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## **Crop establishment, residue retention and nutrient management influence the phenology-mediated greenhouse gases emission in an intensive rice-wheat system**

**Abstract:** The impact of management practices (i.e. crop establishment, tillage, residue addition etc.) on the global warming potential (GWP) and greenhouse gas intensity (GHGI) in rice-wheat cropping system accounting the economic viability is sparsely documented. A field experiment was established in 2020 to gain insight crop phenology mediated greenhouse gas emission into GWP, GHGI and economic viability on crop seasonal scale over three cycles (2020, 2021 and 2022) of rice-wheat rotations under subtropical climatic condition. Treatments were three planting techniques viz., System of rice intensification (SRI) followed by conventional wheat without residues (SRI-CW), Puddle Transplanted rice (TPR) followed by CW with 30% rice residue incorporation (TPR-CW<sub>Ri</sub>) and zero-till direct sowing of rice (ZT-DSR) followed by ZT wheat with 30% rice residue retention (ZTDSR-ZTW<sub>Rr</sub>) and four different nutrient management practices viz., 100% NPK (as per recommended dose) through mineral fertiliser (100% NPK<sub>i</sub>), 75% NPK through mineral fertiliser with 25% N through organics (75% NPK<sub>i</sub> + 25% N<sub>Org</sub>), 50% NPK through mineral fertiliser with 50% N through organics (50% NPK<sub>i</sub> + 50% N<sub>Org</sub>) was followed in both rice and wheat crop and 100% NPK through mineral fertiliser (100% NPK<sub>i</sub>) along with mung bean (*Vignaradiata*) green manure in rice and 100% NPK through mineral fertiliser in wheat (100% NPK<sub>i</sub> + GM). All treatments were established in a split-plot design and repeated three times; where three planting techniques were arranged in main plots and four different nutrient management practices were arranged in sub-plots. The highest system productivity was obtained under ZTDSR-ZTW<sub>Rr</sub> treatment. Moreover, this system reduced the CH<sub>4</sub> and N<sub>2</sub>O emission by 62.7 and 48% respectively over TPR-CW<sub>Ri</sub>, hence, the Global Warming Potential (GWP), as well as gaseous intensity (GHGI), were reduced by 2.0-2.18 and 2.13-2.20 times, respectively than the traditional technique of cultivation. Green manure behaves differently by increasing the system productivity by 4.27% and reducing the GHGI 4.56% over 100% NPK<sub>i</sub>. Thus, ZTDSR-ZTW<sub>Rr</sub> along with 100% NPK<sub>i</sub> and green manuring in rice could be an economically viable opportunity for maintaining future yield standard of the system with lower emission scenario.

**Keywords:** *Direct seeded rice, Zero-tillage, Rice, Wheat, Greenhouse gas intensity*

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## 1. Introduction

Global environmental changes have exposed our food supply chain to an intricate situation [1] especially for South Asian countries, where the rice-wheat system prevailed centuries together. Although, the Green revolution undoubtedly promotes our food grain production but blanket fertilizers' application especially nitrogenous fertilizer, which caused an unprecedented decline in rice and wheat production ~1% at present days [2] and most perilously affected the environment with higher greenhouse gases (GHGs) concentration. Irrigated transplanted flooded rice system predominates over the globe that contributes 75% of rice consumed [3], is the most preferable cultivation system towards farmers, which is water expensive [4,5] and GHGs productive. Economic utilization of water and labour is boon for today's cultivation but in near future, these two will be the scarcest resources [6].

Another important aspect is the anthropogenic GHGs emission that is the major contributor to global climate change [7, 8]. Nitrous oxide ( $N_2O$ ) emission in the agricultural system is mainly of soil origin that accounts for ~20% of global  $N_2O$  emission [9] which is about 60% of total anthropogenic  $N_2O$  emissions. Soil and root respiration accounted for 20% of the total emission through  $CO_2$  and 12% through  $CH_4$  emission [10]. Although,  $CO_2$  is considered as one of the GHGs, but it is used to counterbalance by  $CO_2$  fixation in the terrestrial ecosystem as net primary productivity and thus its effective contribution in global warming potential (GWP) is less than 1% [11].  $CH_4$  and  $N_2O$  having global warming potential 25 and 298, respectively than that of  $CO_2$  over centuries' time span [10]. Thus, they are primarily responsible for global warming. Global warming mostly influences the carbon cycle, and thus the structures and functions of the ecosystem are changing [12] that are designated as climate change. Soil and environmental factors are mostly governing the GHGs emission and those factors are mostly influenced by the management practices in agriculture.

But, drastic change in cultivation technique raises an issue of adaptability. Little Modification in crop establishment method and tillage becomes effective to address the issue. System of rice intensification (SRI), direct-seeded rice (DSR) along with succeeding zero-till wheat crop is some common modifications in management practices under rice-wheat cropping system. The effect of these planting methods and tillage on crop performance, water

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productivity was evaluated by many researchers [13,14]. Environmental impact of these management practices especially GHGs emission was scanty. Another important aspect of crop production is nutrient management especially nitrogen. Application of nitrogenous fertilizers and organic manures augment the emissions of N<sub>2</sub>O, CO<sub>2</sub> and CH<sub>4</sub> from soils [15-17]. But the impact of the conjoint application of mineral fertilizer and organics on GHGs emission together with crop planting techniques at different crop phenological stage in rice-wheat cropping system is very sparse. Rice straw incorporation in wheat crop now becomes a common farmer's practice but, its impact on CH<sub>4</sub> and N<sub>2</sub>O dynamics is insufficient. Interaction among establishment method/tillage, nutrient and residue management on greenhouse gas emission and greenhouse gas intensity is not yet well-understood. Keeping these in view, this study was conducted to examine the effect of planting technique and nutrient management on phenology mediated emissions at different crop growth stages and its relation to agronomic productivity, profitability and greenhouse gas intensity.

## **2. Materials and Methods**

### *2.1. Site description*

A field experiment was conducted for three consecutive years during 2020-2022 at the Research field of Bihar Agricultural University (BAU) (25°23'N, 87°07'E, 37.19 m MSL), Sabour, Bihar-India. Before the initiation of the experiment, a uniformity trial was done with wheat crop during rabi 2019. The initial characteristics of soil in the experimental site were loamy textured (Sand-50%, Silt-28% and Clay-22%), having pH<sub>1:2.5</sub> 7.3, electrical conductivity (EC<sub>1:2</sub>) 0.25 dS m<sup>-1</sup>, organic carbon 4.9 g kg<sup>-1</sup>, available nitrogen 168.5 kg N ha<sup>-1</sup>, available phosphorus 35.2 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and available potassium 135.4 kg K<sub>2</sub>O ha<sup>-1</sup>.

### *2.2. Agro-climatic condition*

The experimental site was situated under the sub-tropical climate with desiccating summer and cool winter. The mean maximum temperature was 35-39°C and minimum temperature 5-10°C. The annual rainfall was about 1250 mm but 80% of the rainfall precipitated between

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mid-June and mid-October. Daily mean values of the weather parameters during the experimentation (Figure 1) was obtained from university's meteorological observatory.

### 2.2. *Experimental details and crop management*

The field experiment was conducted in split-plot design keeping planting technique as the main plot treatment and nutrient management as sub-plot treatment with three replications. The planting techniques were: the system of rice intensification (SRI) followed by conventional wheat (SRI-CW), Puddle Transplanted rice (TPR) followed by conventional wheat with 30% rice residue incorporation (TPR-CW<sub>Ri</sub>) and zero-till direct-seeded rice (ZT-DSR) followed by zero-till wheat with 30% rice residue retention (ZTDSR-ZTW<sub>Rr</sub>). Four different nutrient management practices were followed in the study. These were 100% NPK (as per recommended dose) through mineral fertiliser (100% NPK<sub>i</sub>), 75% NPK through mineral fertiliser with 25% N through organics (75% NPK<sub>i</sub> + 25% N<sub>Org.</sub>), 50% NPK through mineral fertiliser with 50% N through organics (50% NPK<sub>i</sub> + 50% N<sub>Org.</sub>) was followed in both rice and wheat crop according to their recommended dose of fertilizer i.e. 100 kg N + 40 kg P<sub>2</sub>O<sub>5</sub> + 20 kg K<sub>2</sub>O ha<sup>-1</sup> in rice and 120 kg N + 80 kg P<sub>2</sub>O<sub>5</sub> + 60 kg K<sub>2</sub>O ha<sup>-1</sup> in wheat. In fourth treatment, green gram (*Vignaradiata*) was used as a green manure crop in rice along with the 100% NPK, whereas in wheat simply 100% NPK was applied as mineral fertilizer (100% NPK<sub>i</sub> + GM). Vermicompost was used as an organic supplement (N content 1.20%). The amount of rice residue applied in the subsequent wheat crop was 30% of the total rice straw yield either applied on to the field for residue incorporation (Ri) or kept as such on the soil surface after rice harvest for residue retention (Rr). Best management practices were adopted during experimentation as described in Table 1.

### 2.3. *Crop harvest and yield*

Mature crops from entire plots were harvested and threshed separately by manually. Yield was converted to t ha<sup>-1</sup>. The grain yield of rice and wheat is reported at 14% and 12%, grain moisture, respectively. The productivity of different treatments was compared using

system productivity as rice equivalent yield ( $t\ ha^{-1}$ ) and was calculated using the following equation:

$$\text{Rice equivalent yield (t ha}^{-1}\text{)} = \frac{\text{Wheat yield (t ha}^{-1}\text{)} \times \text{Minimum support price of wheat (INR t}^{-1}\text{)}}{\text{The minimum support price of Rice (INR t}^{-1}\text{)}}$$

(Eq. 1)

#### 2.4. Greenhouse gases (GHGs) Collection and analysis

The gas samples i.e.  $CH_4$ ,  $N_2O$  and  $CO_2$  were collected using closed Pyrex glass gas chamber (volume-  $0.32\ m^3$ ) using 50 mL disposable syringe with leur lock at 0, 30 and 120 minutes interval from each plot. The Gas samples were analyzed for  $CH_4$ ,  $CO_2$  and  $N_2O$  concentrations through gas chromatography (Model: Trace GC 1110, Make:Thermofisher) built with electron capture detector (ECD) and flame ionization detector (FID). Methanizer was used for the reduction of  $CO_2$  to  $CH_4$  using a nickel catalyst. Nitrogen was used as carrier gas at a flow rate of  $35\ mL\ min^{-1}$ . The column and detector were maintained at  $60^\circ C$  and  $300^\circ C$ , respectively. The gaseous flux was measured at different crop growth stages viz., maximum tillering, panicle initiation (rice) or ear head emergence (wheat) and physiological maturity stage of the crops. The fluxes were calculated using the following [18]:

$$F = \rho H \left( \frac{dC}{dt} \right) 273 (273 + T)^{-1} \text{ (Eq. 2)}$$

where 'F' is the emission flux ( $mg\ m^{-2}\ hr^{-1}$ ), ' $\rho$ ' is the density of gas at STP, 'H' is the height of chamber above the soil surface (m), 'C' is the gas concentration ( $mg\ m^{-3}$ ), 't' is the time intervals of each time (hr), and 'T' is the air temperature in absolute scale inside the chamber during sampling.

#### 2.5. Global Warming potential (GWP) and GHGs intensity (GHGI)

GWP was calculated by the following formula (Eq. 3) [19] after converting individual emission to their respective  $CO_2$  equivalents.

$$\text{GWP (CO}_2\text{ equivalent Kg ha}^{-1}\text{)} = (CO_2) + (CH_4 \times 25) + (N_2O \times 298) \text{ (Eq. 3)}$$

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The equivalent GWP coefficients for CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were 1, 25 and 298, respectively considering their emission potential in the 100-year time frame as described in IPCC, 2007. GHGI was estimated based on grain produced [19,20]:

$$\text{GHGI (Kg CO}_2\text{ eq. Kg}^{-1}\text{ grain yield)} = \frac{\text{GWP}}{\text{Grain yield}} \text{ (Eq. 4)}$$

### 2.6. Statistical analysis

Data were analyzed through split-plot design as followed during the field experiment. The treatment influence was calculated using analysis of variance (ANOVA) at 5% probability levels ( $p \leq 0.05$ ) [21]. Duncan's multiple range test (DMRT) was carried out using SAS 9.2 (SAS Institute, Cary, NC) [22] where ANOVA was significant.

## 3. Results

### 3.1. Methane emission

Methane (CH<sub>4</sub>) emission was mostly influenced by the crop growing season and planting technique as compared to nutrient management. But the emission behaviour at different crop phenology was mostly governed by their planting techniques [ $p$  (PT\*PS) = <0.0001] rather than nutrient management [ $p$  (NM\*PS) = 0.325] (Table 2; Figure 2 and 3). Although the methane emission was highest at the maximum tillering stage and gradually declined as the maturity progress, but the extent of the decline was the highest in ZTDSR and least in TPR. Amusingly, the magnitude of methane emission was highest in TPR (26.3 mg m<sup>-2</sup> hr<sup>-1</sup>) followed by SRI (20.7 mgm<sup>-2</sup>hr<sup>-1</sup>) and lowest in ZTDSR (9.8 mgm<sup>-2</sup>hr<sup>-1</sup>). Methane emission was almost negligible in wheat as compared to rice and key contributor of total GWP in rice ecology.

### 3.2. Carbon dioxide emission

Carbon dioxide (CO<sub>2</sub>) emission was significantly influenced by planting technique and nutrient management practices. ZTDSR imparted highest CO<sub>2</sub> emission (20.1-24.0 mgm<sup>-2</sup>hr<sup>-1</sup>) followed by SRI-CW (13.0-15.8 mgm<sup>-2</sup>hr<sup>-1</sup>) and TPR-CWRi (11.7-14.3 mgm<sup>-2</sup>hr<sup>-1</sup>) (Figure 2 and 3). Phonological emission of CO<sub>2</sub> was similar to the CH<sub>4</sub> emission in both the crop.

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Nutrient management also significantly influenced CO<sub>2</sub> emission. Application of organics (50% NPK<sub>i</sub> + 50% N<sub>org.</sub>) augmented the CO<sub>2</sub> emission by ~31 % as compared to 100% NPK<sub>i</sub>. There were about 2.5 times more CO<sub>2</sub> emission was recorded in wheat than rice, however; the emission trend was similar for both the crops.

### 3.3. Nitrous oxide emission

Nitrous oxide emission is the key contributor of the total GWP in aerobic ecosystem alike the wheat in our experiments (Figure 2 and 3). Among the different crop phenology, maximum tillering stage of wheat emitted highest N<sub>2</sub>O (0.89 mgm<sup>-2</sup>hr<sup>-1</sup>) and reduced gradually at ear head emergence (0.68 mgm<sup>-2</sup>hr<sup>-1</sup>) and at harvesting (0.39 mgm<sup>-2</sup>hr<sup>-1</sup>) which was about 8-15 times higher than the nitrous oxide emission in rice. Interestingly, ZTDSR-ZTW<sub>Rr</sub> attributed lowest N<sub>2</sub>O emission in both the crops which were 54.5% lower than the TPR-CW. Nitrous oxide emission was aggravated by the extent of mineral nitrogenous fertilizer used. Thus, 100% NPK<sub>i</sub> recorded the highest N<sub>2</sub>O emission as compared to other nutrient management practices. This ill effect could be compensated either by green manure with 100% NPK<sub>i</sub> (~13.4%) application or conjoint application of organic and mineral fertiliser (29-34%). Interaction of planting technique and nutrient management had a profuse influence on N<sub>2</sub>O emission. Thus, ZTDSR-ZTW<sub>Rr</sub> along with 50% NPK<sub>i</sub> + 50% N<sub>org.</sub> lower down the N<sub>2</sub>O emission by ~73.5% compared to conventional production practice in the rice-wheat system (TPR-CW along with 100% NPK<sub>i</sub>)(Figure 2).

### 3.4. . GWP and GHGI

The emission behaviour of the greenhouse gases (GHGs) was enormously varied with the cropping season as well as the management practices and their cumulative impact could be capture by the GWP. Rice attributed 1.6-2.6 times higher GWP than the wheat crop. This was mainly due to the higher total methane emission in rice. TPR-CW<sub>Ri</sub> attributed the highest GWP (28262 Kg CO<sub>2</sub> eq ha<sup>-1</sup>) followed by SRI-CW (26065 Kg CO<sub>2</sub> eq ha<sup>-1</sup>) and ZTDSR-ZTW<sub>Rr</sub> (12979 Kg CO<sub>2</sub> eq ha<sup>-1</sup>) contributed lowest GWP (Table3, Figure 3). In addition, the nutrient management practices also had a significant impact on GWP (Table 3). Greenhouse gas intensity (GHGI) signifies the relative impact of GWP as a function of crop

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yield. The result showed that ZTDSR-ZTW<sub>R</sub> system contributed least GHGI among the planting techniques (1.42 Kg CO<sub>2</sub> eq kg<sup>-1</sup> grain yield) and among the nutrient management practices 100% NPK<sub>i</sub> + GM possessed lowest GHGI (2.32 Kg CO<sub>2</sub> eq ha<sup>-1</sup>).

### 3.5 Grain yield and economics

Rice and wheat grain yield were significantly influenced by their planting technique and nutrient management practices (Table 4). ZTDSR-ZTW<sub>R</sub> attributed the highest system productivity (9.13 t ha<sup>-1</sup>) followed by TPR-CW<sub>Ri</sub> (9.04 t ha<sup>-1</sup>) and SRI-CW (8.60 t ha<sup>-1</sup>). Rice grain yield was excelled in SRI (4.87 t ha<sup>-1</sup>) and wheat grain yield performed better under ZTW<sub>R</sub> (4.70 t ha<sup>-1</sup>). Basically, the zerotill wheat with residue retention gained advantage when sown after the zerotill direct seeded rice. Further, the nutrient management practices exerted a similar influence on grain yield of rice and wheat, although, the inclusion of green manure crop had an excel over in rice grain yield by 4.32% over 100% NPK<sub>i</sub> that eventually increased the system productivity by 4.27%. The interaction of planting techniques and nutrient management showed no any significance influence on grain yield of both the crops and system productivity [(p=0.8358 (rice), p= 0.9832 (wheat), p= 0.9012 (system)]. A similar influence was depicted in system profitability (B:C ratio). ZTDSR-ZTW<sub>R</sub> recorded the highest net B:C ratio (1.92) followed by SRI-CW (1.53) and TPR-CW<sub>Ri</sub> (1.41) (Table 4).

## 4. Discussion

### 4.1. Effect of planting techniques and nutrient management practices on CH<sub>4</sub> emission

Rice is the major of atmospheric CH<sub>4</sub> (Table 2 and 3; Figure 2 and 3) emitter. Submerged conditions favour CH<sub>4</sub> emission resulted from the carbon mineralization [23]. The higher CH<sub>4</sub> emission was found at maximum tillering stage. Jia et al. (2001) [24] articulated a higher CH<sub>4</sub> emission occurs at this stage mostly due to the lower rhizospheric CH<sub>4</sub> oxidation. ZT showed significantly lower methane emissions than CT (Table 3) because, in ZT, there was no disturbance of soil caused less exposure of organic matter as caused by the tillage operation [25]. Organic manure application was further augmented the CH<sub>4</sub> emission by providing labile carbon sources [26-28]. A significant impact of tillage operation was observed during rabi seasons on the emission of methane. We found that the ZT system

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applied to wheat resulted in significantly higher CH<sub>4</sub> emissions than the conventional tillage (CT) systems. Previous studies [29,30] also confirmed that zero tillage attributed higher SOC and moisture content in the surface layers than CT. Methane emission might be influenced by a higher level of organic carbon content and comparatively anaerobic condition of soil microsites under ZT during the rabi - season [31].

#### *4.2. Effect of planting techniques and nutrient management practices on CO<sub>2</sub> emission*

GHGs emission from agricultural soil is a result of a complex interaction between climate and soil physical, chemical and biological environment. Tillage impinges on biological, chemical and physical soil properties and therefore influences the release of the greenhouse gases [32]. Tillage enhances the surface roughness and void spaces that iterate the CO<sub>2</sub> emission to the atmosphere [33,34]. In our study, we have found less CO<sub>2</sub> emission under ZTDSR as compared to SRI and TPR (Table 2 and 3; Figure 2). Plant acquires highest root biomass during its maximum tillering stage, simultaneously, the microbial and root respiration also enhanced; hence, higher CO<sub>2</sub> emission was observed. This could be due to the higher availability of root exudates and organic matter facilitates heterotrophic decomposition [34].

#### *4.3. Effect of planting techniques and nutrient management practices on N<sub>2</sub>O emission*

N<sub>2</sub>O produced in soils is mainly by dual microbial processes i.e., nitrification and denitrification [35]. Tillage influences physical, chemical and biological soil properties and therefore influences the emission of the greenhouse gases [32]. But there is large uncertainty regarding the higher N<sub>2</sub>O emissions from zero tillage than conventional tillage soils [36,37] or N<sub>2</sub>O emissions diminish after the long-term practice of no-tillage [38-40]. In our study, we have found a significant reduction in N<sub>2</sub>O emission under ZTDSR-ZTW<sub>R</sub> as compared to conventional practice (Table 2 and 3). Residue addition in zero tillage had increased carbon: nitrogen ratio associated with this combination caused temporary immobilization of nitrogen which may act as a substrate for further nitrification and denitrification process, be the cause of reduced N<sub>2</sub>O emission [41]. Mineral fertilization further augmented the N<sub>2</sub>O emission

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because nitrogen fertilizer application provides the substrate for the processes driving the soil N<sub>2</sub>O emissions [42,43], resulted in higher emissions of N<sub>2</sub>O to the extent of 73% of the total annual emission [44].

#### *4.4. Global warming potential and greenhouse gas intensity*

The impact of different management practices on CH<sub>4</sub> and N<sub>2</sub>O emissions estimated through GWP for a 100-year horizon. Rice systems have been identified as a substantial source of CH<sub>4</sub> emissions [45]. Water management in rice systems is the prime factor for methane emission [46], in addition to carbon input (i.e. residue addition) [12,25] and fertilizer management [47-49] because methane is the end product of organic matter decomposition under anaerobic condition [50]. Intermittent wetting and drying during the rice-growing season (in SRI) substantially reduced the GWP by emitting a lesser amount of CH<sub>4</sub> as compared to TPR. Sander et al. [51] also found that periodical drying and wetting condition had reduced the GWP during the cropping season by 26% relative to continuous flooded condition. The rice rhizosphere at the maximum tillering stage is subjected to intense reducing conditions among the all phenological stages of rice, prop up the formation of CH<sub>4</sub> [46,52], emission hike could also be due to anaerobic decomposition of root exudates and decomposed rice roots biomass [23]. Declined CH<sub>4</sub> emission at crop maturity may result in due to less C input into the soil from below-ground crop biomass, assimilates for methane production [53]. Methane and nitrous oxide emission are the key regulating factor for GWP and they bear a trade-off relationship. GWP in wheat was 2.28 times less under the ZT system as compared to the conventional one. This may be due to higher mineralization of nitrogen caused higher substrate availability for denitrification. This observation was consistent with the other studies carried out by [54] and [33]. Conventional tillage attributed higher gas diffusion rates than ZT and made an impossible barrier for further reduction of N<sub>2</sub>O to N<sub>2</sub> by the denitrifying organisms [55].

GHGI appraises the agronomic efficiency of management practices that begins to address both climate change and future food supply concerns [56]. ZTDSR-ZTW<sub>Ri</sub> reduced the GHGI by 2.13-2.20 times than SRI-CW and TPR-CW<sub>Ri</sub> (Table 3). Our experiment attains

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lower yield in ZTDSR, however, long term study showed that the ZTDSR excel over the TPR [57]. To our knowledge, these are the first instances where yield, profitability, GWP and GHGI are taken into account together for assessing the best management practices in rice-wheat systems. Consistent with our hypothesis, these results suggested the modification in planting techniques and nutrient management strategies bring into maximum produce at the same time reduce GWP and maximize profitability in the intensive rice-wheat production system [56,58].

## 5. Conclusions

We analyzed the results from our field studies and found that the planting techniques and nutrient management practices had an immense influence on GHGs emissions, productivity and profitability in the rice-wheat system. The cost incurred in all of these options must be taken into consideration while assessing the economic viability of any system. SRI had increased the grain yield by 18.5% over ZTDSR, whereas ZTW<sub>Rr</sub> attributed 34.7% higher grain yield over CW. However, the highest system productivity (REY) was obtained under ZTDSR-ZTW<sub>Rr</sub> system. This system also curtailed down CH<sub>4</sub> and N<sub>2</sub>O emission by 62.7 and 48% respectively over TPR-CW<sub>Ri</sub>, consequently, the GHGI and GWP were reduced by 2.13-2.20 and 2.0-2.18 times, respectively. Green manure behaves differently than other nutrient management practices. It did not influence the GWP but, the significant reduced the GHGI by increasing the system productivity by 4.27% was and reducing the GHGI 4.56% over 100% NPK<sub>i</sub>. Thus, ZTDSR-ZTW<sub>Rr</sub> along with 100% NPK<sub>i</sub> and green manuring in rice could be an economically feasible option to retard greenhouse gas emission and uphold future food supply. However, the trade-off relationship between CH<sub>4</sub> and N<sub>2</sub>O must be taken under consideration while adopting any mitigation strategies to reduce GWP in rice-wheat systems.

### **Disclaimer (Artificial intelligence)**

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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UNDER PEER REVIEW

**Table 1:** Crop management during the experiment

Crop	Variety	Spacing	Seed rate (kg ha <sup>-1</sup> )	Fertiliser management	
				Type	Time of application
Rice	RajendraSu washini	SRI- 25 x 25 cm	SRI- 5 kg ha <sup>-1</sup>	Urea	Full dose phosphorus and potassium were applied as DAP and MoP respectively as basal and along with 1/3 of the N through DAP and urea and remaining N was top-dressed through urea in two equal splits at maximum tillering and panicle emergence)
		TPR-20 x 15 cm	TPR- 50 kg ha <sup>-1</sup>	Diammonium phosphate (DAP)	
		DSR-Manual line sowing	DSR- 30 kg ha <sup>-1</sup>	Muriate of potash (MoP)	
Wheat	HD-2967	Row to Row- 22 cm	100 kg ha <sup>-1</sup>	Urea Diammonium phosphate (DAP) Muriate of potash (MoP)	Full dose phosphorus and potassium were applied as DAP and MoP respectively as basal and along with 1/3 of the N through DAP and urea and remaining N was top-dressed through urea in two equal splits at maximum tillering and ear head emergence)

**Table 2:** Two-way ANOVA for the effects of the crop planting technique (PT), nutrient management (NM) and the crop phenological stage (PS) on the CH<sub>4</sub>, CO<sub>2</sub> and N<sub>2</sub>O emissions during the two annual rice-wheat rotations of 2013 and 2014.

Season	Factor	df	CH <sub>4</sub> (mg m <sup>2</sup> hr <sup>-1</sup> )			CO <sub>2</sub> (mg m <sup>2</sup> hr <sup>-1</sup> )			N <sub>2</sub> O (mg m <sup>2</sup> hr <sup>-1</sup> )		
			SS	F	P	SS	F	P	SS	F	P
Rice	PT	2	50.55	5270.85	<0.0001	56.22	3600.89	<0.0001	0.049	8911.70	<0.0001
	NM	3	2.06	143.36	<0.0001	3.90	166.66	<0.0001	0.004	503.48	<0.0001
	PT*NM	6	0.42	14.59	<0.0001	0.11	2.26	0.0485	0.0001	6.21	<0.0001
	PS	2	2.82	294.31	<0.0001	1.79	114.39	<0.0001	0.003	562.44	<0.0001
	PT*PS	4	1.94	100.93	<0.0001	0.07	2.47	0.0529	0.0005	50.37	<0.0001
	NM*PS	6	0.03	1.19	0.3251	0.40	8.47	<0.0001	0.0001	9.88	<0.0001
	PT*NM*PS	12	0.16	2.75	0.0044	0.25	2.71	0.0050	0.0004	12.90	<0.0001
	Model	41	58.04	295.19	<0.0001	62.76	196.08	<0.0001	0.058	510.10	<0.0001
	Error	66	0.32			0.515			0.0002		
Wheat			SS	F	P	SS	F	P	SS	F	P
	PT	2	0.62	3290.35	<0.0001	478.97	6595.34	<0.0001	4.24	1300.78	<0.0001
	NM	3	0.07	253.09	<0.0001	60.07	551.45	<0.0001	1.38	283.56	<0.0001
	PT*NM	6	0.005	10.20	<0.0001	0.79	3.65	0.0034	0.03	3.41	0.0054
	PS	2	0.057	304.29	<0.0001	7.32	100.82	<0.0001	4.50	1381.97	<0.0001
	PT*PS	4	0.0009	2.44	0.0555	2.26	15.62	<0.0001	0.15	22.66	<0.0001
	NM*PS	6	0.0014	2.61	0.0248	0.28	1.29	0.2733	0.08	7.84	<0.0001
	PT*NM*PS	12	0.0043	3.87	0.0002	0.37	0.84	0.6082	0.21	11.01	<0.0001
	Model	41	0.758	197.26	<0.0001	550.31	369.64	<0.0001	10.61	158.83	<0.0001
Error	66	0.006			2.39			0.107			

**Table 3:** Effect of planting technique and nutrient management on total GHGs emission in the rice-wheat cropping system

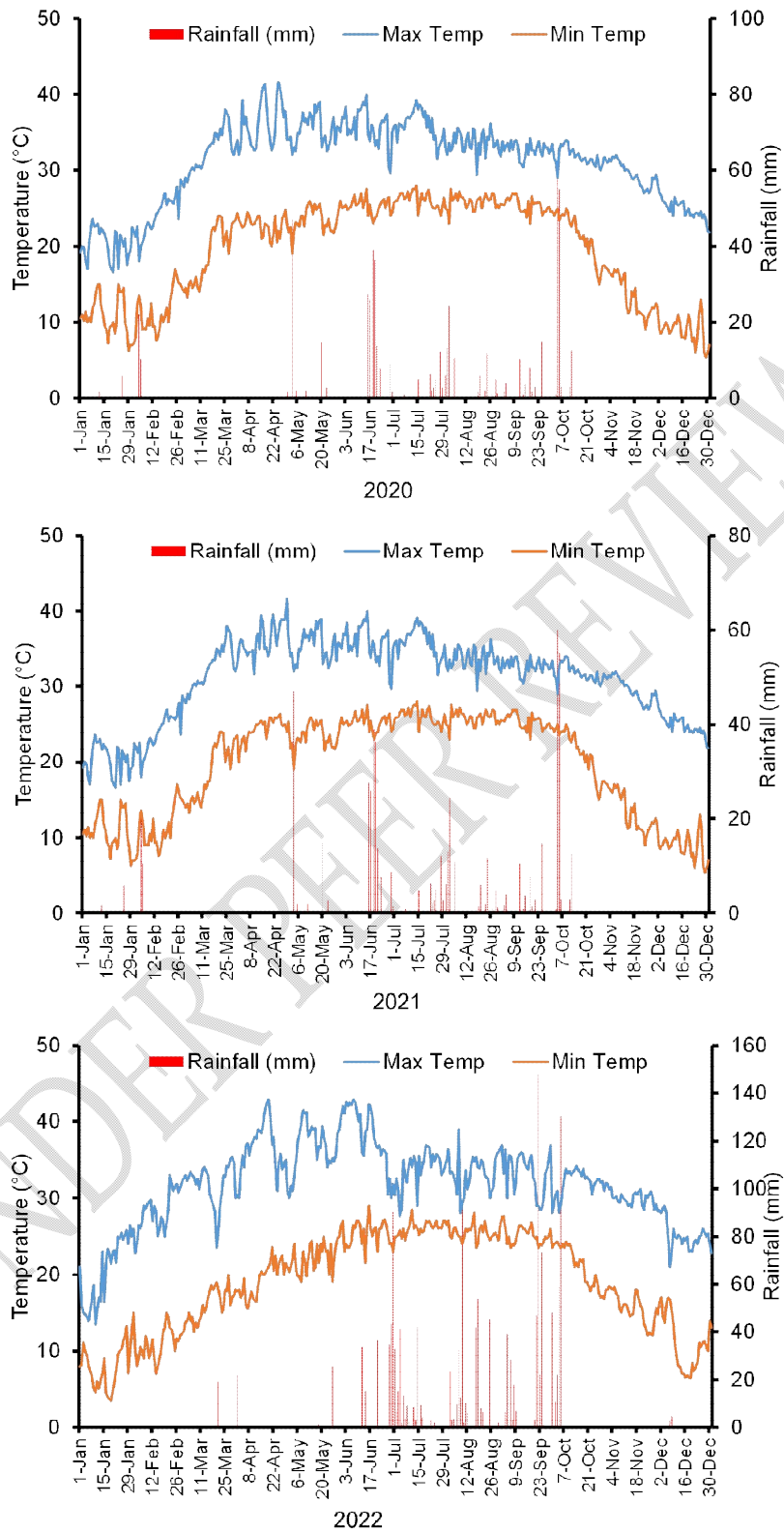
Treatments	Total emission (Kg ha <sup>-1</sup> )						GWP		GHGI		
	CH <sub>4</sub>		CO <sub>2</sub>		N <sub>2</sub> O		(Kg CO <sub>2</sub> eq ha <sup>-1</sup> )		(Kg CO <sub>2</sub> eq kg <sup>-1</sup> Grain yield)		
	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	System
<b>Crop Planting Technique</b>											
SRI-CW	627.98b	4.94b	442.51b	1193.47b	1.56b	27.32a	16608b	9457a	3.41b	2.71a	3.03b
TPR-CWRi	795.31a	7.56a	394.13c	1900.08a	0.84c	18.95b	20526a	7736b	4.42a	1.88b	3.13a
ZTDSR-ZTWRr	297.36c	2.12c	675.36a	342.72c	2.41a	12.60c	8829c	4150c	2.15c	0.88c	1.42c
<b>Nutrient Management</b>											
100% NPK <sub>i</sub>	515.59b	3.93d	340.70c	902.16c	1.86a	24.80a	13784b	8390a	2.98d	1.99a	2.43c
75% NPK <sub>i</sub> + 25% N <sub>Org</sub>	590.89a	5.14b	413.28b	1205.57b	1.48b	17.24c	15627a	6471b	3.52b	1.64b	2.55b
50% NPK <sub>i</sub> + 50% N <sub>Org</sub>	629.09a	5.85a	491.90a	1485.79a	1.37b	16.03c	16629a	6408b	3.90a	1.67b	2.76a
100% NPK <sub>i</sub> +GM	557.42b	4.44c	366.91c	988.85c	1.70a	20.66b	14810ab	7258ab	3.07c	1.65b	2.32d
<i>P-Value</i>	**	**	**	**	**	**	**	**	**	**	**

Values within a column, followed by different letters are significantly different at  $p < 0.05$  by Duncan's multiple range test.

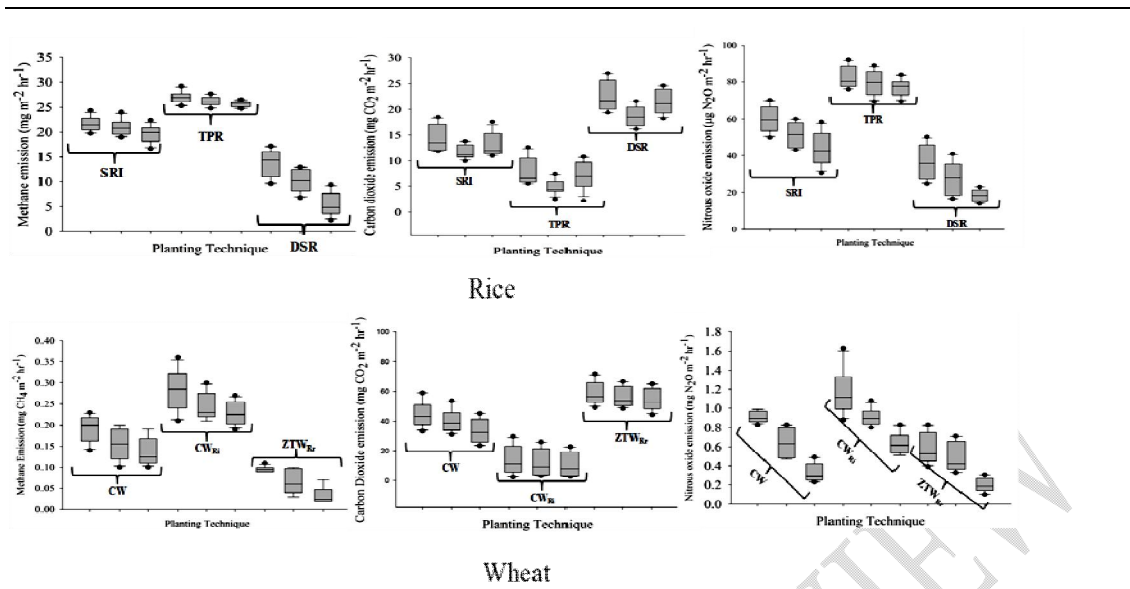
**Table 4:** Effect of planting technique and nutrient management on grain yield and economics in a rice-wheat cropping system

Treatments	Yield (Mg ha <sup>-1</sup> )		REY (Mg ha <sup>-1</sup> )	B:C ratio
	Rice	Wheat		
<b>Crop Planting Technique</b>				
SRI-CW	4.87a	3.49c	8.60b	1.53b
TPR-CW <sub>Ri</sub>	4.64b	4.12b	9.04a	1.41c
ZTDSR-ZTW <sub>Rr</sub>	4.11c	4.70a	9.13a	1.92a
<b>Nutrient Management</b>				
100% NPK <sub>i</sub>	4.63b	4.21a	9.13c	1.68b
75% NPK <sub>i</sub> + 25%N <sub>Org</sub>	4.44c	3.95b	8.66b	1.56c
50% NPK <sub>i</sub> + 50% N <sub>Org</sub>	4.26d	3.83b	8.35b	1.48c
100% NPK <sub>i</sub> +GM	4.83a	4.39a	9.52a	1.84a
<i>P-Value</i>	**	**	**	**
M*S	0.8358	0.9832	0.9012	0.3135

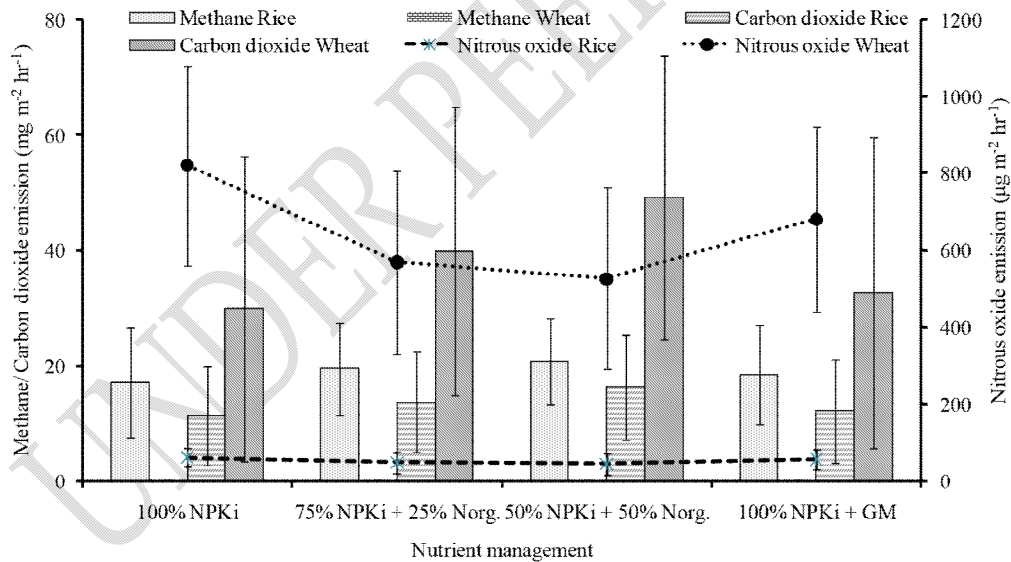
Values within a column, followed by different letters are significantly different at  $p < 0.05$  by Duncan's multiple range test.



**Figure 1.** Meteorological data of the experimental Years 2020, 2021, 2022



**Figure 2:** Seasonal emission of GHGs emission in various Crop Growth Stages of rice and wheat as influenced by planting technique [The boxes in the above figure in each cluster indicate the different crop growth stage (From left maximum tillering, Panicle initiation (rice)/Ear Head emergence (wheat) and maturity stage)]



**Figure 3:** Seasonal emission of GHGs emission in various Crop Growth Stages of rice and wheat as influenced by nutrient management