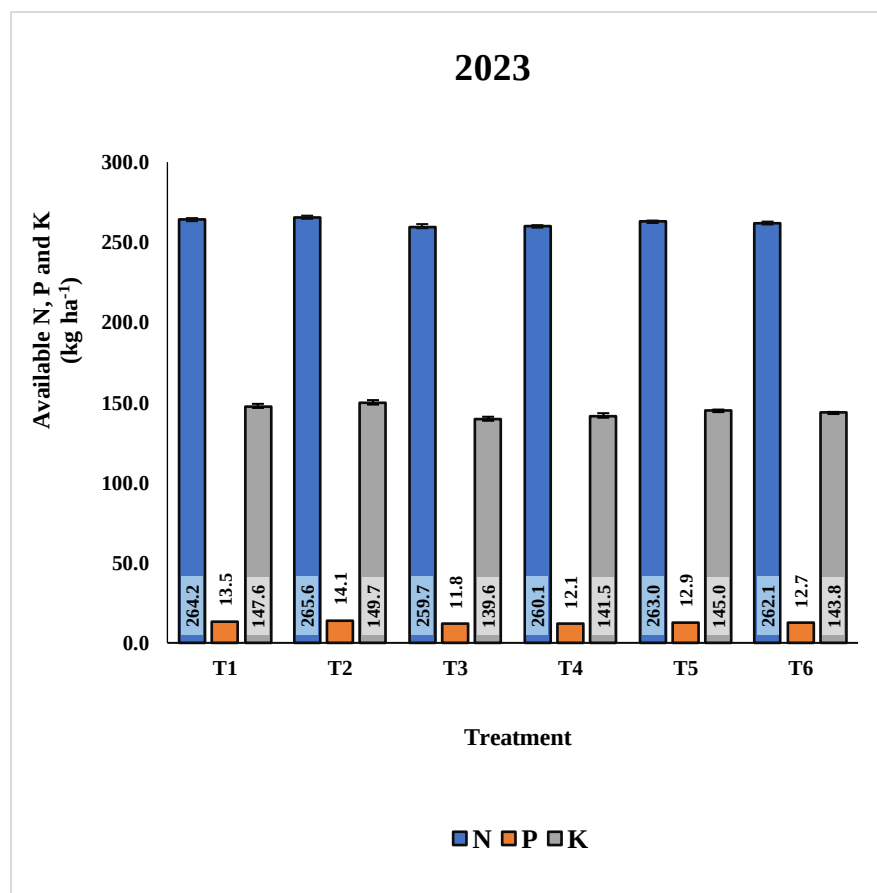


Fig 30. Soil NPK (kg ha⁻¹) after rice harvest during 2023 and 2024 at Una

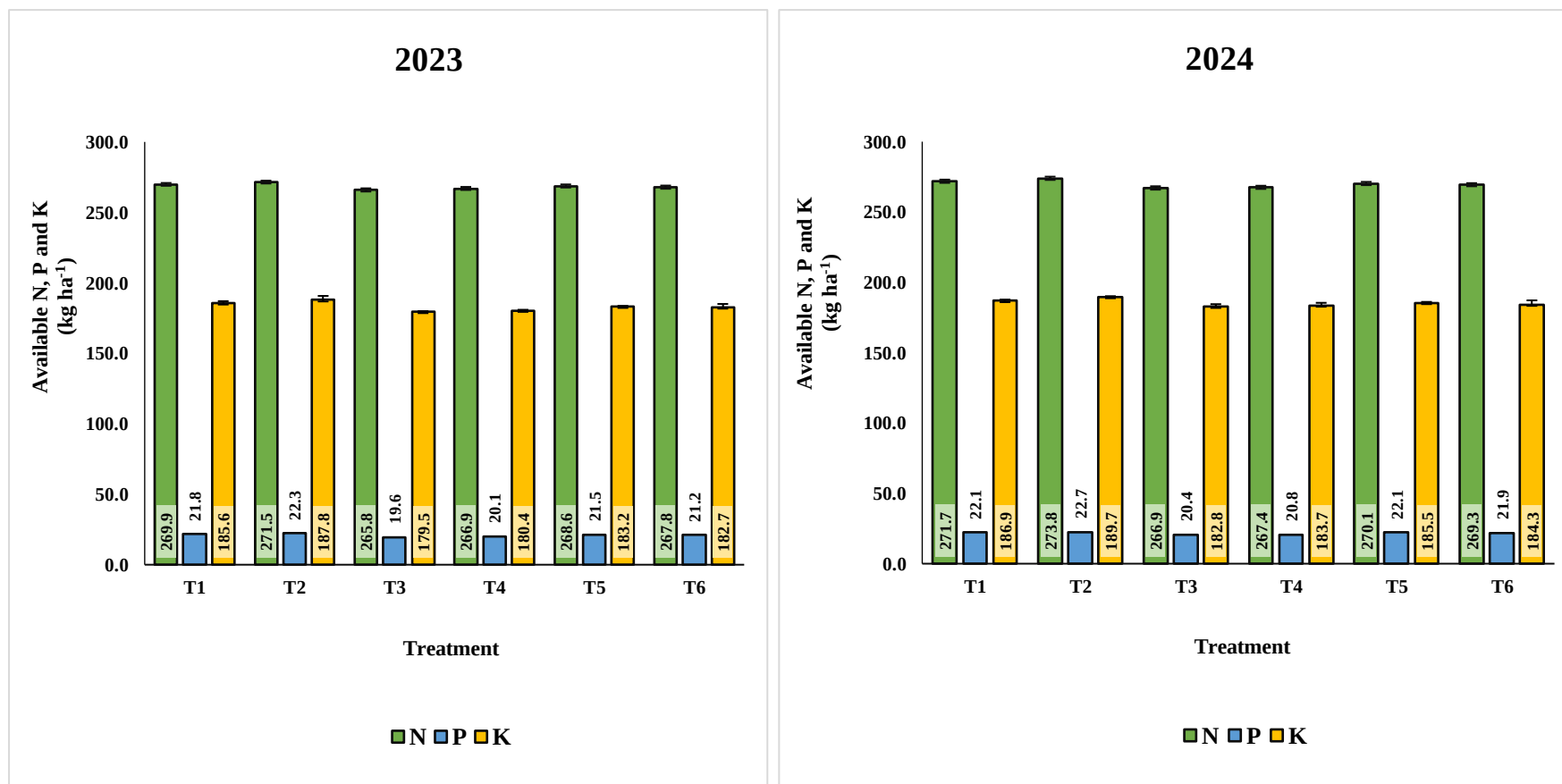


Fig 31. Soil NPK (kg ha⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

Soil microbiological properties

Soil microbiological properties, similar to physico-chemical properties, are integral to soil functioning, as they regulate biological activity and nutrient transformations within the soil system. Microbial biomass carbon (MBC) represents the living component of soil organic matter and serves as a sensitive indicator of changes in soil management, while dehydrogenase activity reflects overall microbial oxidative activity and metabolic intensity.

In the present study, both MBC and dehydrogenase activity varied significantly across rice establishment methods, seasons, and locations, indicating differential microbial responses to variations in soil moisture regimes, organic carbon availability, and the degree of soil disturbance.

At Palampur, direct-seeded rice (DSR) treatments showed significant superiority over transplanted rice (PTR) treatments in terms of MBC and dehydrogenase activity (Table 34; Fig. 32). Among the DSR establishment methods, the highest MBC (225.8, 228.7, and 227.2 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) and dehydrogenase activity (4.5, 4.9, and 4.7 µg TPF g⁻¹ h⁻¹ in 2023, 2024, and pooled data, respectively) were recorded under T₅ (DSR *SAVAH-134* Full Page hybrid). However, T₅ was found statistically at par with T₆ (DSR *SAVAH-134* Full Page hybrid with AFD), T₄ (DSR *SAVAH-134*), and T₃ (DSR *PR-126*) across both years and pooled data. In contrast, transplanted rice establishment methods recorded lower MBC and dehydrogenase activity. T₁ (PTR *PR-126*) exhibited the lowest MBC (212.1, 215.7, and 213.9 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) and dehydrogenase activity (2.1, 2.3, and 2.2 µg TPF g⁻¹ h⁻¹ in 2023, 2024, and pooled data, respectively). T₂ (PTR *SAVAH-134*) recorded slightly higher MBC (213.6, 216.1, and 214.9 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) and dehydrogenase activity (2.2, 2.5, and 2.3 µg TPF g⁻¹ h⁻¹ in 2023, 2024, and pooled data, respectively), but remained statistically at par with T₁.

At KVK Una, MBC and dehydrogenase activity also exhibited significant differences among rice establishment methods during both years and in pooled analysis (Table 35; Fig. 33). The DSR treatments consistently recorded higher MBC and dehydrogenase activity compared to transplanted methods. Among the DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) registered the maximum MBC (207.0, 209.7, and 208.4 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) along with the highest dehydrogenase activity (2.1, 2.3, and 2.2 µg TPF g⁻¹ h⁻¹ during the corresponding periods). Treatment T₅ was statistically comparable with T₆, T₄, and T₃ across both years and pooled data. In contrast, transplanted rice treatments recorded

relatively lower microbiological activity. T₁ (PTR *PR-126*) exhibited the lowest MBC values (193.2, 196.6, and 194.9 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) along with the minimum dehydrogenase activity (1.2, 1.3, and 1.3 µg TPF g⁻¹ h⁻¹). T₂ (PTR *SAVAH-134*) showed marginally higher MBC (195.5, 199.4, and 197.4 mg kg⁻¹) and dehydrogenase activity (1.3, 1.4, and 1.4 µg TPF g⁻¹ h⁻¹ in 2023, 2024, and pooled data, respectively), but remained statistically at par with T₁.

At HAREC Dhaulakuan, MBC and dehydrogenase activity varied significantly among rice establishment methods during both years and in pooled analysis (Table 36; Fig. 34). The DSR treatments consistently exhibited higher microbial activity compared to transplanted rice. Among the DSR establishment methods, T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the highest MBC values (220.7, 223.0, and 221.8 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) along with the maximum dehydrogenase activity (5.0, 5.1, and 5.0 µg TPF g⁻¹ h⁻¹ during the corresponding periods). Treatment T₅ remained statistically at par with T₆, T₄, and T₃ across both years. In contrast, transplanted rice treatments showed comparatively lower microbial activity. T₁ (PTR *PR-126*) recorded the lowest MBC values (209.3, 211.3, and 210.3 mg kg⁻¹ in 2023, 2024, and pooled data, respectively) with corresponding dehydrogenase activity (2.5, 2.6, and 2.5 µg TPF g⁻¹ h⁻¹). T₂ (PTR *SAVAH-134*) exhibited slightly higher MBC (211.1, 214.4, and 212.7 mg kg⁻¹) and dehydrogenase activity (2.6 µg TPF g⁻¹ h⁻¹ in pooled data), but remained statistically comparable with T₁.

Table 34 – Soil microbial biomass carbon and dehydrogenase activity after rice harvest during 2023 & 2024 at Palampur

Treatments	2023		2024		Pooled	
	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)
T ₁	212.1	2.1	215.7	2.3	213.9	2.2
T ₂	213.6	2.2	216.1	2.5	214.9	2.3
T ₃	217.8	4.2	220.2	4.6	219.0	4.4
T ₄	220.5	4.3	222.4	4.8	221.4	4.6
T ₅	225.8	4.5	228.7	4.9	227.2	4.7
T ₆	223.0	3.0	225.3	3.2	224.1	3.1
CD (p=0.05)	8.4	0.4	8.5	0.4	5.0	0.3

Table 35 – Soil microbial biomass carbon and dehydrogenase activity after rice harvest during 2023 & 2024 at Una

Treatments	2023		2024		Pooled	
	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)
T₁	193.2	1.2	196.6	1.3	194.9	1.3
T₂	195.5	1.3	199.4	1.4	197.4	1.4
T₃	201.1	1.8	202.8	1.9	201.9	1.9
T₄	203.5	2.1	205.7	2.2	204.6	2.1
T₅	207.0	2.1	209.7	2.3	208.4	2.2
T₆	204.7	1.4	208.9	1.6	206.8	1.5
CD (p=0.05)	6.1	0.3	7.2	0.4	3.6	0.2

Table 36 – Soil microbial biomass carbon and dehydrogenase activity after rice harvest during 2023 & 2024 at Dhaulakuan

Treatments	2023		2024		Pooled	
	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)	MBC (mg kg ⁻¹)	DHA (µg TPF g ⁻¹ h ⁻¹)
T₁	209.3	2.5	211.3	2.6	210.3	2.5
T₂	211.1	2.6	214.4	2.6	212.7	2.6
T₃	215.7	4.7	217.3	4.9	216.5	4.8
T₄	217.9	4.8	218.6	5.0	218.3	4.9
T₅	220.7	5.0	223.0	5.1	221.8	5.0
T₆	216.8	3.1	218.5	3.4	217.6	3.2
CD (p=0.05)	5.9	0.4	5.7	0.4	4.2	0.3

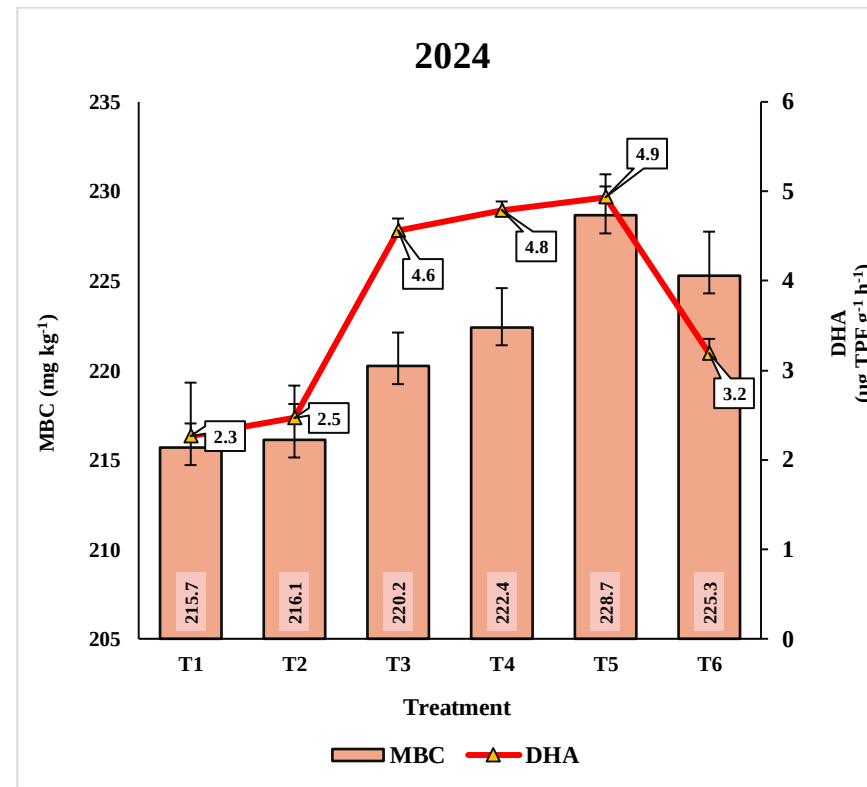
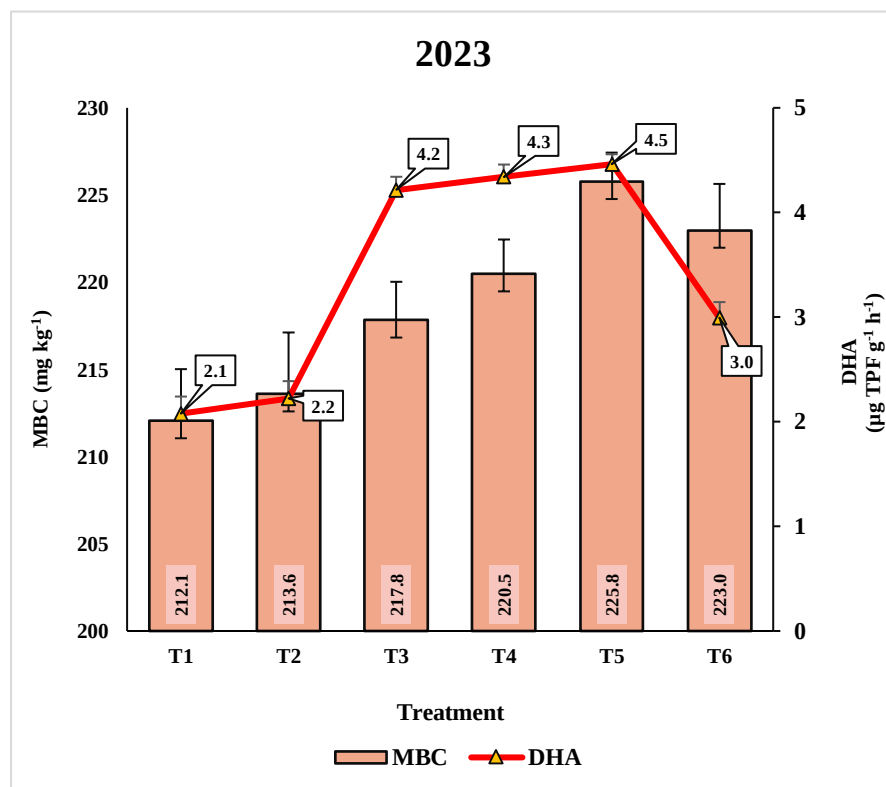


Fig 32. Soil microbial biomass carbon (mg kg⁻¹) and dehydrogenase activity (μg TPF g⁻¹ h⁻¹) after rice harvest during 2023 and 2024 at Palampur

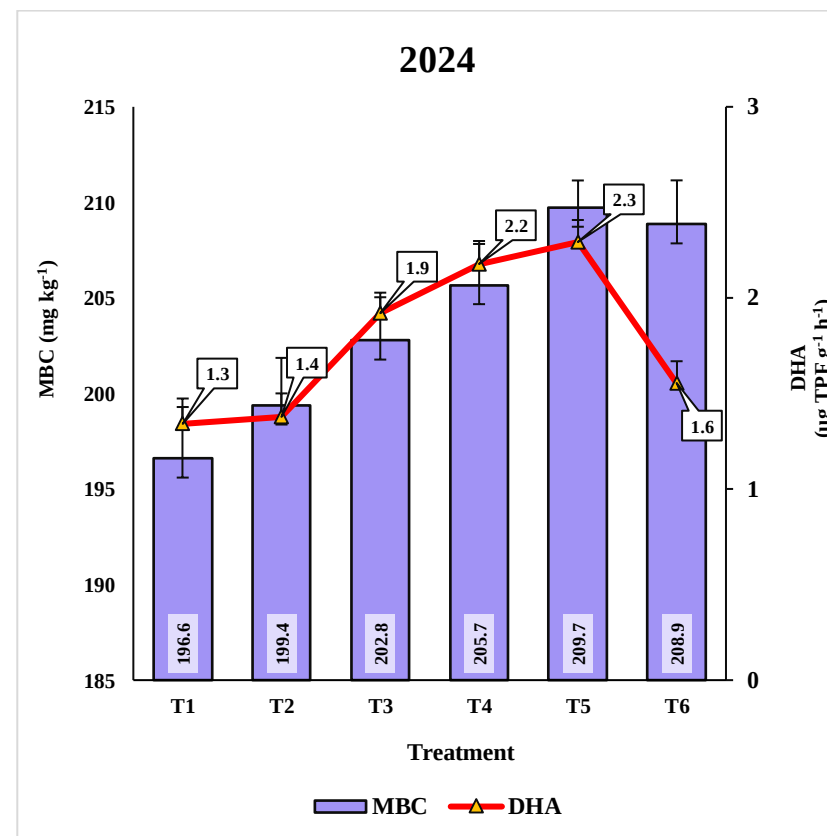
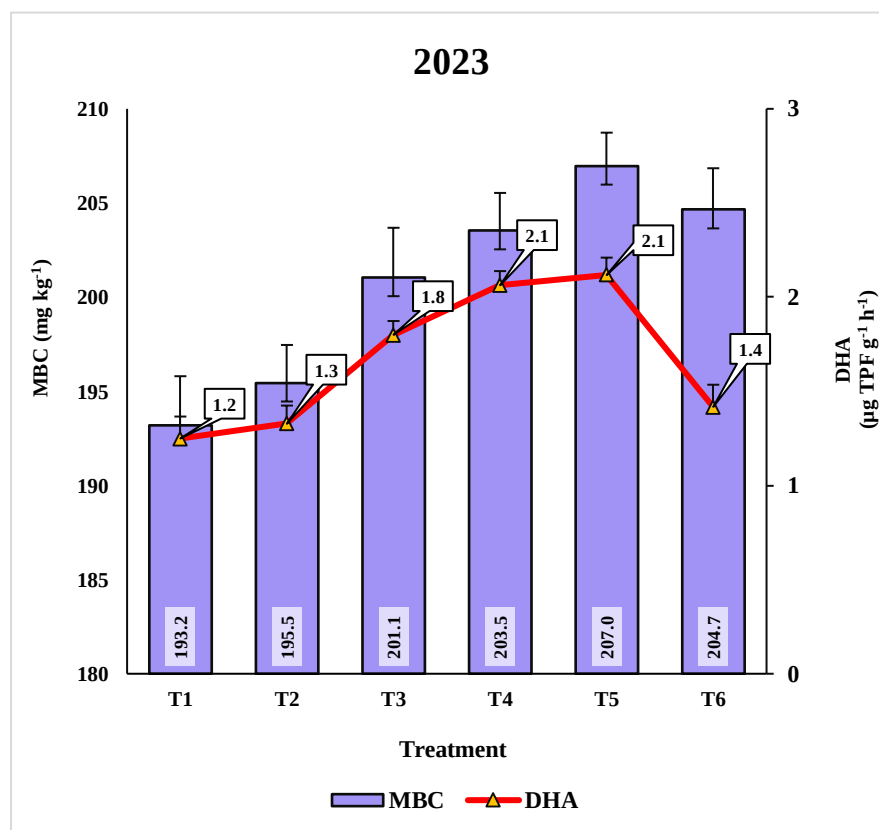


Fig 33. Soil microbial biomass carbon (mg kg⁻¹) and dehydrogenase activity (μg TPF g⁻¹ h⁻¹) after rice harvest during 2023 and 2024 at Una

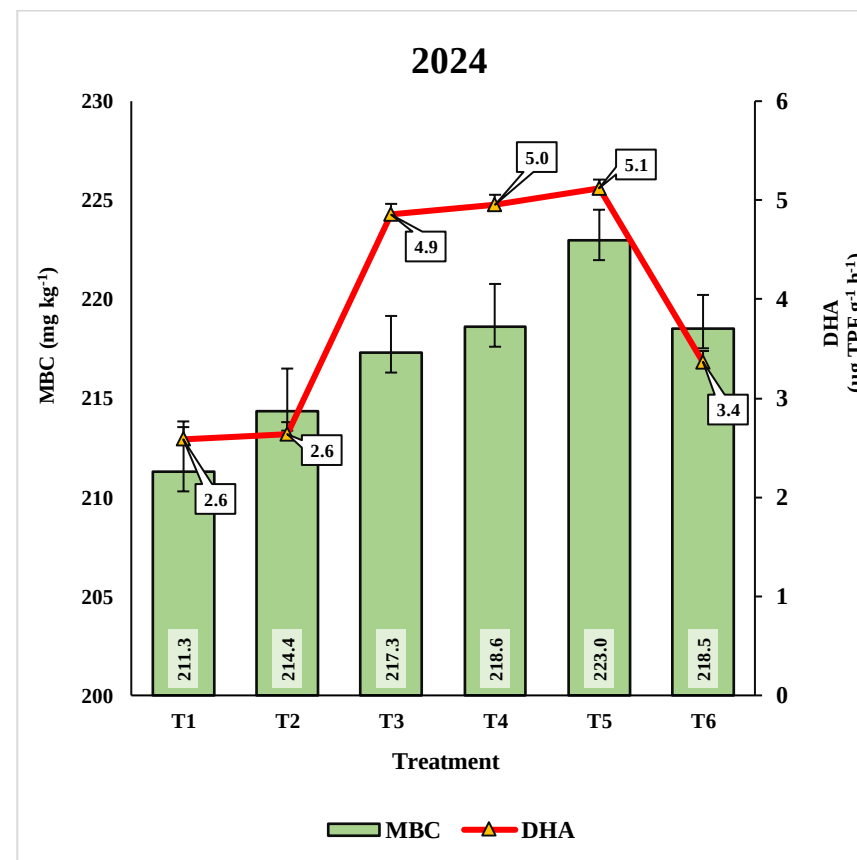
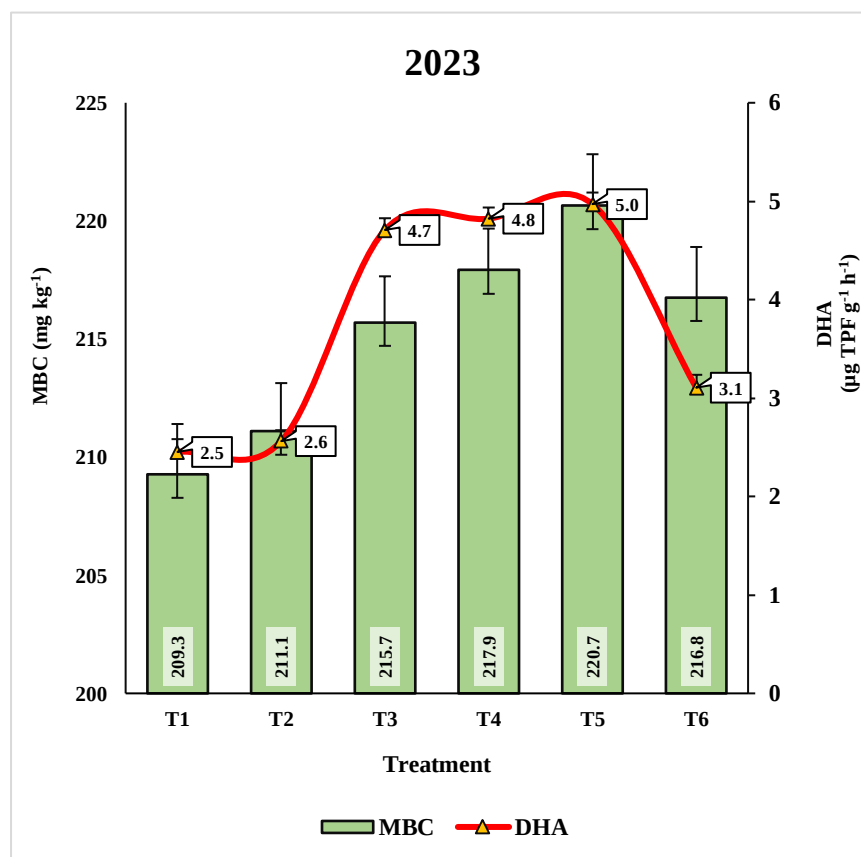


Fig 34. Soil microbial biomass carbon (mg kg⁻¹) and dehydrogenase activity (μg TPF g⁻¹ h⁻¹) after rice harvest during 2023 and 2024 at Dhaulakuan

SUMMARY

- Across all three locations (Palampur, Una and Dhaulakuan) and seasons, puddled transplanted rice (PTR) treatments consistently recorded the highest grain, straw and biological yield compared to direct seeded rice (DSR) treatments.
- Among transplanted treatments, T₂ (PTR *SAVAH-134* hybrid) produced the maximum grain yield, although it remained statistically at par with T₁ (PTR *PR-126*), indicating the yield advantage of the hybrid over the popular variety under puddled conditions.
- Within the DSR system, T₅ (DSR *SAVAH-134* Full Page hybrid) emerged as the most productive treatment, recording significantly higher grain, straw and biological yield compared to other DSR treatments across locations and years.
- The grain yield advantage of T₅ over other DSR treatments (T₃, T₄ and T₆) clearly demonstrated the superiority of the *SAVAH-134* Full Page hybrid under direct seeding, irrespective of agro-climatic location.
- Alternate wetting and drying (T₆) resulted in comparatively lower grain yield than T₅, indicating potential reductions attributed to intermittent moisture stress under AFD conditions.
- T₃ (DSR *PR-126*) consistently recorded the lowest grain, straw and biological yield across all the locations, years and pooled data, highlighting the poor adaptability of the *PR-126* variety under DSR conditions.
- Overall, while PTR ensured maximum productivity, DSR with *SAVAH-134* Full Page hybrid (T₅) provided a viable compromise between yield performance and resource-efficient management, especially in water-limited environments.

Methane (CH₄) emissions

- Methane emissions were significantly higher under puddled transplanted rice (T₁ and T₂) across all locations, confirming PTR as a major contributor to CH₄ emissions.
- **T₅ (DSR *SAVAH-134* Full Page hybrid) consistently recorded the lowest CH₄ emissions, achieving nearly 90 per cent reduction compared to transplanted treatments at all locations and in pooled analysis.**
- **Among DSR treatments, T₅ emitted significantly lower CH₄ flux than AFD-based DSR (T₆), indicating that continuous aerobic soil conditions under T₅ effectively suppressed methanogenesis.**
- Although AFD (T₆) substantially reduced CH₄ emissions compared to PTR, its emissions remained higher than T₅ due to periodic anaerobic conditions.

- Pooled analysis across locations also confirmed that DSR systems, particularly T₅, was highly effective in mitigating methane emissions from rice ecosystems.

Carbon dioxide (CO₂) emissions

- Highest CO₂ flux was consistently recorded under T₆ (DSR with AFD) across all locations, indicating enhanced soil respiration due to repeated wetting – drying cycles.
- All DSR treatments (T₃, T₄ and T₅) recorded slightly lower CO₂ emissions than T₆, though differences among them were marginal.
- Transplanted rice treatments (T₁ and T₂) recorded significantly lower CO₂ emissions compared to all the DSR treatments, likely due to suppressed soil respiration under prolonged anaerobic conditions.
- Location-pooled data clearly indicated that AFD-based DSR increased CO₂ emissions, whereas PTR systems minimized CO₂ flux despite higher CH₄ emissions.

Nitrous oxide (N₂O) emissions

- T₆ (DSR with AFD) consistently recorded the highest N₂O emissions across locations, years and pooled data, confirming AFD as a major driver of N₂O release due to frequent aerobic – anaerobic transitions.
- Transplanted treatments (T₁ and T₂) emitted moderate N₂O fluxes, significantly lower than T₆ but higher than DSR treatments without AFD.
- Among all the treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the lowest N₂O emissions, indicating stable soil moisture conditions and reduced nitrification – denitrification losses.
- Within the DSR system, T₅ consistently outperformed T₃ and T₄, demonstrating the combined effect of variety and establishment method in reducing N₂O emissions.
- Pooled analysis across locations confirmed that DSR without AFD (especially T₅) offers the maximum mitigation potential for N₂O emissions in rice systems.

Carbon footprints (kg CO₂ eq. kg⁻¹ grain)

- Across all locations, DSR *PR-126* (T₃) recorded the highest carbon footprint, indicating greater emission intensity due to comparatively lower grain yields under this treatment.
- Transplanted rice systems (T₁ *i.e.*, PTR *PR-126* and T₂ *i.e.*, PTR *SAVAH-134*), though associated with higher absolute emissions, generally exhibited lower carbon footprints than T₃ because higher grain yields diluted emissions on a per-unit yield basis.
- **At Palampur, Una and Dhaulakuan, DSR *SAVAH-134* Full Page hybrid (T₅) resulted in the lowest carbon footprints, demonstrating superior emission efficiency per unit grain produced.**

- The AFD-based DSR hybrid treatment (T₆) also reduced carbon footprints relative to transplanted systems at all locations, though values remained marginally higher than treatment T₅.
- Pooled analysis across locations also showed that DSR rice establishment methods, particularly T₅, offer the most climate-efficient option when emissions are expressed relative to grain yield.

Global warming potential (kg CO₂ eq. ha⁻¹)

- Global warming potential varied significantly with establishment method, location and season, reflecting differences in cumulative greenhouse gas emissions per unit area.
- Across all locations, transplanted rice systems (T₁ and T₂) recorded the highest GWP, underscoring the strong contribution of continuous flooding to methane emissions.
- All DSR treatments substantially reduced GWP compared to transplanted rice, confirming the mitigation potential of direct seeding.
- Among DSR treatments, varietal DSR (T₃ and T₄) showed moderate reductions in GWP, whereas hybrid-based DSR systems (T₅ and T₆) achieved markedly lower values.
- **DSR SAVAH-134 Full Page hybrid (T₅) consistently recorded the lowest GWP at Palampur, Una and Dhaulakuan across years and pooled data.**
- Pooled data across all locations revealed that T₅ maintained the minimum GWP, establishing it as the most effective treatment for reducing area-scaled greenhouse gas emissions.
- Overall, the results demonstrated that DSR with high-yielding hybrids, particularly without continuous flooding, offer the greatest mitigation of global warming potential while sustaining productivity.

Carbon credits (tCO₂e ha⁻¹)

- **Across all three locations and both years, T₅ (DSR SAVAH-134 Full Page hybrid) consistently recorded the highest carbon credits, confirming its superior capacity to mitigate greenhouse gas emissions relative to both transplanted and other direct-seeded systems.**
- When T₁ (PTR *PR-126*) was taken as the baseline, carbon credit gains clearly highlighted the advantage of DSR hybrid-based systems, with T₅ outperforming all other treatments at Palampur, Una and Dhaulakuan.
- The AFD-based hybrid treatment T₆ consistently recorded the lowest carbon credits among DSR treatments, indicating that although AFD reduced GWP compared to transplanted rice, its mitigation potential remained inferior to non-AFD DSR hybrid (T₅).

- A similar trend was observed when T₂ (PTR *SAVAH-134*) was considered as the baseline, further reinforcing that DSR *SAVAH-134* Full Page hybrid (T₅) delivers the highest and most stable carbon credit gains across environments.
- **Location-wise consistency of T₅ across Palampur, Una and Dhaulakuan indicates that its mitigation advantage is** environmentally stable and transferable across agro-climatic conditions.
- **Overall, the study demonstrated that** direct-seeded rice with high-yielding hybrids, particularly T₅, maximizes carbon credit generation, **thereby offering strong potential for inclusion in climate-smart agriculture and carbon trading or incentive-based mitigation frameworks.**

Water productivity (kg m⁻³)

- Water productivity (kg m⁻³) varied significantly with rice establishment method, season and location, reflecting differences in both yield performance and water use efficiency.
- **Across all three locations and years, T₅ (DSR *SAVAH-134* Full Page hybrid) consistently recorded the highest water productivity, indicating superior utilization of applied water.**
- Hybrid-based DSR treatments (T₅ and T₆) generally outperformed transplanted systems and varietal DSR in terms of water productivity, particularly under pooled analysis.
- Transplanted treatments (T₁ and T₂) and DSR *SAVAH-134* (T₄) showed intermediate water productivity and were often statistically at par with each other.
- DSR *PR-126* (T₃) consistently recorded the lowest water productivity across locations and years, highlighting inefficient water use relative to yield.
- The consistent superiority of T₅ across Palampur, Una and Dhaulakuan confirmed that direct-seeded rice with high-yielding hybrids markedly enhances water-use efficiency.
- Overall, the results establish DSR *SAVAH-134* Full Page hybrid (T₅) as the most water-efficient rice establishment method under diverse agro-climatic conditions.

Nutrient uptake (kg ha⁻¹)

- Nutrient uptake (N, P and K) varied significantly with rice establishment method, season and location, reflecting differences in crop growth, biomass production and nutrient use efficiency.
- Across all locations and years, transplanted treatments (T₁ and T₂) consistently recorded higher nutrient uptake compared to direct-seeded rice (DSR) treatments.
- Among all treatments, T₂ (PTR *SAVAH-134*) recorded the highest grain, straw and total uptake of nitrogen, phosphorus and potassium across all three locations.

- Hybrid-based DSR treatments (T₅ and T₆) showed improved nutrient uptake compared to varietal DSR treatments, indicating better nutrient acquisition and biomass production under hybrid cultivation.
- Further, the lowest uptake of N, P and K was consistently recorded under T₃ (DSR *PR-126*) across locations and years, indicating comparatively lower nutrient extraction due to reduced biomass and grain yield.
- The higher nutrient uptake in transplanted systems may be attributed to better root establishment, improved nutrient availability under puddled conditions and higher biomass accumulation.

Soil physico – chemical properties

- Soil physico-chemical properties varied with establishment method, season and location, influencing soil structure, moisture retention, pH and soil organic carbon status.
- Direct-seeded rice (DSR) methods improved soil condition by lowering bulk density, increasing water-holding capacity and enhancing soil organic carbon (SOC) compared to transplanted systems.
- Transplanted treatments showed higher bulk density, slightly higher soil pH and lower SOC due to repeated puddling and faster organic matter decomposition.
- T₅ (DSR *SAVAH-134 Full Page hybrid*) consistently recorded the most favourable soil environment with lowest bulk density, highest water-holding capacity and maximum SOC across locations.
- Other DSR treatments (T₃ and T₄) maintained better soil physical structure and carbon status than transplanted methods, though slightly inferior to T₅.
- Soil pH showed only minor numerical variation across treatments and remained relatively stable irrespective of establishment method.
- Particle density and porosity were not significantly affected, although DSR tended to maintain slightly better porosity than transplanted systems.
- T₆ (DSR hybrid with AFD) maintained intermediate soil conditions, with better physical properties and SOC than transplanted methods but slightly lower than continuous DSR.
- The consistent improvement in soil structure and carbon build – up under DSR was observed across Palampur, Una and Dhaulakuan, confirming the strong influence of establishment method on soil health.
- **Overall, DSR – especially T₅ created a better soil physico-chemical environment by reducing compaction, improving moisture retention and increasing SOC, which supports sustainable crop productivity.**

Soil available NPK status

- Soil available N, P and K varied with rice establishment method, season and location, indicating differences in post-harvest soil fertility status.
- Transplanted treatments generally maintained higher residual NPK in soil compared to direct-seeded rice (DSR) methods.
- T₂ (PTR *SAVAH-134*) consistently recorded the highest availability of N, P and K across locations and seasons, closely followed by T₁ (PTR *PR-126*).
- Among DSR treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) maintained comparatively higher residual NPK, followed by T₆, T₄ and T₃.
- T₃ (DSR *PR-126*) consistently recorded the lowest available NPK, indicating relatively greater nutrient depletion or poorer nutrient retention under this treatment.
- Differences in available phosphorus were statistically non-significant, but the overall numerical trend of P availability followed the same pattern as N and K across treatments.
- Higher residual NPK under transplanted systems may be associated with differences in nutrient uptake patterns, soil – water regime and nutrient transformations under puddled conditions.
- Hybrid-based DSR (T₅) showed better nutrient retention than other DSR methods which might be due to improved nutrient cycling and soil fertility balance under this system.
- All in all, transplanted rice maintained slightly higher residual soil fertility, while T₅ among DSR treatments helped conserve more NPK compared to other DSR methods.

Soil microbiological properties

- Soil microbiological properties, particularly microbial biomass carbon (MBC) and dehydrogenase activity (DHA), varied significantly with rice establishment methods across Palampur, Una and Dhaulakuan.
- Direct-seeded rice (DSR) treatments consistently recorded higher microbial biomass and enzymatic activity compared to transplanted rice (PTR) systems at all locations.
- **Among the treatments, T₅ (DSR *SAVAH-134* Full Page hybrid) recorded the highest MBC and dehydrogenase activity across locations and years, indicating a more biologically active soil environment.**
- However, T₅ remained statistically at par with other DSR treatments, particularly T₆, T₄ and T₃, suggesting that most DSR methods supported improved microbial activity.
- In contrast, transplanted rice treatments showed comparatively lower microbial activity, with T₁ (PTR *PR-126*) consistently recording the lowest MBC and dehydrogenase activity.

- T₂ (PTR SAVAH-134) showed slightly higher microbial parameters than T₁ but remained statistically at par with it across locations.
- Overall, DSR particularly T₅ created a more favourable soil biological environment by enhancing microbial biomass and enzymatic activity across the experimental locations.

CONCLUSIONS

- Across all the locations (Palampur, Una and Dhaulakuan) and seasons (2023, 2024), puddled transplanted rice (PTR) ensured significantly highest grain yield, however, this productivity advantage was accompanied by greater water consumption and higher greenhouse gas emissions. Among transplanted treatments, the SAVAH-134 hybrid outperformed PR-126, highlighting the benefit of hybrid vigour under puddled conditions. Within the direct-seeded system, DSR SAVAH-134 Full Page hybrid (T₅) consistently emerged as the most productive treatment, clearly surpassing other DSR and AWD-based options across environments. Although slightly lower yielding than PTR, T₅ achieved a favourable yield compromise while markedly improving resource-use efficiency. Methane emissions were drastically reduced under T₅, with nearly ninety per cent mitigation compared to transplanted rice, establishing its strong climate advantage. Unlike AWD-based DSR, which increased CO₂ and N₂O emissions due to repeated wetting – drying cycles, T₅ maintained lower CO₂ flux and recorded the lowest N₂O emissions.
- Consequently, T₅ exhibited the lowest carbon footprint and global warming potential across locations and years. Furthermore, carbon credit generation was also maximized under T₅, demonstrating its high mitigation potential relative to both PTR and other DSR – AWD treatment. Water productivity was also highest under T₅, indicating superior conversion of water into grain yield. In contrast, DSR PR-126 consistently showed poor yield, low water productivity and high emission intensity. Overall, DSR SAVAH-134 Full Page hybrid (T₅) provided the most effective integration of high crop productivity, enhanced water productivity and reduced carbon footprint. In terms of long – term sustainability, the advantage of T₅ was further supported by its positive effects on nutrient uptake and soil health. While PTR, particularly T₂, recorded the highest uptake of N, P and K due to enhanced nutrient availability under flooded conditions, T₅ achieved significantly higher nutrient uptake than all other DSR treatments, indicating efficient nutrient use under aerobic soil conditions.
- Moreover, T₅ markedly improved soil physical properties by reducing bulk density and enhancing water-holding capacity across locations. Soil chemical and microbiological properties also responded positively under T₅, with significantly higher soil organic carbon, microbial biomass carbon and dehydrogenase activity compared to transplanted systems. Although transplanted treatments maintained slightly higher soil available nutrients and soil pH, DSR – based treatment T₅ promoted

superior carbon buildup and biological activity, which are critical for long-term soil fertility and system resilience. Among all DSR treatments, *SAVAH-134* Full Page hybrid under direct seeding (T₅) demonstrated an optimal balance of higher grain yield, improved water productivity, reduced greenhouse gas emissions and enhanced soil physico – chemical and microbiological properties. Based on its consistent and superior performance across locations and seasons, T₅ under direct – seeded conditions can be rightly recommended as a climate-smart, resource – efficient and sustainable rice establishment practice for farmers in similar agro – climatic regions.

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Glimpses of Greenhouse gases sampling at Department of Soil Science Experimental Farm at CSK.HPKV, Palampur



Glimpses of Greenhouse gases sampling and their analysis at Palampur, at KVK, Una and Savanah Seed Pvt.Ltd. Scientist Dr. Vinod Verma visits to the sampling site



Glimpses of Greenhouse gases sampling at HAREC, Dhaulakuan Experimental Farm