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Research article

Double transplantation as a climate resilient and sustainable resource management strategy for rice production in eastern Uttar Pradesh, north India

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ABSTRACT

-Enhancing the productivity of rainfed crops, especially rice, while coping with climate adversities and saving critical natural resources is essential for ensuring the food and nutrition security of a growing population. With this context, the present study was undertaken to validate promising farm innovation and adaptation practices used by small-medium landholding farmers for rice cultivation in eastern Uttar Pradesh (UP), north India, as well as to examine the sustainability of innovative practices for large-scale adoption. For this, a 3-year study comprising extensive field surveys and experiments was undertaken to compare single transplantation (ST) and double transplantation (DT) in rice along with organic addition (farm-yard manure, FYM) on crop growth, yield, climate resilience, soil quality, and overall sustainability i.e., social (women involvements and labour productivity), environmental (water productivity and nutrient use efficiency), and economic (benefit:cost ratio) dimensions of sustainability. Field experiments were conducted in triplicate using two local rice varieties (*MotiNP-360* and *Sampurna Kaveri*) in two agroclimatic zones, namely the middle Gangetic plains and the Vindhyan zone, in the Mirzapur district of eastern Uttar Pradesh. The DT practices of rice with and without farm yard manure (FYM) (replacing at a dose of 25% NPK) were evaluated over conventional methods of rice cultivation (i.e., ST, as control) and analysis was done periodically. The DT practice improved growth ($p < 0.05$), percent fertile tiller and grain ($p < 0.05$), and rice yield (15–20% higher than ST), while also improving soil quality, yield indices, water and labour productivity, and the benefit-cost ratio. The DT practice also resulted in early maturity (10–15 days earlier than ST), created more labour days for women, decreased lodging and pest/disease incidence, as well as a subsequent reduction in the use of synthetic chemical pesticides and associated environmental costs. Importantly, the residual effects of FYM application significantly improved ($p < 0.05$) the grain yield in subsequent years of cropping. Optimizing DT cultivation practices, preferably with FYM input for various agroclimatic regions, is essential for large-scale sustainable rice production under changing climatic conditions.

1. Introduction

Optimizing innovative crop production strategies for various agro-climatic regions of the world is critical for keeping food production within planetary boundaries while meeting the UN-Sustainable Development Goals (UN-SDGs) and achieving global sustainability (Rockström et al., 2009). Sustainable and resilient practices are also essential for ensuring food production in times of climate change and associated global environmental changes (Eisenstein, 2020). It has been estimated that agriculture alone accounts for the largest water usage (~70%) (Walter et al., 2017) and leads to the largest non-point sources of pollution due to the rampant use of agrochemicals like pesticides and fertilisers (Rhind, 2009). Hence, the validation of promising cultivation practices for saving critical natural resources like water is essential and

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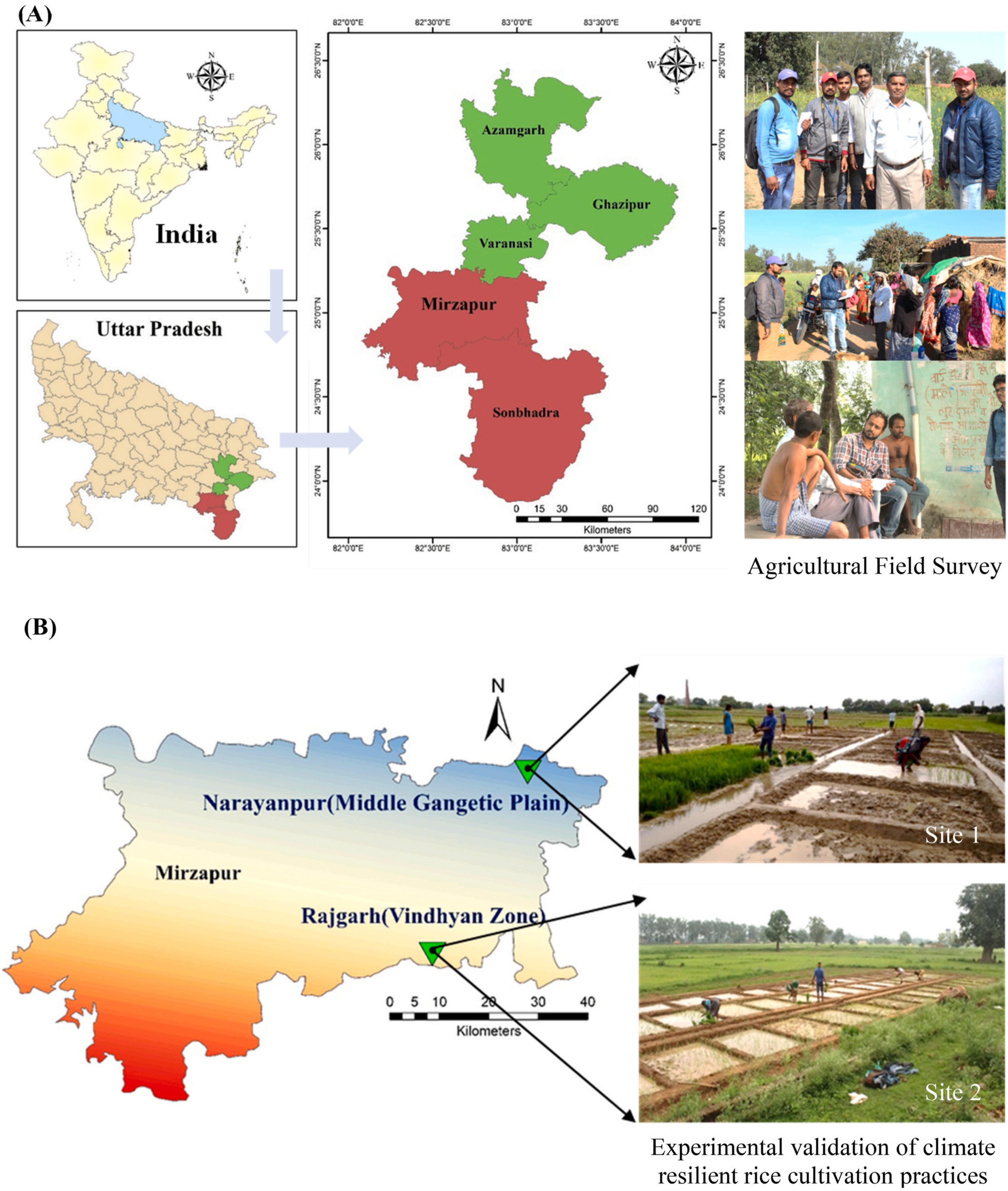

Fig. 1. Locations of field survey and experimental validation of various climate resilient rice cultivation practices in eastern Uttar Pradesh, North India. **(A)** Extensive survey has been conducted in five districts of eastern Uttar Pradesh for exploring various climate adaptive practices employed by farmers for rice cultivation and for understanding the level of deployment of various practices by the local farmers; **(B)** Based on the survey results, field experiments were conducted in Mirzapur district as the district has two distinct agroclimatic regions such as middle Gangetic floodplain (Narayanpur block) and Vindhyan region (dryland region). The former site (Site-1) is in Pachevaran village (25°1618′ N, 82° 9500′ E), whereas the later one (Site-2) is in Rajgarh village (24°926′ N, 82°1987′ E).

indeed the need of the hour (Dubey et al., 2022). Also, the adoption of suitable cultivation practices that stimulate the soil microbiota (Elhaissoufi et al., 2021), innate endurance and tolerance of crops against pests and diseases, floods, submergence, and water lodging, etc. is also important for food production under the changing climatic conditions (Khatoon et al., 2020; Harindintwali et al., 2021; Maroli et al., 2021; Thompson et al., 2022).

Rice is one of the important rainfed crops and is a staple diet in most of the Asian countries (where >90% of the world's rice is produced) and parts of the Pacific (www.fao.org). According to the estimates of the Food and Agriculture Organization of the United Nations (UN-FAO), more than half of the global population relies on rice for calories and protein (www.fao.org). In order to feed a rapidly growing population, especially in developing nations, food production would need to almost double (www.fao.org). However, on one hand, increasing population and resultant land-use changes (especially for urbanisation and other developmental activities) reduce the per-capita land availability for agriculture (Zuo et al., 2018), whereas intensive cultivation practices reduce the quality of soil and thereby the agricultural yield, including rice production (Dubey et al., 2022). On the other hand, erratic weather events such as changing rainfall patterns, droughts, flooding, submergence, occurrence and prevalence of newer pests and diseases, etc., undermine the productivity of rice (Wheeler and Braun, 2013). Therefore, the adoption of climate-resilient and planet-friendly cultivation of rice is essential for ensuring food and nutritional security in India and other Asian countries (Cui et al., 2018; Ishfaq et al., 2020; Panneerselvam et al., 2020; Ji et al., 2021; Banayo et al., 2022).

Innovative rice cultivation practices are being reported from different rice cultivating regions across the world. These practices include providing smallholder farming communities with science-and evidence-based management practices such as dry direct seeded rice cultivation to help them cope with challenges (Alam et al., 2018; Cui et al., 2018; Ishfaq et al., 2020), sustainable intensification (Zuo et al., 2018), investigating the synergistic effects of nutrients (Ji et al., 2021), deploying modern molecular tools for improving desirable traits in rice i.e., improving seed germination, growth, yield, tolerance, and nutritional quality (Zhang et al., 2020; Reddy et al., 2021; Ayaad et al., 2021), engineering soil microbiome by co-inoculation of plant-growth promoting microorganisms (Kumar and Dubey, 2020), adoption of organic and resource conserving practices (Dubey et al., 2022), farm mechanization (https://www.irri.org/mechanization-and-postharvest) and engineering of the soil microbiome. However, the adoption of various technologies by marginal and subsistence farmers in developing nations mainly depends upon their cost-effectiveness as well as their willingness to adopt (i.e., social, or cultural barriers). Therefore, the validation of suitable cultivation strategies that can be easily employed by the local farmers is of paramount significance.

Like in other Asian countries, rice is also a staple crop in India, cultivated on ~44 Mha of land and contributing 20% of the total rice production across the world (Gujja and Thiyagarajan 2009). It has been predicted that rice production has to be increased to 130 Mt by 2030 to feed a growing Indian population (Gujja and Thiyagarajan 2009). However, 13.6 Mha of land is prone to drought, 2.25 Mha faces flood and 6 Mha of land is prone to submergence and waterlogging conditions, which results in a significant yield gap (Barah, 2005; Gujja and Thiyagarajan 2009; Pandey and Bhandari, 2022). Smallholding and marginalized farmers are more vulnerable to these stresses as they mostly utilize lowlands for rice production due to its relatively low rental/purchasing cost (Mohanty and Yamano, 2017; Kumar et al., 2019). Reducing a yield gap of 1.3–1.8 million tonnes can result in 300–400 USD ha^{-1} of additional benefits (Mohanty and Yamano, 2017). As a result, documenting, validating, and upscaling climate adaptive and innovative farm practices is critical for increasing the productivity of rainfed crops, particularly rice, under changing conditions (Dubey et al., 2020, 2022). Also, exploiting the native ecological knowledge of farmers is essential to conserve critical natural resources. While rice is commonly cultivated by a single transplantation method, double transplantation is an alternative method adopted by very few small/-medium farmers in some S.E. Asian countries like Bangladesh, India, Nepal, and Myanmar (Azad and Hossain, 2006; Khatun et al., 2007; Ashem et al., 2010; Singh et al., 2017; Kumar et al., 2019). Though rice is commonly cultivated in most of the Indian states, only a small number of farmers (mainly tribal communities) in a few states like Assam, Bihar, Meghalaya, West Bengal and eastern Uttar Pradesh are practicing double transplantation (Singh et al. 2003, 2017; Khatun et al., 2007; Satapathy et al., 2015; Das et al., 2017; Kumar et al., 2019). However, no detailed studies are available on the overall sustainability assessment of the double transplantation method in rice i.e., unveiling its social, environment, and economic importance as well as its linkage with UN SDG goals and target. As a result, the current study was aimed to: (i) examine the level of adoption of double transplantation by local farmers in five different districts of eastern Uttar Pradesh (UP), North India; (ii) investigate the ecological and economic benefits of double transplantation used in two experimental fields in two different agro-climatic zones (one in the Indo-Gangetic flood-plain and the other in the dryland of the Vindhyan hill region) of eastern UP, with or without the addition of farmyard manure; and (iii) assess the nexus between double transplantation practice and UN-SDGs in Indian context, and thereby develop a suitable package of practices for sustainable rice production in eastern Uttar Pradesh, North India.

2. Material and methods

2.1. Field survey and experimental site

A three-year study (2016–2018) was conducted to validate climate resilient practices for sustainable rice production in two agroclimatic zones in eastern Uttar Pradesh, North India, namely the middle Gangetic plain (floodplain) and the Vindhyan zone (dryland) (Dubey et al., 2020, Fig. 1). Prior to the field trials, a year-long survey (July 2016–June 2017) consisting of both direct field visits and through structured questionnaires was conducted on a two-tier basis. The types of various climate smart practices adopted by local farmers were studied during the initial round, whereas the extent of adoption of these practices by local farmers based on their landholding, such as small (<0.5ha), medium (0.5ha–2ha) and large (>2ha) were noted during the second survey. Altogether, 456 local farmers belonging to the three different landholdings were contacted to identify the most promising climate-smart practices employed by them for rice production.

The study region (i.e., Eastern Uttar Pradesh) is majorly a rainfed system, predominantly following rice-wheat cropping (Dubey et al. 2020, 2022). Based on the field survey and through the interaction with the local farmers, it was found that the practices such as single transplantation, double transplantation, and the application of farm yard manure (FYM) were the adaptive cultivation practices for rice preferred by the local farmers. While single transplantation is more prevalent in various agro-climatic zones of India, only a few small-scale farmers are employing double transplantation in rice. Therefore, a two-year field validation of both transplantation methods has been employed for two locally grown rice cultivars, viz., Moti-NP-360 (140 days), and Sampurna Kaveri (150 days) in the above two agro-climatic zones for onsite validation with or without the application of FYM. Also, before starting the actual experiment, one-year conventional farming practice (i.e., single transplantation of rice) was done at both sites for homogenization of soil quality and field conditions.

2.2. Experimental design and field crop management

Field plots (10 × 5 m^2 size) were arranged in a randomized block design (RBD) in the above-mentioned sites for various rice cultivation practices such as single transplantation (ST), double transplantation (DT), ST + FYM, and DT + FYM for two locally grown rice varieties.

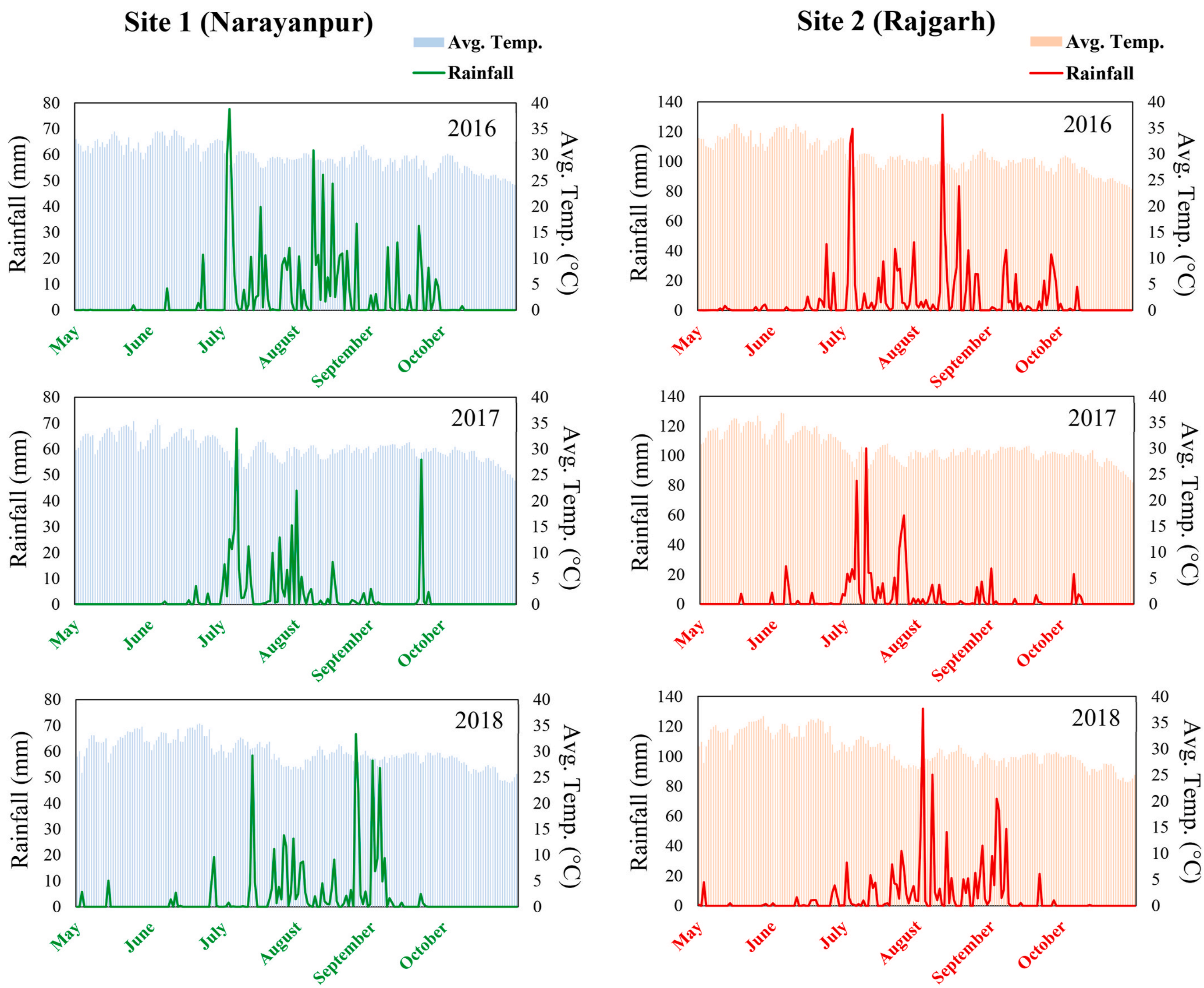

Fig. 2. Graph showing daily average temperature (°C) and rainfall (mm) during rice cropping months (i.e., from May to October) at two selected sites in Mirzapur district of eastern UP (Narayanpur and Rajgarh) over the study period.

Each plot within a particular transplantation trial was separated with earthen bunds, whereas plots for two different transplantations (i.e., space between single and double plantation plots) were separated by a distance of two feet with earthen bunds. Land preparation such as plowing, puddling, levelling, etc. was done 2–3 weeks prior to rice transplantation. Regarding FYM addition, it was applied in both plantation types during the land preparation stage itself and was at a rate of 8 ton ha^{-1} during the first year only. Moreover, inorganic NPK fertilizers in the form of Urea, Di-ammonium phosphate (DAP) and Muriate of potash (MOP) were given at 75% (112.5 Kg: 45 Kg: 45 Kg) in FYM amended plots, whereas 100% of inorganic fertilizers were applied in plots without FYM amendment. As needed, top dressing such as zinc ($ZnSO4$) and sulphur (gypsum) in 1.5% urea solution was applied when the leaves became dusty brown or yellow (as per local farmer's practice).

2.3. Single and double transplantation of rice

In single transplantation (ST), rice seedlings were grown in nurseries for 20–35 days and after that the seedlings were directly transplanted into the main field with a planting density of 3–4 seedlings hill^{-1} and a spacing pattern of 20 × 20 cm (row x row) (Guan et al., 2022). Though ST is the most common practices of rice cultivation, it lacks endurance to withstand heavy rainfall, flood, semi/deep water submergence, plant lodging or poor crop stand during pre-monsoon rain and the delay in monsoon rain (specially in lowlands), and thereby often resulted in poor survival rate of transplanted seedlings (merely 2–3 seedlings). However, in double transplantation, a two-time transplantation (i.e., double) of rice seedlings were done from nurseries to intermediary fields and then to the main rice fields. In DT practices, rice seedlings were initially grown in nurseries for 20–30 days and after that transferred the seedlings into an intermediary field bed with a planting density of 10–12 seedlings hill^{-1} and a spacing pattern of 10 × 10 cm (row x row) and eventually, after 15–25 days, the final transplantation into the main rice field with a planting density of 1–2 seedlings hill^{-1}and a spacing pattern of 15 × 15 cm (row x row). Hence, the DT provides an expanded window of almost 40–50 days (20–30 days in nursery + 15–25 days intermediary field) for seedling growth, in comparison to merely 20–35 days window in ST. The DT practice offers merit in establishing small sized nursery beds (up to 1/3rd size is reduced) with reduced seeding rate by up to 50%, thereby saving nursery input cost. The 1/10th land area of the main field is utilized as an intermediary field which offset any additional land requirement in DT practice.

For single plantation, a rice nursery (3.75 m^2 bed size) was established between 5–6th of June and the grown seedlings were manually

Table 1

The details of variable input cost for nursery bed, intermediary field (field bed-1) and main field (field bed-2) showing the difference in quantity of inputs for ST (single transplantation) and DT (double transplantation) practices in the two studied sites i.e., Narayanpur and Rajgarh. The values shown in column (quantity ha^{-1}) is same for studied cultivars and is only for the initial year of trial. The year wise ($^{\$}$), site wise ($^{\#}$), and practice wise i.e. shift from ST to DT practice (*) variation that incurred in input cost due to variation in quantity ha^{-1} for various input parameters are highlighted through respective symbols.

Activities/operations			Input unit ha^{-1} in field beds	Unit Cost (INR)	Quantity ha^{-1}			
					Narayanpur (site 1)		Rajgarh (site 2)	
					ST	DT	ST	DT
Nursery field Bed	Seeding *		Kg ha^{-1}	75	24	12	24	12
	Land Preparation	Ploughing	hour ha^{-1}	30	2.5			
		Puddling + Levelling		40	4			
	Inorganic Fertilizer	Urea (N)	Kg ha^{-1}	6	8			
		Di-ammonium phosphate (P)		26	10			
	Farm yard manure (FYM) *		ton ha^{-1}	1000	0.6	0.2	0.6	0.2
	Irrigation (Diesel pump rental charge) $^{\$ *\#}$		hours ha^{-1}	40	14	6	20	8
	Human Labour (Irrigation + Nursery establishment) $^{\$ *\#}$		men-hour ha^{-1}	50				
Field Bed-1 (Intermediary field)	Land Preparation*	Ploughing *	hour ha^{-1}	30	NA	2	NA	2
		Puddling + Levelling *		40		4		4
	Inorganic* Fertilizer*	Urea (N) *	Kg ha^{-1}	6		12		12
		Di-ammonium phosphate (P) *		26		3		3
	Farm yard manure (FYM) *		ton ha^{-1}	1000		0.8		0.8
	Irrigation (Diesel pump rental charge) $^{\$ *\#}$		hours ha^{-1}	50		9.5		14
	Human Labour $^{\$ *}$	Irrigation $^{\$ *\#}$	Men-hour ha^{-1}			9.5		14
		Fertilizer Input *				1		1
		Seedling transplantation, nursery to bed 1 *	Women-day- ha^{-1}	200		12		12
Field Bed-2 (Main field)	Land Preparation	Ploughing	hour ha^{-1}	30	8			
		Puddling + Levelling		40	16			
	Inorganic Fertilizer $^{\$}$	Urea (N) $^{\$}$	Kg ha^{-1}	6	150 [25% less in FYM amended plots]			
		Di-ammonium phosphate (P) $^{\$}$		26	60 [25% less in FYM amended plots]			
		Muriate of Potash (K) $^{\$}$		16	60 [25% less in FYM amended plots]			
		Sulphur (S)		120	8			
		Zinc (Zn)		100				
	Farm yard manure (FYM) $^{\$}$		ton ha^{-1}	1000	NA [8-ton ha^{-1} - Applicable only for FYM amended plots]			
	Irrigation (Diesel pump rental charge) $^{\$\#}$		hours ha^{-1}	50	96		168	
	Human labour $^{\$}$	Seedling transplantation (bed 1 to bed 2) *	women-day ha^{-1}	200	32	22	32	22
		Fertilizer Input	men-hours ha^{-1}	50	15			
		Irrigation $^{\$\#}$			96		168	
		Weeding	women-day ha^{-1}	200	27			
		Harvesting						
		Post harvesting activities (men-day ha^{-1})	men-day ha^{-1}	300	13			
		Post harvesting activities (women-day ha^{-1})	women-day ha^{-1}	200	18			

transplanted (3–4 seedlings per hill; 20 × 20 cm spacing) in the main field between 5–6th of July, i.e., 30 days after sowing (DAS). However, in double plantation, the nursery (1.25 m^2 bed size) was established between 19 and 20th of May and the initial grown seedlings were first transplanted (8–10 seedlings hill^{-1}; 15 × 15 cm spacing) in an intermediary field (5 m^2 bed size) between 12 and 15th of June (24–25 DAS), and eventually the second transplantation (1–2 seedlings hill^{-1}; 20 × 20 cm spacing) of grown seedlings to the main field was done between 2–4th of July (42 DAS). The water level in the nursery bed (50 mm in Narayanpur and 80 mm in Rajgarh field) and in the intermediary field bed (150 mm at both sites) was maintained throughout via irrigation. The irrigation was followed as per the local weather conditions in the selected sites, and the daily average temperature and rainfall dataset are shown in Fig. 2 (www.mausam.imd.gov.in). Accordingly, in floodplain area (i.e., Narayanpur), the water level in the main field was maintained at a depth of ~150 mm at every 15-day interval up to 65–80 days after transplantation (DAT), whereas in dryland (Rajgarh), the water level (~150 mm) was maintained at every 12-day interval up to 72–84 DAT. After that, the soil was kept saturated unless flooding occurred by monsoon rainfall and periodic irrigation/chemical fertilizer inputs and weeding were done manually.

2.4. *Crop growth and yield attributes*

After the transplantation, nine plants were randomly tagged in each plot and studied for the plant growth attributes. The tiller number of seedlings^{-1} was counted during both the vegetative (40 DAT) and reproductive stages (75DAT) and the productive tiller number of seedlings^{-1} was counted to estimate the percentage of fertile tiller. Rice was harvested at maturity (i.e., 105 DAT) and growth traits such as tiller length, i.e., from stem base to panicle tip (cm), panicle length (cm), grain and straw yield (ton ha^{-1}) were measured (Mahamud et al., 2013). Panicles at maturity were hand-threshed to segregate both fertile (filled) and non-fertile (non-filled) grains, and the 1000-husked grain weight and the percentage of fertile grains were calculated accordingly. The post transplantation crop growth rate (PTCGR, gm hill^{-1} day^{-1}) was assessed in accordance with Radford (1967). The impact of various transplantation techniques, as well as FYM addition, on leaf vascular structure and grain endosperms (grain intactness) was evaluated using a scanning electron microscope (EVO 18 Research, ZEISS, Jena, Germany) with a resolution of 2–200 μm for grain and 2 μm for leaf (Hao et al., 2019). The resilient attributes in response to submergence/lodging, pest infestation/diseases, etc., were measured by counting the number of

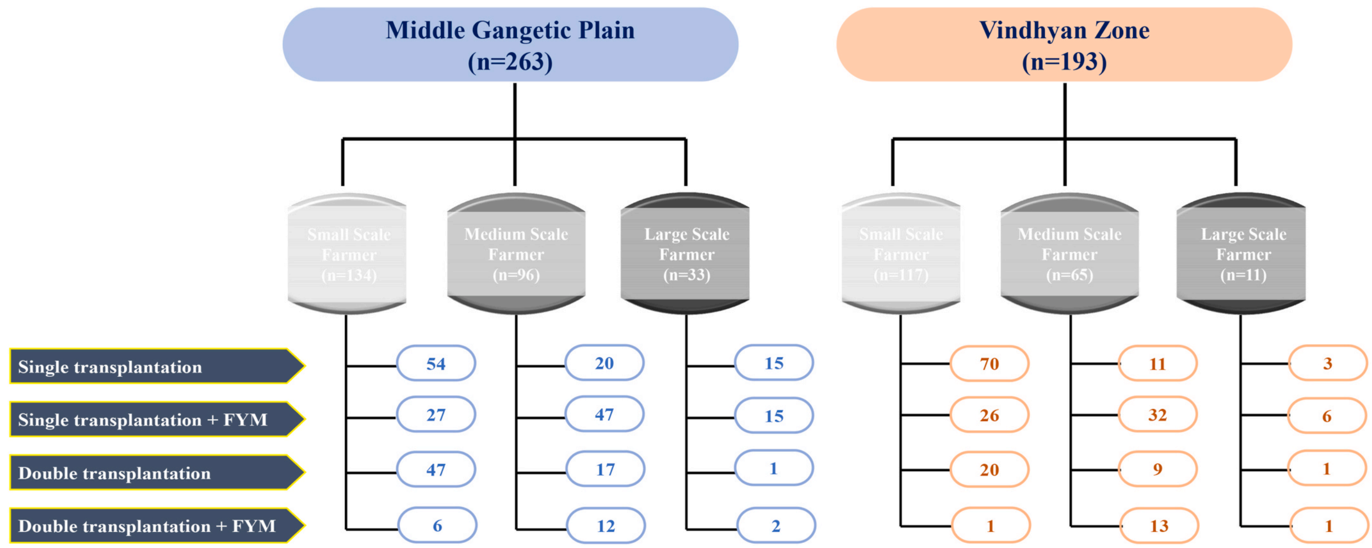

Fig. 3. Scale at which four different agronomic practices i.e., Single transplantation (ST: Control), ST + FYM, Double transplantation (DT) and DT + FYM) employed by farmers in middle Gangetic plain (MGP, n = 263) and Vindhyan zone (VZ, n = 193) of eastern Uttar Pradesh, North India. Farmers were classified into small (S), medium (M) and large (L) based on landholding.

plants susceptible to various factors per unit area. Days to maturity were determined by 80% of spikelets' attaining physiological maturity (Unkovich et al., 2010).

The grain yield and straw yield were determined at maturity by harvesting plants manually (i.e. from ground level), sun drying and weighing, and finally the grain weight was adjusted to 14% moisture content (Alam et al., 2018). The harvest index (HI) was computed based on the fraction of grain yield in total aboveground biomass (grain + straw) (Unkovich et al., 2010). The sustainability assessment of studied agronomic practices was done in terms of the sustainability yield index (SYI) by offsetting the variation in annual grain yield (Rao et al., 2014).

2.5. Soil sampling and analysis

Soil sub-samples were collected from a depth of 0–15 cm after 90 DAT and were mixed to form a composite sample for each plot and immediately taken to the laboratory for further analysis. The collected soil samples were sieved and oven dried (6 mm mesh; 80 °C) for estimating bulk density (gm cm^{-3}), moisture content (%) and water holding capacity (%) (Estefan et al., 2013). The remaining soil samples were air dried, sieved (2 mm mesh), and stored in refrigeration (4 °C) and were subjected to physio-chemical and microbiological analysis. pH and electrical conductivity (EC) were analysed by the CyberScan-500 pH and EC meter. Soil organic carbon (SOC) and available nitrogen (AN) were estimated in accordance with Walkley and Black (1934) and Kalra and Maynard (1991). Soil microbial biomass carbon and nitrogen (MBC and MBN) were determined by a modified chloroform fumigation-extraction method (Vance et al., 1987). The fresh soil samples were estimated for total microbial counts (bacterial and fungal) (Jett et al., 1997; Marotz et al., 2001) and soil enzyme dehydrogenase activity (SDA) (Casida et al., 1964). The observed grain yield in the N fertilized field plot as well as in the false control plot (i.e., with no fertilizer treatment), the agronomic efficiency (AE) of applied N (as urea fertilizer), also termed as agronomic nitrogen use efficiency (NUE), was calculated (Dobermann, 2007; Hao et al., 2019).

2.6. Economic performance and overall sustainability assessment

The economic performance of different agronomic interventions was compared using total variable input cost (TC), gross return (GR), gross margin (GM), and benefit: cost ratio (BCR) (Alam et al., 2018).The TC was calculated by computing various input costs during the entire cultivation stage, including the cost incurred for nursery bed, intermediary field (bed-1), main field (bed-2), land preparation (hour ha^{-1}), seeding, inorganic chemical fertilizers (Kg ha^{-1}), organic FYM input (ton ha^{-1}), irrigation cost (hour ha^{-1}) and human labour charges (men-day-ha^{-1} or women-day-ha^{-1}). The unit price of each operation and minimum gender-specific wages were computed based on the prevailing charges in the study region (Table 1). The socio-environmental sustainability of rice production under rapidly increasing daily labour cost (social factor), and declining water table owing to warming climate (environmental factor), relies majorly on labour and water labour productivity respectively. The labour productivity (grain yield $labour^{-1}$) of both male and female labourers was computed for each practice (Stuart et al., 2018). The number of labour days per rice season was estimated by dividing the total labour cost per season (in nursery bed + field bed-1+ field bed-2) by the average daily wage rate (INR Rs. 200 and 300 for women and men's labour, respectively). Irrigation water productivity (IWP) of various plantation methods was computed by dividing the grain yield to the amount of water utilized for irrigation (m^3 ha^{-1}) (Stanhill, 1986; Alam et al., 2018). The nexus (i.e., synergies and trade-offs) between double plantation practice and UN-SDG targets in Indian context are assessed based on network analysis done via SDG interlinkages Analysis and Visualisation tool (V4.0) of IGES (https://sdginterlinkages.iges.jp/visualisationtool.html; https://www.iges.or.jp/en).

2.7. Statistical analysis

The observed datasets (mean ± SD) for rice growth attributes, yield components, climate resilience and soil quality parameters were subjected to one-way ANOVA followed by Duncan's Multiple Range Test (DMRT) (SPSS 23.0 Software). Also, stepwise linear regression was analysed for finding determinant variables for harvest index (HI) and sustainability yield index (SYI). Paired student's t-test was performed to test the significant difference in benefit: cost ratio (BCR) over the experimental years.

Table 2
The effect of various cultivation practices on growth attributes (tiller number, tiller length, panicle length, grains per panicle and 1000 grain weight) in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. ST = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

Year	Practices	Tiller No. seedlings^{-1}		Tiller length (cm)		Panicle length (cm)		Grains panicle^{-1}		1000-grain weight (Test weight) (g	
		Moti	SK	Moti	SK	Moti	SK	Moti	SK	Moti	SK
Narayanpur											
2017	ST (Control)	5.0 ± 0.8^{a}	4.8 ± 0.9^{a}	94.9 ± 2.8^{a}	94.2 ± 5.4^{a}	16.4 ± 0.5^{a}	18.7 ± 1.4^{a}	280.4 ± 14^{a}	292.8 ± 20.4^{a}	23.9 ± 2.7^{a}	26.9 ± 2.9^{a}
	ST + FYM	5.8 ± 0.7^{a}	5.7 ± 0.8^{a}	100.8 ± 3.9^{b}	100.6 ± 5.7^{ab}	19.6 ± 0.8^{b}	20.8 ± 1.9^{ab}	292.3 ± 16.6^{ab}	307.8 ± 20.7^{abc}	27.2 ± 2.9^{bc}	30.6 ± 3.1^{b}
	DT	12.5 ± 1.2^{b}	11.7 ± 1.4^{b}	108 ± 6.1^{c}	110.3 ± 5.3^{c}	20.4 ± 1.2^{bc}	20.8 ± 1.3^{ab}	313.7 ± 28^{bcd}	315.9 ± 16.2^{bc}	32.4 ± 2.4^{d}	31.9 ± 2.5^{b}
	DT + FYM	17.1 ± 1.8^{c}	16.6 ± 1.9^{c}	115.7 ± 4.2^{d}	112.8 ± 5.7^{c}	21.3 ± 1.3^{cd}	23.4 ± 2.8^{cd}	326.7 ± 19.5^{de}	326.8 ± 25.3^{cd}	35.6 ± 2.5^{e}	36.1 ± 3.4^{c}
2018	ST (Control)	4.8 ± 0.7^{a}	4.8 ± 0.9^{a}	96.6 ± 2.6^{ab}	96.7 ± 2.6^{a}	19.5 ± 1.3^{b}	20.9 ± 2.2^{ab}	282.8 ± 14.1^{a}	298.9 ± 10.6^{ab}	25.2 ± 2^{ab}	27.1 ± 3.9^{a}
	ST + FYM	5.7 ± 0.9^{a}	5.4 ± 0.8^{a}	105.4 ± 4.8^{c}	106.6 ± 9.4^{bc}	21.8 ± 1.8^{de}	21.9 ± 2.6^{bc}	301.1 ± 24.3^{abc}	326.1 ± 23.5^{cd}	28.4 ± 2.3^{c}	32.6 ± 2.8^{b}
	DT	12.6 ± 2.6^{b}	11.7 ± 1.7^{b}	108.9 ± 5.3^{c}	113.3 ± 7.9^{c}	23.1 ± 1.7^{ef}	22.9 ± 1.6^{bcd}	318.4 ± 30.1^{cd}	327.4 ± 24.7^{cd}	32.9 ± 2.5^{d}	32.8 ± 2.4^{b}
	DT + FYM	18.8 ± 1.2^{d}	18.5 ± 2.1^{d}	119.8 ± 6.2^{d}	122.4 ± 9.5^{d}	24.0 ± 1.5^{f}	25.3 ± 3.5^{d}	342.4 ± 20.9^{e}	342.2 ± 21.1^{d}	36.3 ± 2.4^{e}	37.3 ± 2.7^{c}
Rajgarh											
2017	ST (Control)	4.0 ± 1^{a}	3.8 ± 1.2^{a}	90.3 ± 2.4^{a}	90.9 ± 6.9^{a}	16.2 ± 1.1^{a}	19.8 ± 1.4^{a}	223.2 ± 16.7^{a}	223.8 ± 16.9^{a}	21.8 ± 2.5^{a}	24.9 ± 2.9^{a}
	ST + FYM	4.3 ± 1^{a}	4.3 ± 0.7^{a}	95.2 ± 3.5^{bc}	99.4 ± 4.9^{bc}	19.2 ± 1.1^{bc}	20.8 ± 1.5^{abc}	228.8 ± 16.7^{ab}	229 ± 17.4^{a}	25.8 ± 2.6^{b}	29.3 ± 3^{b}
	DT	6.0 ± 1.2^{bc}	5.9 ± 1.3^{bc}	95.4 ± 4^{bc}	100.1 ± 4.0^{bc}	20.2 ± 1.3^{cd}	21.6 ± 1.8^{abc}	244 ± 10.8^{bcd}	243.2 ± 26.6^{ab}	31.7 ± 2.6^{c}	30.3 ± 1.8^{bc}
	DT + FYM	8.5 ± 1.8^{d}	8.3 ± 1.8^{d}	100.1 ± 5.8^{d}	102.0 ± 5.2^{bc}	20.4 ± 1.3^{cde}	22.4 ± 2.4^{bcd}	255.2 ± 14.1^{de}	256.2 ± 26.9^{bc}	35.3 ± 3.3^{d}	35.5 ± 3.2^{ef}
2018	ST (Control)	4.1 ± 0.8^{a}	4.1 ± 0.9^{a}	93.3 ± 6.4^{ab}	97.9 ± 5.5^{b}	18.4 ± 1.9^{b}	20.5 ± 1.4^{ab}	235.4 ± 13.3^{abc}	239 ± 20.2^{ab}	22.4 ± 2.7^{a}	25.9 ± 2.7^{a}
	ST + FYM	5.3 ± 1.1^{ab}	5.1 ± 1.0^{ab}	98.8 ± 3.7^{cd}	103.8 ± 5.0^{bcd}	21.0 ± 2.3^{de}	21.9 ± 1.7^{bc}	241 ± 21.2^{bcd}	245.2 ± 17.5^{abc}	27.1 ± 2.9^{b}	32.2 ± 2.7^{cd}
	DT	6.8 ± 2.0^{c}	7.0 ± 1.0^{c}	99.2 ± 1.3^{cd}	104.5 ± 5.7^{cd}	21.8 ± 1.8^{de}	22.5 ± 2.1^{cd}	247.3 ± 19.3^{cd}	265.1 ± 23.9^{c}	32.4 ± 2.5^{c}	34.2 ± 2.5^{de}
	DT + FYM	9.4 ± 1.9^{d}	9.6 ± 1.4^{d}	105 ± 4.9^{e}	108.5 ± 8.0^{d}	22.1 ± 2.3^{e}	23.8 ± 2.1^{d}	268.7 ± 14.2^{e}	297.2 ± 17^{d}	36.1 ± 2.4^{d}	37.5 ± 2.9^{f}

3. Results and discussion

3.1. Prevailing practices in eastern UP and the scale of adoption of various practices

The prevailing rice cultivation practices in eastern UP (such as ST, ST + FYM, DT, and DT + FYM) as well as the scale of adoption of such practices by various farmers (i.e., small-scale, medium and large-scale farmers, based on their landholdings) in both middle Gangetic plain and Vindhyan zone is presented in **Figure (3)**. For this, an year-long extensive field survey has been conducted among the farming communities of various landholdings in five districts of the eastern UP to know the prevailing adaptive practices employed in the region as well as the level of adoption of such practices for the overall benefits. (Fig. 3). Out of the response received from 456 farmers surveyed, the majority of them (71.49%) are following ST practices with or without FYM (i.e., 38% of the farmers followed ST whereas 33.5% of farmers were adopted ST + FYM), while the remaining farmers (28.51%) followed DT practices with or without FYM input (i.e., 21% of DT and 7.5% of DT + FYM). Though ST was the most prevalent practice employed for rice cultivation in the region, the field survey revealed that those who were adopting DT practices received additional benefits such as higher yields and farm returns (15–25% higher returns in DT than ST practices), resilience to flood submergence/lodging, and tolerance to pests and diseases (17–30% of less incidence of pest and diseases in DT than ST). Hence, field trials were further conducted to evaluate the ecological, economic, and overall sustainability of DT practices along with FYM addition in comparison to the conventional ST method.

3.2. The effect of ST, DT, along with FYM addition on plant growth and yield

The impact of two different transplantation methods (ST and DT) along with the addition of FYM replacing 25% of the recommended fertilizer dose (RDF) on plant growth attributes such as tiller and panicle lengths (cm), tiller number of seedlings^{-1}, grain panicles^{-1}, and 1000-grain weight (test weight) of two different locally used rice varieties (*Moti-NP360* and *Sampurna Kaveri*) are presented in Table (2). Among the various practices, the DT + FYM resulted in the highest number of tiller seedlings^{-1} in both *Moti-NP360* and *Sampurna Kaveri* varieties in Narayanpur and Rajgarh and it varied from 4.8 to 18.8 in Narayanpur and 3.8 to 9.6 in Rajgarh. Similarly, the tiller length and panicle length varied from 94.2 cm to 122.4 cm and 16.4 cm–25.3 cm in Narayanpur and from 90.3 cm to 108.5 cm and 16.2 cm–23.8 cm in Rajgarh, respectively. Similarly, the number of grain per panicle in DT + FYM varied from 322 to 342 in Narayanpur and 268 to 314 in Rajgarh. Moreover, the DT + FYM resulted in higher grain ($p < 0.001$) weight (test weight) than control (ST) and other practices. As evidenced from the field data, the FYM addition significantly increased the growth and yield of both rice varieties in DT + FYM and ST + FYM compared to the control (without FYM, i.e., 100% RDF). However, the significance was more prominent in DT + FYM than in ST + FYM. Literature reported the positive impact of FYM addition on improved growth variables in rice cultivated in various conditions such as rainfed (Bastia et al., 2021),

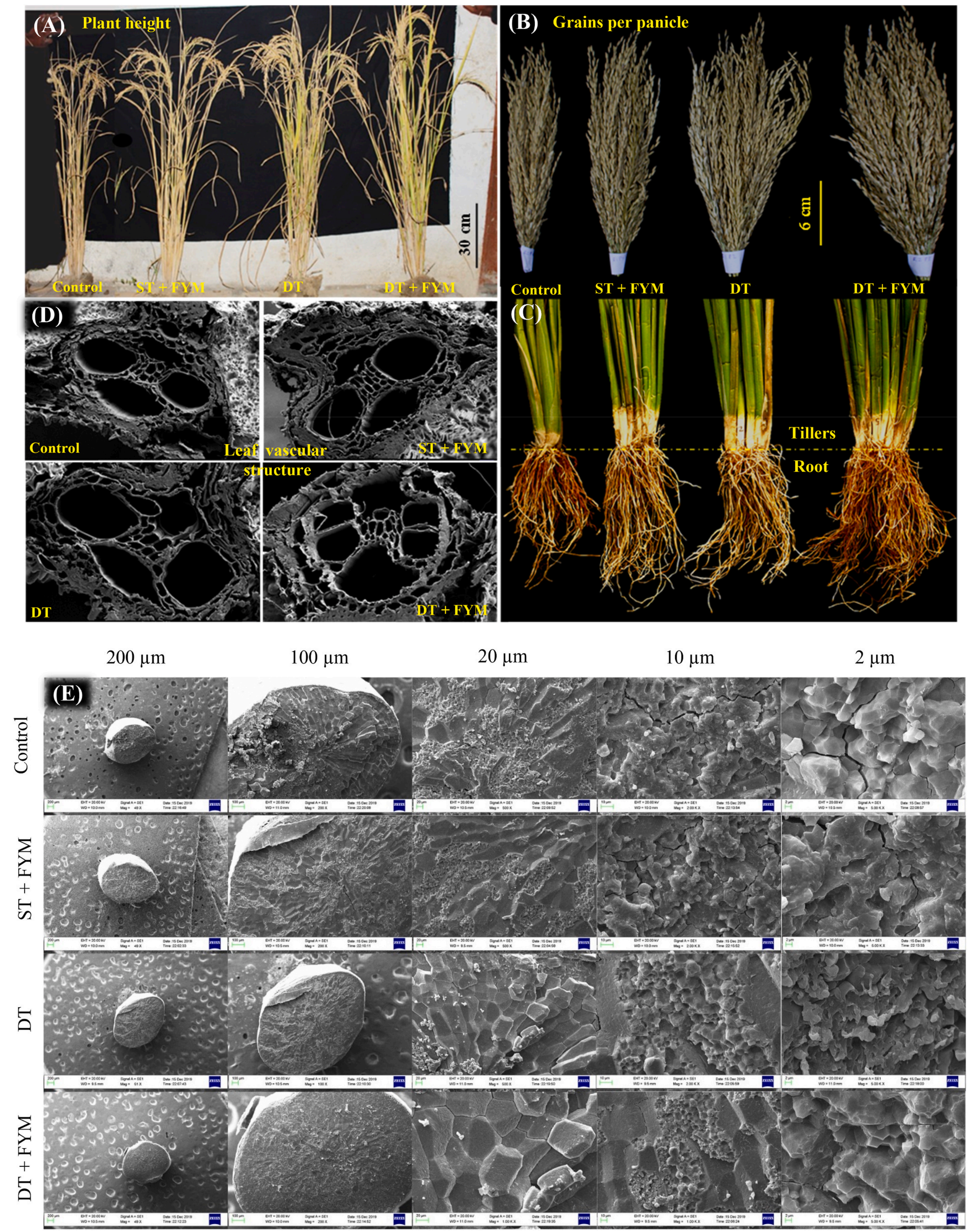

Fig. 4. The effect of various cultivation practices on morphological responses *viz.* **(A)** plant height, **(B)** grains per panicle **(C)** above (tillers) and below growth (root length and density), **(D)** vascular structure of flag leaf at 45 days after transplantation; on anatomical response *viz.* **(E)** SEM photographs showing the effect of various practices on grain endosperm structure i.e., in terms of compactness and intactness.

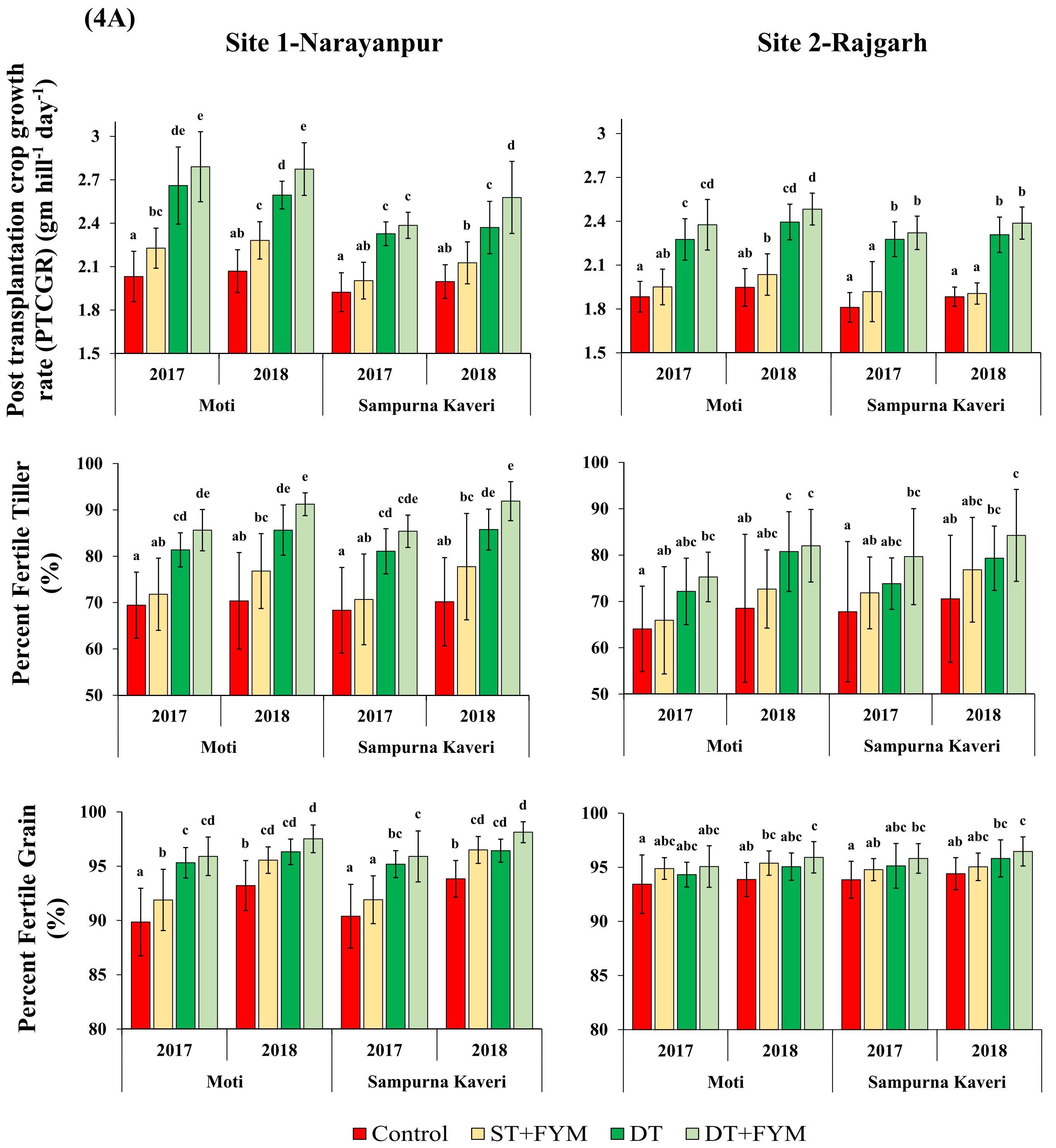

Fig. 5(A). The effect of various cultivation practices on post transplantation crop growth; percent fertile tiller; and percent fertile grains in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. Figure legends: Control = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

upland/mountain areas (Rao et al., 2016; Ditzler et al., 2018), dryland (Rao et al., 2016), Trans-Gangetic plains and Central Plateau and hills in India (Das et al., 2019), Mazandaran, Iran (Saber et al., 2021) and also in other south Asian countries like Bangladesh, Bhutan, Nepal, Pakistan and Srilanka (Ghimire et al., 2017).

While there was no significant difference in tillers per seedlings in both ST and ST + FYM trials of rice varieties (*Moti-NP360* and *Sampurna Kaveri*) in the Narayanpur site (middle Indo-Gangetic plain), the adoption of both DT and DT + FYM in the same sites resulted in a significant increase in tillers seedlings^{-1}. However, in the Rajgarh site (Vindhyan

Table 3
The effect of various cultivation practices on grain and straw yield, harvest index and sustainability yield index in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. ST = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

Year	Practices	Grain yield		Straw yield		Harvest Index (%)		Sustainability Yield Index (%)	
		Moti	SK	Moti	SK	Moti	SK	Moti	SK
Narayanpur									
2017	ST (Control)	5.38 ± 0.02^{a}	5.41 ± 0.01^{a}	5.89 ± 0.11^{bc}	5.66 ± 0.27^{ab}	47.71 ± 0.46^{a}	48.9 ± 1.24^{ab}		
	ST + FYM	5.55 ± 0.06^{b}	5.57 ± 0.03^{b}	6.13 ± 0.11^{cd}	6.05 ± 0.55^{abc}	47.53 ± 0.59^{a}	47.98 ± 2.15^{a}		
	DT	5.87 ± 0.03^{c}	5.87 ± 0.11^{c}	5.4 ± 0.22^{a}	5.54 ± 0.15^{a}	52.11 ± 0.94^{c}	51.44 ± 0.21^{c}		
	DT + FYM	6.2 ± 0.06^{e}	6.27 ± 0.15^{e}	6.17 ± 0.07^{cd}	6.04 ± 0.3^{abc}	50.14 ± 0.03^{b}	50.96 ± 0.99^{bc}		
2018	ST (Control)	5.38 ± 0.01^{a}	5.42 ± 0.02^{a}	5.71 ± 0.2^{b}	5.59 ± 0.35^{ab}	48.51 ± 0.93^{a}	49.26 ± 1.62^{ab}	82.44	82.63
	ST + FYM	6.03 ± 0.19^{d}	6.13 ± 0.05^{d}	6.46 ± 0.1^{e}	6.33 ± 0.04^{c}	48.27 ± 0.49^{a}	49.19 ± 0.27^{ab}	83.59	83.19
	DT	5.99 ± 0.07^{cd}	6.08 ± 0.08^{d}	5.43 ± 0.24^{a}	5.58 ± 0.12^{a}	52.44 ± 0.94^{c}	52.18 ± 0.42^{c}	89.61	88.94
	DT + FYM	6.49 ± 0.04^{f}	6.53 ± 0.03^{f}	6.28 ± 0.05^{de}	6.13 ± 0.17^{bc}	50.81 ± 0.31^{b}	51.57 ± 0.60^{c}	94.21	94.96
Rajgarh									
2017	ST (Control)	5.11 ± 0.2^{a}	5.18 ± 0.03^{a}	5.87 ± 0.1^{b}	6.08 ± 0.13^{a}	46.55 ± 0.59^{a}	46.03 ± 0.42^{bc}		
	ST + FYM	5.21 ± 0.03^{a}	5.2 ± 0.04^{a}	6.14 ± 0.14^{c}	6.73 ± 0.14^{c}	45.91 ± 0.64^{a}	43.62 ± 0.69^{a}		
	DT	5.61 ± 0.09^{b}	5.7 ± 0.11^{b}	5.48 ± 0.09^{a}	6.34 ± 0.15^{ab}	50.59 ± 0.38^{de}	47.33 ± 0.27^{de}		
	DT + FYM	5.93 ± 0.11^{c}	5.97 ± 0.15^{c}	6.21 ± 0.03^{c}	6.88 ± 0.03^{c}	48.82 ± 0.48^{c}	46.43 ± 0.67^{cd}		
2018	ST (Control)	5.21 ± 0.04^{a}	5.24 ± 0.04^{a}	5.72 ± 0.16^{b}	6.41 ± 0.28^{b}	47.65 ± 0.86^{b}	44.99 ± 1.20^{b}	82.24	82.09
	ST + FYM	5.74 ± 0.07^{b}	5.77 ± 0.03^{b}	6.18 ± 0.09^{c}	6.94 ± 0.14^{c}	48.14 ± 0.46^{bc}	45.42 ± 0.54^{bc}	82.4	80.72
	DT	5.7 ± 0.05^{b}	5.7 ± 0.1^{b}	5.43 ± 0.08^{a}	6.17 ± 0.11^{ab}	51.22 ± 0.18^{e}	48.03 ± 0.01^{e}	90.31	90.41
	DT + FYM	6.16 ± 0.04^{d}	6.22 ± 0.1^{d}	6.21 ± 0.1^{c}	6.92 ± 0.07^{c}	49.78 ± 0.29^{d}	47.31 ± 0.36^{de}	95.01	93.89

zone), though there was a difference in growth and tillers seedlings^{-1} in various practices, the effect was not so pronounced as in the case of the Narayanpur site, owing to the sites' specific characteristics (dryland) such as poor quality of soil as well as no previous rice cultivation practiced in the Rajgarh sites. The site-specific difference in yield of the rice-wheat production system was reported earlier (Dubey et al., 2022) as the management as well as inherent edaphic and agrometeorological conditions also govern the crop performance (Bastia et al., 2021; Dossou-Yovo and Saito, 2021). However, the DT practices, with or without FYM addition, significantly increased both tiller and panicle length in Narayanpur and Rajgarh, and the effect was more pronounced in the Narayanpur site than in Rajgarh. Similar to this, an increasing trend was also observed for the number of grains panicle^{-1} at both sites and for both rice cultivars. Furthermore, the DT practice with or without FYM addition significantly increases ($p < 0.05$) the rice test grain weight, as demonstrated in each field trial (Table 2). Moreover, DT practice with or without FYM input showed relatively better results in the Moti NP360 variety than in the *Sampurna Kaveri*. There was a significant difference in test weight in both rice varieties grown in rainfed and drylands. In Narayanpur, the test weight of *Moti-NP360* showed an increase of 13.3%, 33%, and 46.4%, respectively, for ST + FYM, DT, and DT + FYM, then control, whereas in the case of *Sampurna Kaveri*, the pattern for various cultivation practices was found to be 17.1%, 19.8%, and 35.9%, respectively. However, in the Rajgarh site, the percent increase of test weight of Moti NP360 for various practices over control trials was recorded as 19.7%, 45.1%, and 61.6%, respectively, whereas for *Sampurna Kaveri*, it was found as 20.9%, 26.7%, and 43.6%, respectively (Table 2).

The positive effect of DT and FYM additions on the growth and yield of rice is shown in Figure (4). The field trials clearly indicate that DT practices with or without FYM addition significantly improved ($p < 0.05$) the overall growth, including total plant height, tiller number, width, tiller length, total grain number, and grain weight in *Moti-NP360* than ST practices The effect was more pronounced in the second year. Previous studies pertaining to DT cultivation in other agro-ecological regions of India showed increased plant-growth and yield traits in DT than in other practices (Azad and Hossain, 2006; Khatun et al., 2007; Ashem et al., 2010; Satapathy et al., 2015; Das et al., 2017; Singh et al., 2017). For instance, Ashem et al. (2010), reported an increase of 15.3% in tiller length, 16.6% in panicle length, and 12.7% in straw yield in DT compared to conventional practices. Satapathy et al. (2015) reported higher increases in tiller and panicle length in DT than respective controls, and studies have also reported improved growth attributes in DT practices used in a variety of conditions, including late transplantation in lowlands (Ashem et al., 2010; Satapathy et al., 2015), hilly regions (Das et al., 2017), sub-humid systems in India (Singh et al., 2017), and flood prone systems in Bangladesh (Azad and Hossain, 2006). Moreover, DT practices also resulted in higher grain yields (up to 45–80%) (Ashem et al., 2010; Das et al., 2017) and harvest index. Similar to the morphological variations, the DT practices also resulted in improved anatomical features like elongated/enlarged vascular structures in rice. Because vascular tissues are in charge of nutrient and water acquisition and mobilization in plants (Morgan and Connolly, 2013), elongated vascular structures caused by DT practices may result in better nutrient and water acquisition, improved plant growth, and a difference in yield between DT and ST practices. Literature provides evidence that agronomic practices significantly influence the vascular structure and thereby increase nutrient efficiency in crops (Farooq et al., 2019; Ren et al., 2021). The SEM analysis of grains (endosperm structure) also revealed that DT practices significantly improved the grain structure and filling (primarily the compactness and intactness of the endosperm) in rice (Fig. 4E), resulting in a greater increase in test grain weight than the control and ST + FYM addition. The observed relative intactness in grain was further corroborated by the corresponding 1000-grain weights of different practices (Table 2). The DT + FYM resulted in higher grain weight in both Moti and Sampurna Kaveri in Narayanpur (36.3 ± 2.4 g, 37.3 ± 2.7 g, respectively) and Rajgarh sites (36.1 ± 2.4 g, 37.5 ± 2.9 g, respectively) than any other practices. Cultivation/management practices play a crucial role in yield and grain quality in rice, and previous studies reported that irrigational and fertigation systems (Dossou-Yovo and Saito, 2021; Zhang et al., 2021), cultural practices (Majumder and Banik, 2021), dry cultivation (Chen et al., 2020), ratoon cultivation (Huang et al., 2020), planting pattern (Du et al., 2021) etc. affect the grain quality and integrity, i.e. endosperm structure (Hao et al., 2019). Hence, as shown in Fig. 4D and E, DT practices resulted in improved vascular structure and subsequent improvement in nutrient use efficiency, grain filling, microstructure (Li et al., 2007), endosperm integrity, and overall yield.

The impact of various practices such as control, ST + FYM, DT, DT + FYM on post-transplantation crop growth (PTCGR, gm hill^{-1} day^{-1}), percent fertile tillers (PFT), as well as percent fertile grains (PFG) are presented in Figure 5A. Regardless of rice cultivars, a significant

Table 4
The effect of various cultivation practices on soil quality changes in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. ST = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

Soil Quality Parameters	Initial data before experiments	Changes observed during the second year field trial							
		Moti NP 360				Sampurna Kaveri			
		Control	ST + FYM	DT	DT + FYM	Control	ST + FYM	DT	DT + FYM
Narayanpur									
PH	7.96 ± 0.13	7.7 ± 0.05^{a}	7.44 ± 0.12^{b}	7.44 ± 0.12^{b}	7.29 ± 0.11^{b}	7.72 ± 0.18^{a}	7.43 ± 0.03^{b}	7.46 ± 0.03^{b}	7.31 ± 0.06^{b}
Electrical Conductivity (dS meter^{-1})	0.2 ± 0.01	0.223 ± 0.01^{a}	0.27 ± 0.0^{b}	0.24 ± 0.01^{a}	0.28 ± 0.03^{b}	0.21 ± 0.02^{a}	0.28 ± 0.02^{b}	0.24 ± 0.03^{a}	0.29 ± 0.01^{b}
Moisture Content (%)	5.33 ± 0.21	5.25 ± 0.04^{a}	6.46 ± 0.06^{b}	5.53 ± 0.02^{c}	6.57 ± 0.02^{d}	5.23 ± 0.03^{a}	6.38 ± 0.07^{b}	5.42 ± 0.08^{c}	6.55 ± 0.08^{d}
Water Holding Capacity (%)	41.97 ± 1.31	41.1 ± 0.11^{a}	46.1 ± 0.1^{b}	42.1 ± 0.2^{c}	50 ± 0.12^{d}	41.0 ± 0.04^{a}	48.02 ± 0.26^{b}	43.27 ± 0.47^{c}	50.06 ± 0.27^{d}
Available Nitrogen (Kg ha^{-1})	209.1 ± 19.2	271.8 ± 7.2^{a}	296.9 ± 7.2^{b}	263.4 ± 12.5^{a}	301.0 ± 12.5^{b}	271.7 ± 7.2^{a}	301.1 ± 12.5^{b}	271.8 ± 26.1^{a}	305.2 ± 19.2^{b}
Microbial Biomass Nitrogen (μg g^{-1})	31.13 ± 5.19	31.12 ± 5.2^{a}	41.5 ± 5.2^{ab}	31.12 ± 5.1^{a}	43.23 ± 7.9^{b}	33.15 ± 7.9^{a}	43.23 ± 7.9^{ab}	31.12 ± 5.1^{a}	44.96 ± 3^{b}
Soil dehydrogenase (μg gm^{-1} dry soil)	111.3 ± 6.73	117.1 ± 10.6^{a}	153.8 ± 15.2^{b}	113.6 ± 5.87^{a}	163.8 ± 15.5^{b}	110.3 ± 9.9^{a}	163.7 ± 10.9^{b}	110.3 ± 9.91^{a}	161.3 ± 9.92^{b}
Total Bacterial Count (10^{7} g^{-1} Soil)	4.83 ± 1.53	4.17 ± 0.3^{a}	21.23 ± 1.5^{b}	4.2 ± 0.8^{a}	26.13 ± 3.16^{c}	4.56 ± 1.04^{a}	21.8 ± 1.8^{b}	4.83 ± 0.6^{a}	24.27 ± 3.5^{b}
Total Fungal Count (10^{4} g^{-1} Soil)	10.0 ± 3.0	8.67 ± 2.5^{a}	24.67 ± 7.4^{b}	9.0 ± 3.5^{a}	26 ± 6.6^{b}	9.33 ± 0.58^{a}	26 ± 8.5^{b}	9.67 ± 1.5^{a}	26.67 ± 3.2^{b}
Microbial C:N ratio	6.62	7.39	8.03	8.37	8.97	7.13	7.85	8.76	8.76
Rajgarh									
PH	6.31 ± 0.02	6.56 ± 0.23^{a}	6.66 ± 0.06^{a}	6.45 ± 0.16^{a}	6.70 ± 0.09^{a}	6.46 ± 0.04^{a}	6.53 ± 0.19^{a}	6.41 ± 0.16^{a}	6.58 ± 0.06^{a}
Electrical Conductivity (dS meter^{-1})	0.13 ± 0.01	0.25 ± 0.01^{c}	0.22 ± 0.01^{ab}	0.2 ± 0.01^{a}	0.24 ± 0.01^{bc}	0.25 ± 0.01^{bc}	0.223 ± 0.01^{ab}	0.217 ± 0.02^{a}	0.26 ± 0.01^{c}
Moisture Content (%)	3.43 ± 0.49	4.39 ± 0.1^{a}	5.22 ± 0.02^{b}	4.22 ± 0.05^{c}	5.12 ± 0.09^{b}	4.63 ± 0.06^{a}	5.28 ± 0.04^{b}	4.30 ± 0.08^{c}	5.36 ± 0.12^{b}
Water Holding Capacity (%)	31.67 ± 3.33	36.2 ± 0.55^{a}	42.07 ± 0.17^{b}	36.02 ± 0.08^{a}	43.04 ± 0.06^{c}	37.03 ± 0.06^{a}	41.16 ± 0.31^{b}	38.05 ± 0.49^{c}	43.12 ± 0.31^{d}
Available Nitrogen (Kg ha^{-1})	142.2 ± 26.1	117.1 ± 14.5^{a}	129.6 ± 7.2^{b}	125.4 ± 21.7^{b}	129.6 ± 19.2^{b}	112.9 ± 12.5^{a}	129.6 ± 26.1^{b}	117.1 ± 19.1^{ab}	125.4 ± 25.1^{b}
Microbial Biomass Nitrogen (μg g^{-1})	12.1 ± 2.99	24.21 ± 2.9^{a}	29.39 ± 2.9^{a}	22.48 ± 5.9^{a}	29.39 ± 5.9^{a}	24.2 ± 3^{ab}	29.39 ± 2.9^{b}	20.75 ± 5.2^{a}	27.66 ± 2.9^{ab}
Soil dehydrogenase (μg gm^{-1} dry soil)	51.86 ± 3.65	74.98 ± 7.62^{a}	91.66 ± 9.95^{b}	72.83 ± 2.97^{a}	102.7 ± 7.2^{b}	75.31 ± 7.9^{a}	100.2 ± 1.43^{b}	73.66 ± 5.43^{a}	100.1 ± 13.2^{b}
Total Bacterial Count (10^{7} g^{-1} Soil)	4.43 ± 0.83	3.9 ± 0.66^{a}	19.77 ± 1.2^{b}	4.43 ± 0.8^{a}	22.93 ± 1.6^{c}	3.87 ± 0.5^{a}	20.56 ± 1.7^{b}	4.3 ± 0.1^{a}	21.9 ± 2.0^{b}
Total Fungal Count (10^{4} g^{-1} Soil)	4.0 ± 1.0	5.33 ± 2.08^{a}	13.33 ± 3.06^{b}	5.0 ± 1.7^{a}	12.33 ± 2.5^{b}	5.66 ± 2.08^{a}	15.0 ± 4.0^{b}	5.67 ± 2.52^{a}	16.33 ± 3.05^{b}
Microbial C:N ratio	7.0	6.0	9.7	6.74	8.25	6.0	9.7	7.3	8.98

increase in crop growth and fertile tillers was found in DT and DT + FYM practice over control (ST), while the ST + FYM practice imparts positive but non-significant changes. Especially, the PTCGR in *Moti-NP360* on an average enhanced by 21.9% and 28.1% due to DT practice and by 26.8% and 35.7% due to DT + FYM practices in Rajgarh (dryland) and Narayanpur sites (floodplain), respectively. On the other hand, in *Sampurna Kaveri,* DT practice resulted in an increase of PTCGR by 24.1% and 19.8%, whereas the DT + FYM practice resulted in a significant increase of 27.4%, and 26.5% in the above two sites, respectively. However, in the case of percent fertile tiller (PFT), it was found higher in Narayanpur site for both cultivars than Rajgarh. For instance, PFT in *Moti-NP360* increased due to DT practice by 15.2%, 19.4% and by DT + FYM practice by 18.6%, 26.5%, while in *Sampurna Kaveri* enhanced by 10.7%, 20.4% (DT) and by 18.5%, 27.9% (DT + FYM) in Rajgarh and Narayanpur sites respectively. Contrastingly, the percent fertile grains (PFG) was found to be higher due to FYM addition with or without DT particularly in Narayanpur site, whereas in Rajgarh, the increase in PFG was significant in DT + FYM practice only. Despite the common practices and varieties employed at both sites, the variation in crop fertility rate in Rajgarh was mainly due to the lack of agricultural use (i.e., fallowed/abandoned) since last several years owing to the barren nature of the land (Dubey et al., 2022). However, comparatively better performance (i.e. year wise) observed during the subsequent stages, clearly indicates the positive impacts of sustainable practices on overall crop growth and performance (Bastia et al., 2021; Dossou-Yovo and Saito, 2021). Previous studies also proved that the cultivation practices play a decisive role in important agronomic traits such as post-transplantation crop growth, percent fertile tillers, percent fertile grains etc. and innovative practices like machine transplantation (Zhong et al., 2021), irrigation schedules (Zhang et al., 2021), planting pattern (Du et al., 2021), tillage (Ghimire et al., 2017), soil fertility management (Bastia et al., 2021) etc. affected the growth traits in rice. DT practices employed in hilly regions of Meghalaya, India showed an increase in tiller number (from 7 to 12) and panicle per square meter (16%) over ST (Das et al., 2017).

The effect of DT with or without FYM on grain yield, straw yield, harvest index (HI) and sustainability yield index (SYI) of two different rice varieties grown at two different sites are presented in **Table (3)**. It is evidenced that irrespective of rice varieties and sites, the grain yield was enhanced by ST + FYM, DT, DT + FYM with a significant increase by DT + FYM ($p < 0.05$). In Narayanpur, DT + FYM resulted in an increase of yield by 20.54% during the second year, whereas in Rajgarh, it was found to be 18.41%, whereas in the case of Rajgarh, ST + FYM was not

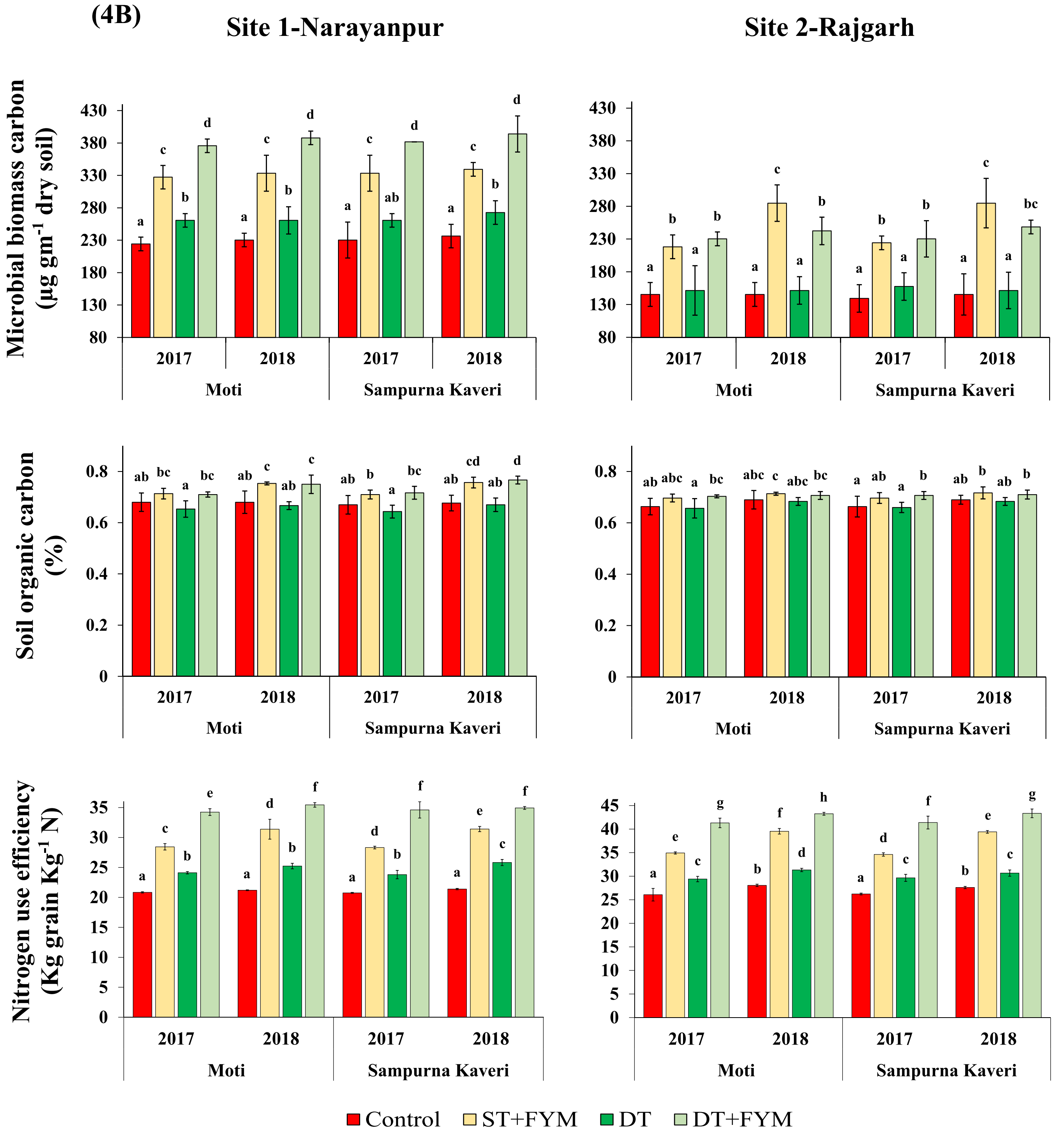

Fig. 5(B). The effect of various cultivation practices on soil microbial biomass carbon; dehydrogenase enzyme; and nitrogen use efficiency (NUE) in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. Figure legends: Control = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

so significant during the first year. Nevertheless, the performance was comparable during the subsequent year (Table 3). The straw yield was mainly enhanced in both ST and DT practices with FYM addition such as ST + FYM and DT + FYM. In Narayanpur, the average straw yield (for both varieties) in ST + FYM and DT + FYM practice was increased by 13.23% and 9.84% than the control, whereas in Rajgarh, it was increased up to 8.11% and 8.23% than the respective control (i.e. 100% RDF). On the contrary to this, the harvest index (HI) was found to be increased due to DT (i.e. both DT and DT + FYM) than ST + FYM and control with relatively significant results in DT alone in both sites. As a result, the DT increased the HI by 8.4% and 5.2% in Moti NP360 and Sampurna Kaveri respectively, whereas ST + FYM during the second

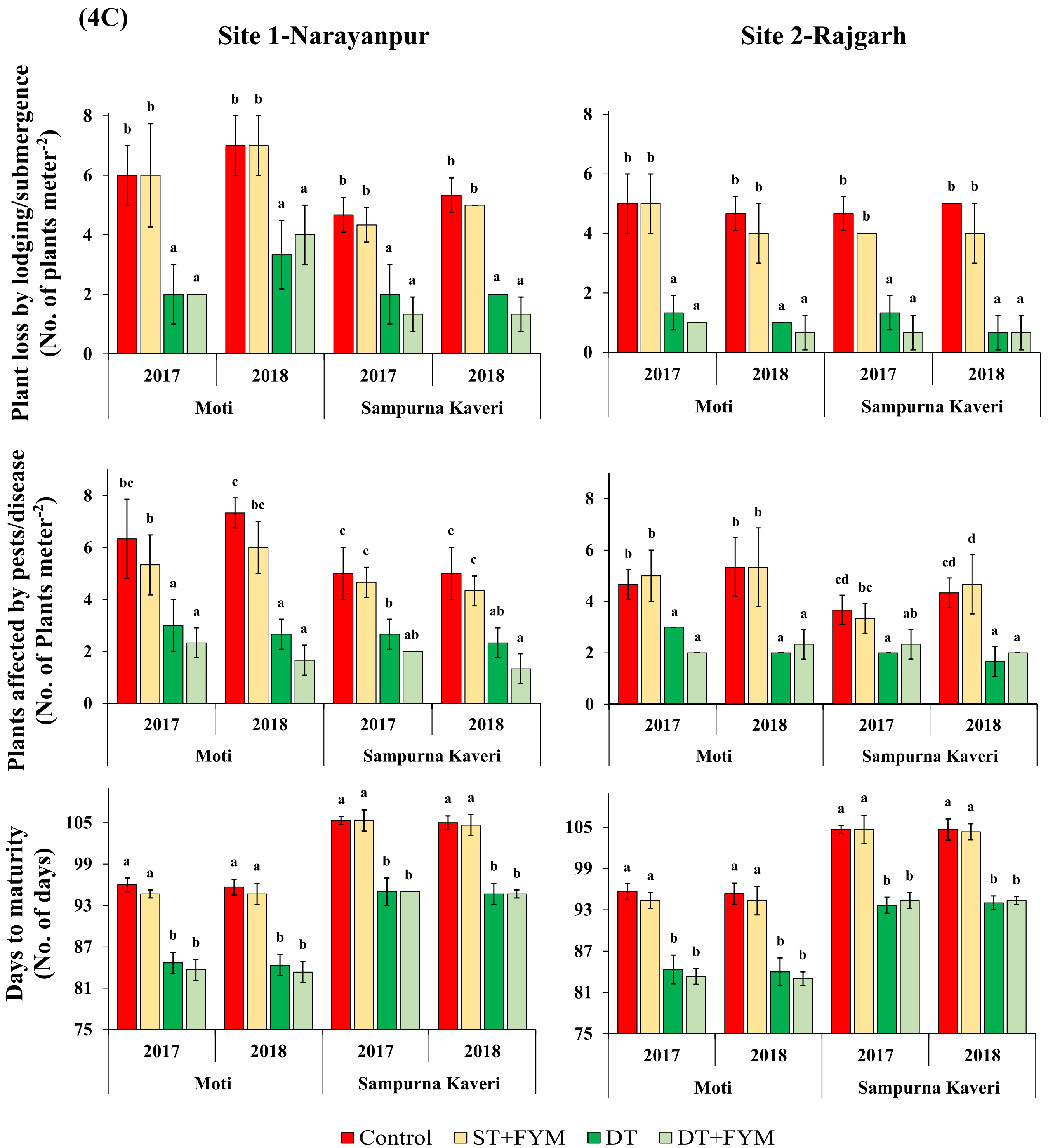

Fig. 5(C). The effect of various cultivation practices on post transplantation rice plant performance in terms of plant loss by lodging/submergence; plant affected by pests/disease; and days to maturity in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Data shown are the Mean ± SD. Mean values followed by different letters within a particular column are significantly different at $p < 0.05$ by DMRT. Figure legends: Control = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure.

year showed better results due to the carryover effect of FYM application during the first year. Among the various practices, DT has resulted in a higher sustainability yield index (SYI) of 8.17% in *Moti-NP360*, and 9.97% in *Sampurna Kaveri*, whereas DT + FYM has resulted in an increase of SYI of almost 15% in both varieties (Table 3). Apart from the addition of various organic inputs (including FYM) (Ghimire et al., 2017; Ditzler et al., 2018; Das et al., 2019; Ji et al., 2021; Bastia et al., 2021; Dubey et al., 2022), the type of cultivation practices also determined the growth attributes in rice. For instances, machine transplantation (Zhu et al., 2019; Zhong et al., 2021) and also the DT

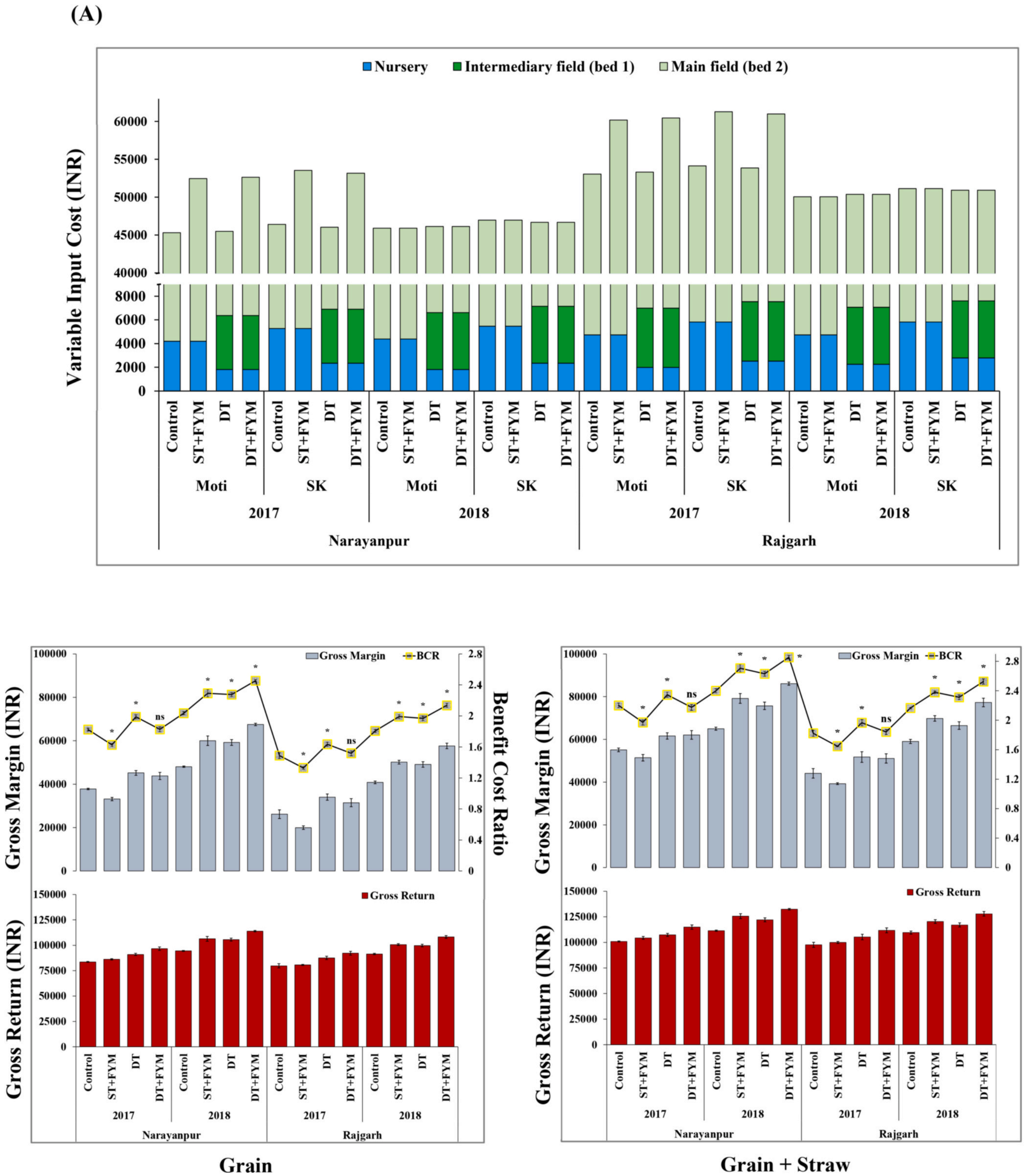

Fig. 6(A). The effect of various cultivation practices on economic performance of different agronomic practices in terms of variable input cost, gross return, gross margin, and benefit: cost ratio (BCR) in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Figure legends: Control = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure. The asterisk marks (*) shows significant difference with two-tailed p-value at p = 0.001.

practices (at the pilot-scale) employed at other agronomic regions such as low-lying and flood prone areas (Azad and Hossain, 2006; Ashem et al., 2010; Kumar et al., 2019), rainfed areas (Satapathy et al., 2015), hilly-regions (Das et al., 2017), Gangetic plain (Singh et al., 2017), rice-vegetable cropping system (Khatun et al., 2007) etc. had resulted in higher leaf area index, panicle bearing tiller, number of filled grains per panicle, dry matter accumulation, yield and farm returns than the conventional practices and an yield increase of up to 80% was reported

(B)

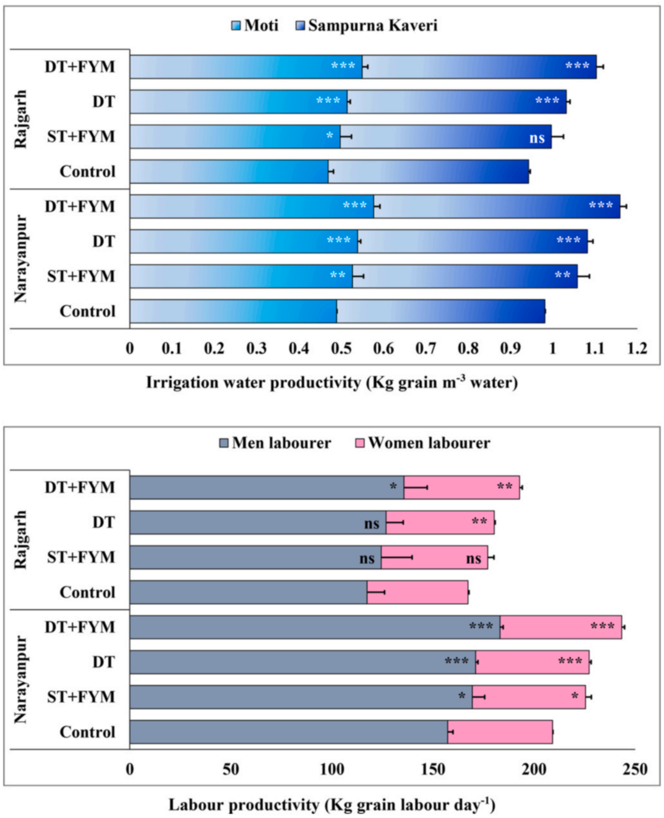

Fig. 6(B). The effect of various cultivation practices on irrigation water productivity, and labour productivity in two different locally grown rice varieties (*Moti-NP360* and *Sampurna Kaveri*) grown at Narayanpur (middle Gangetic plains) and Rajgarh (Vindhyan zone) experimental sites in Mirzapur district of eastern Uttar Pradesh. Figure legends: Control = Single transplantation with 100% RDF; ST + FYM = Single transplantation with 75% RDF +25% FYM; DT = Double transplantation with 100% RDF; DT + FYM = Double transplantation with 75% RDF +25% FYM; FYM = Farm yard manure. The asterisk marks (*, **, ***) show significant difference with two-tailed p-value at ($p < 0.05$, $p < 0.01$, and $p < 0.001$), respectively.

earlier than ST (Das et al., 2017). Singh et al. (2014) reported that innovative practices targeted to improve soil moisture as well as integrated nutrient management in rice-based cropping system in mid tropical plain zone of India resulted in an yield increase of up to 40%, whereas Ditzler et al. (2018) validated sustainable farmland interventions based on organic inputs (including FYM addition) on Basmati rice in hilly regions of Uttarakhand, India. Similarly, Thwe et al. (2019) reported that the demographics and especially the farming practices like the addition of nutrient input determined the higher level of yield in lower Myanmar and a study from Dera Ismail Khan, Pakistan (Baloch et al., 2014) has proved that planting techniques like direct seeding and transplanting on flat had resulted in higher yield than direct seeding and transplanting on ridges. The cultivation systems like system of rice intensification (SRI) resulted in improved plant height, effective tillers (10–45%), panicle length, dry matter, root dry weight (24–57%) and root volume (10–66%) in rice (Gopalakrishnan et al., 2014). Hence, innovative practices such as DT in combination with FYM addition resulted in better agronomic traits in both rice varieties grown at two different locations and can be recommended as an alternative approach to improve grain yield, profitability and agronomic traits in rice.

3.3. The effect of various practices on soil quality

The effects of various transplantation methods and FYM addition on the physical, chemical, biological, and microbial properties of soils in different sites are presented in Table (4) and Figure 5B. The results indicate that the FYM input as well as DT practice in rice optimized the soil pH in both alkaline (Narayanpur) and acidic (Rajgarh) natures. The effect was more noticeable in Narayanpur as the site was intensively receiving inorganic fertilizers and, therefore, the addition of organic inputs like FYM with recommended usage of fertilizers optimized the soil pH and EC from the first year itself. Irrespective of the cultivars, EC was significantly changed ($p < 0.05$) in both ST and DT with FYM addition in Narayanpur, whereas in Rajgarh, it was not statistically significant. Similarly, both ST and DT practices with FYM addition ($p < 0.05$) enhanced the soil moisture and subsequent water holding capacities of soils in both sites, and the effect was more noticeable in Narayanpur than in Rajgarh. However, the FYM addition along with either ST or DT enhanced the soil moisture (>16%) and water holding capacity (15.7%) of even the dryland soils of Rajgarh. Several previous studies have correlated the impact of various organic additions on positive soil physical quality changes over time (Khatun et al., 2007; Preethi et al., 2013; Gopalakrishnan et al., 2014; Rao et al., 2014; Chen et al., 2017; Das et al., 2019; Bastia et al., 2021; Dubey et al., 2022).

The effects of various practices on chemical and biological properties, including microbial properties such as soil organic carbon (SOC), microbial biomass carbon (MBC), available nitrogen (AN) and microbial biomass nitrogen (MBN), nitrogen use efficiency (NUE), soil dehydrogenase (SDA), microbial C:N ratio, as well as fungal and bacterial counts, were studied accordingly (Table 4 and Fig. 5B), and a differential response was observed for the resilience practice DT + FYM input in both rainfed and dryland areas. Though the FYM addition with DT practices enhanced SOC at both Narayanpur and Rajgarh, the increase in SOC in Rajgarh was not statistically significant. The SOC content in Narayanpur and Rajgarh before the field trials was 0.686% and 0.64%, respectively, and it was further increased up to 10–12% in Narayanpur and up to 4% in Rajgarh in both ST and DT with FYM input. However, in middle Gangetic areas such as Narayanpur, where intensive agricultural practices have been prevalent for decades, even resilient DT practices without FYM addition resulted in a 1.9% decrease in SOC content. Therefore, the integration of both resilient as well as organic additions is imperative for maintaining the soil fertility and overall farm productivity.

On the other hand, the FYM addition resulted in a significant increase in MBC and MBN in both sites during the field trials (Table 4 and Fig. 5B). The MBC was increasing even in DT practices. However, the MBN content was not significantly affected in Narayanpur, whereas it was slightly reduced in Rajgarh. Irrespective of the rice varieties and fields, the agronomic nitrogen use efficiency (NUE) was enhanced significantly in ST + FYM (37–42%), DT (12–17.5%), and DT + FYM (57–63%). Despite the increase in NUE by various agronomic practices, the available N content was increased in soil (5.4–12.8%) due to the residual effect of the FYM and DT practices. The FYM addition also played a major role in balancing the microbial C:N ratio in both Narayanpur and Rajgarh. At the former site, it was found to be in the order of control < ST + FYM < DT < DT + FYM, whereas in Rajgarh it was in the order of control < DT < DT + FYM < ST + FYM (Table 4). The ST and DT practices with FYM addition also significantly improved soil dehydrogenase, microbial as well as fungal counts in both varieties grown in each site. Though the DT practices did not alter the soil properties, DT + FYM significantly enhanced the soil qualities in several ways (Table 4). The SRI practices in combination with fertilizer or organic inputs (Gopalakrishnan et al., 2014) and even the addition of animal manures and plant-based residues (Dubey et al., 2022) resulted in improved soil quality traits like total nitrogen, organic carbon, soil dehydrogenase, MBC, total bacteria and fungi. Similarly, Chen et al. (2017) reported the improved physical, chemical and biological properties of the soil due to the long-term application of manures and inorganic fertilisers, whereas Preethi et al. (2013) observed such changes due to organic addition even in flooded rice. The addition of organic

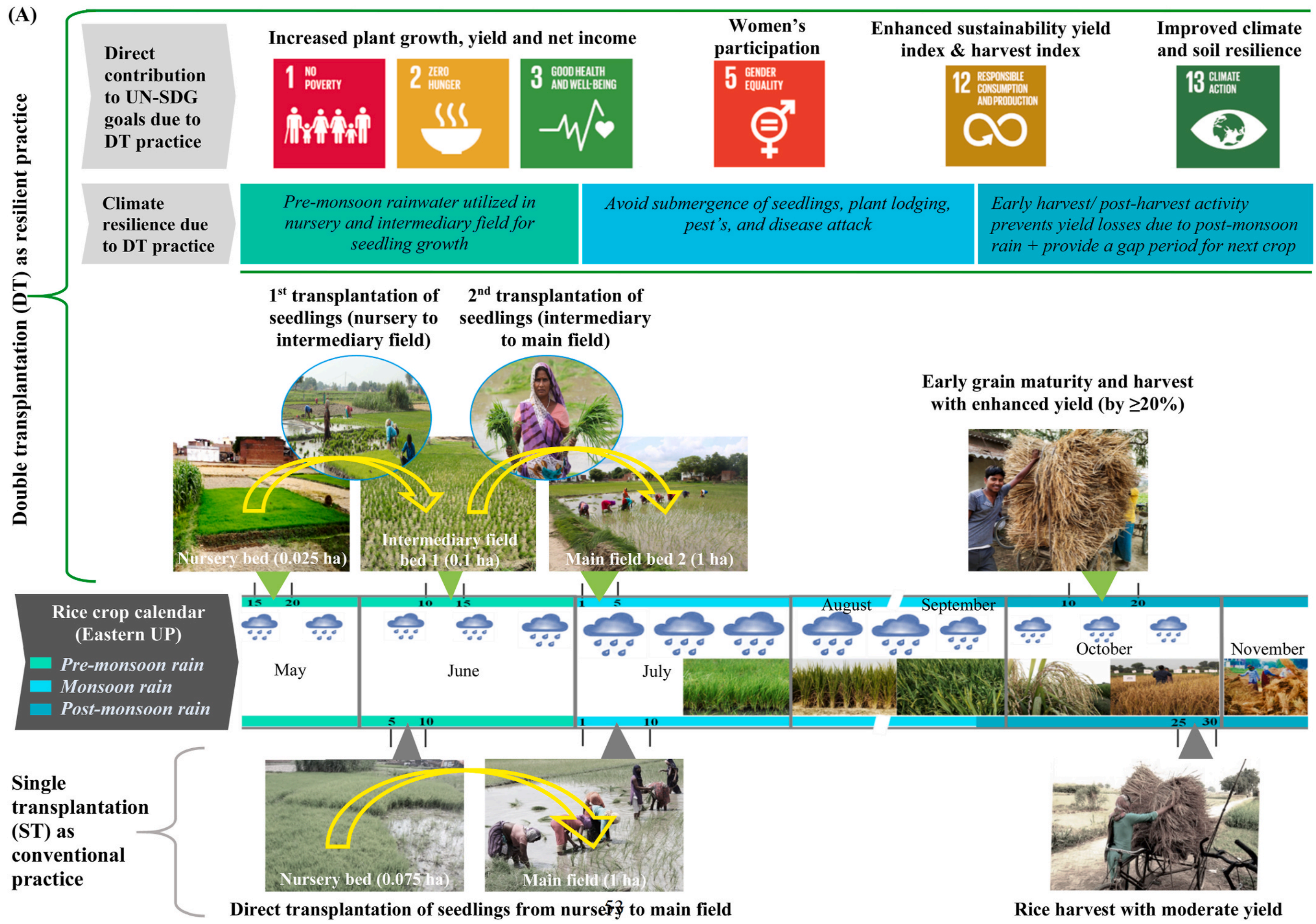

Fig. 7(A). Schematic diagram showing the crop calendar (shifts in important dates) and overall agronomic practices employed for single (ST, conventional) and double (DT) transplantation practices in rice cropping as well as the sustainability benefits out of these practices. Dates and months shown here specify a window for nursery establishment, first transplantation of rice seedlings (locally called *Sanda*) from nursery bed to slightly large size intermediary field (bed-1, which is part of the main field only) and second transplantation of rice seedlings from intermediary field (bed-1) to main field (bed-2). Double transplantation is an adaptive agriculture practice employed by local farmers in eastern UP for high growth and yield of rice crop production in a sustainable manner.

manures like FYM enhances the microbial activities (Peacock et al., 2001) in the soil and therefore improves the enzymatic (Crecchio et al., 2001) and nutrient profile (Crecchio et al., 2001) of the soil. Variation in MBC and MBN indicates variation in mineralisation and uptake of nutrients due to enhanced microbial activity on organic addition in soil (Gunapala and Scow, 1998; Singh et al., 2015). For example, in lowland field conditions, poultry manure is a relatively better organic option as it fast mineralises and has a high carbon pool and a low C:N ratio (Anik et al., 2017). Therefore, innovative practices like DT, along with FYM addition, confer both improved endurance and agronomic traits in rice, while improving the chemical and biological properties of the soil also.

3.4. Climate resilience due to double transplantation in rice

The effect of various practices on adaptive traits in rice crops, such as days to maturity, occurrence and prevalence of pests and diseases, as well as the plant loss/mortality due to lodging and submergence, is illustrated in Fig. (5C). Irrespective of the experimental fields and varieties, the practices such as DT and DT + FYM resulted in better resilience ($p < 0.05$) than ST and ST + FYM. Moreover, by employing DT + FYM, the plant loss by lodging/submergence during the vegetative growth phase (up to 45 DAT) was significantly reduced by 55% (Moti-NP360) and 73% (Sampurna Kaveri) in Narayanpur and by 83% (*Moti-NP360*) and 86% (Sampurna Kaveri) in Rajgarh sites (Fig. 5C). There was a significant reduction in the occurrence of the common diseases in rice such as bacterial blight/blast and brown spot, sheath blight/rot, neck blast and glume discolouration and also reduced the damages due to pest attack from leaf/plant hoppers, rice bugs, rice gall midge, army worm, stem borers, and injuries due to dead heart tiller, leaf folder injury, white head panicle, whorl maggot leaf injury, etc. in rice during the various stages of plant growth (Fig. 5C).

Apart from conferring increasing tolerance to pests/diseases/lodging/submergence, the adoption of DT with or without FYM also reduced the days to maturity (DM) by up to 10 days in Sampurna Kaveri and 13 days in Moti-NP360 (Fig. 5C). Thus, the attainment of early maturity by said practices prevents the yield loss from lodging due to heavy storms/rains and results in early harvesting, thereby providing ample time for farmers to complete post-harvest field operations. Pest infestation due to leaf folders, stem borers (Lepidoptera: Pyralidae) and planthoppers (Homoptera: Delphacidae) is common in Asia, which has significantly reduced rice production to a considerable extent (Catindig et al., 2009; Horgan et al., 2016). Evidently, an annual loss of 1 million tons of rice in China has been reported since the year 2000, and crop damage equivalent to 0.2 Mha and >3 Mha of rice fields occurred in central Java and Thailand, respectively, in the year 2011 alone due to planthopper damage (IRRI, 2015). The ecological methods of pest management could save 150 USD ha^{-1} on insecticide and earn an income of 120 USD ha^{-1} from sesame plantations done at field bunds as a biological pest control method (Lv et al., 2015). Hence, the adoption of simple, effective, and resilient cultivation practices such as DT not only

Table 5
The interlinkage between double planation (DT) and UN-SDGs.

SDG Goals and Targets directly in sync with Double Transplantation (DT) practice			
Goal Number	Specific Goal	Target Number	Specific Targets
1	No Poverty	1.1	End extreme poverty
		1.3	Implement social protection system to the poor
		1.5	Build resilience of the poor to climate and other disasters
2	Zero Hunger	2.1	End hunger
		2.2	End malnutrition
		2.3	Double agricultural productivity
		2.4	Build sustainable food production systems
3	Good Health and Well-being	3.d	Improve health risk management
5	Gender Equality	5.1	End gender discrimination
		5.4	Value unpaid domestic work
		5.5	Enhance women's participation in decision-making and public life
		5.a	Women equal rights to economic resources
		5.b	Use of technologies for women empowerments
		5.c	Strengthen policies for gender equality
12	Responsible Consumption and production	12.2	Sustainable resource use
		12.4	Sound management of chemicals and wastes
		12.5	Reduce waste generation
		12.6	Promote social and environmental reporting by companies
		12.c	Removal market distortions
13	Climate Action	13.1	Strengthen resilience to climate change
		13.2	Integrate climate change measures into national policies
		13.3	Raise awareness on mitigation and adaptation
		13.a	Finance developing countries for mitigation
		13.b	Enhance capacity for climate change planning

provides enhanced endurance and tolerance in rice but also shortens the crop duration by early maturity so that the farmers can do necessary field preparations for subsequent cropping. Moreover, the early harvest of rice also provides an optimum dew point for wheat seed emergence due to its early sowing, and could also provide an option of incorporating new crops such as mustard followed by mung bean; or early pea followed by late wheat; or potato followed by cowpea, chilli, or mungbean (Dar et al., 2020).

Furthermore, the seedling health is also sustained in DT than in ST and is found to be much better when planted early and is transferred into the next field (bed-1). This is unlikely in ST, in which the overcrowded seedlings are allowed to grow for 2–3 months in the same nursery (under water stressed conditions), and therefore, prone to nutrient deficiency and disease incidence like leaf blast and brown spot etc. (Kumar et al., 2019). Though DT is adopted by farmers based on community knowledge to boost the resilience of the rice agroecosystem, the innovative way of raising and transplanting in DT significantly reduces the seeding rate compared to ST and other conventional practices without reducing the yield. Furthermore, DT has been shown to be beneficial even in conditions such as dry spells or inundation (Kumar et al., 2019), as the increased tolerance and endurance brought by DT practices reduce pesticide usage significantly.

3.5. Economic performance, labour and water productivity, and overall sustainability

In addition to the ecological and environmental benefits, the impact of DT practices on economic return is also important for assessing the overall sustainability of such practices (Fig. 6). Since rice is a water and labour-intensive crop, the variation in input cost in different practices per year for two different varieties grown in two different sites was mainly due to the difference in the amount of water required for irrigation, the labour charges, addition of organics while replacing NPK fertilizers, seeding rate and due to the difference in the practices (ST or DT) (Table 1; Fig. 6A). Although the ST practices required only fields for raising nursery and then subsequent transplantation to the main field (single transplantation), the DT practices required land for raising nursery, an intermediate field for the first transplantation, and then to the main crop field for final transplantation (double transplantation). Nevertheless, the economic returns were higher in DT than in ST. The input cost was considerably higher in both ST + FYM and DT + FYM during the first year, mainly due to the FYM addition. However, during the second year, the input cost (except the seed cost) was reduced considerably in the above two practices due to the non-addition of FYM (i.e., the FYM was applied in the first year and the residual effect was noted during the second year). The exclusive cost incurred in intermediary field (bed-1) in DT practice is compensated by cost reduction in nursery and main field (bed-2), thereby lending nearby cost for both ST and DT. On average, the practices such as ST + FYM, DT, and DT + FYM resulted in higher gross return (GR) and gross margin (GM). Hence, the benefit-cost ratio (BCR) was higher in both DT and DT + FYM for both sites. Irrespective of the sites and varieties, the year-wise difference in economic returns clearly indicates that the BCR was significantly higher in DT throughout the experimental trials than control during the first year ($p = 0.001$). Although the addition of FYM initially reduced the BCR in ST + FYM compared to the control, the BCR increased significantly in both ST + FYM and DT + FYM during the second year, with the BCR being higher in DT + FYM ($p = 0.001$) (Fig. 6A).

One of the misconceptions regarding DT practices found during the field survey and interactions with the local farmers is the additional requirements of water and labour productivity for employing double transplantation, as farmers' fears that the two-time nurturing and transplantation in DT will lead to significant input cost. As a result, the irrigation water productivity and labour productivity of various practices were computed and presented in Fig. 6B. Irrespective of the sites and varieties, the DT + FYM increased the water productivity in the range of 17–18%, while the DT practice alone only resulted in an increase of water productivity of 9–11%. The labour productivity (Fig. 6B) was also increased in both DT and DT + FYM in both sites. However, it was not significantly increased in Rajgarh in the case of men's labour productivity for DT. Regarding women's labour productivity, it was significantly increased in both DT and DT + FYM in Narayanpur ($P < 0.001$) as well as in Rajgarh ($P < 0.01$), while also creating greater number of labour days (for transplantation activities) as job opportunity for women in agriculture. Previous research (Singh et al., 2014; Baloch et al., 2014; Gopalakrishnan et al., 2014; Thwe et al., 2019) demonstrated a positive correlation between farming practices and nutrient management and grain yield and profitability (gross margin), and even site-specific practices resulted in a yield increase of 20–40% and a 40% increase in net profit (Singh et al., 2014). Apart from conferring tolerance and endurance to crop during its various stages of growth, innovative practices also improve the irrigation water use efficiency, thereby reducing the overall water footprint in rice production (Gopalakrishnan et al., 2014). When compared to single transplanted rice, the DT practices used in a tribal farming community in Northeast India resulted in a net benefit increase of more than three-folds and a BCR increase of 56.7% (Das et al., 2017).

The present study results clearly indicate that DT with or without FYM addition is a significantly more beneficial practice for middle

(B)

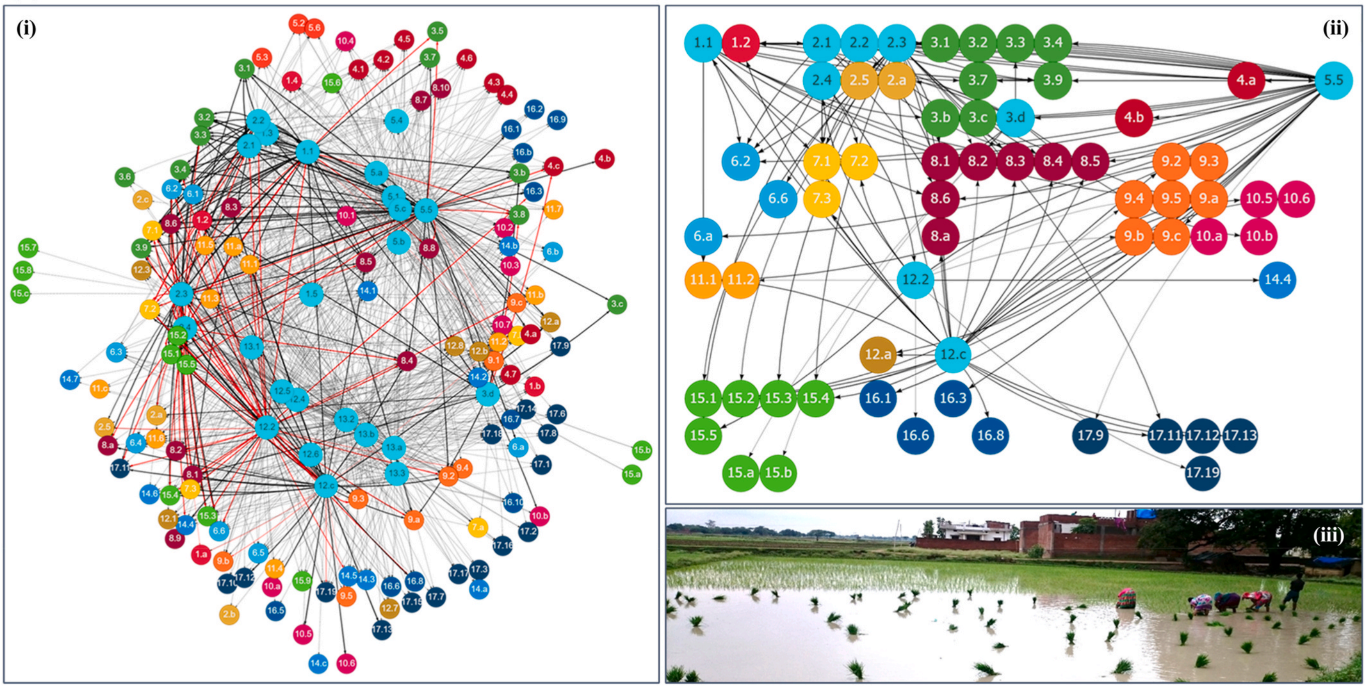

Fig. 7(B). Interlinkages between selected SDG targets which are advocated to be attained by DT practice and the remaining SDGs targets in Indian context. Each node represents an SDG Target. Selected targets are shown in fluorescent blue circles. Each line with an arrow linking two nodes represents a directed/causal link between two targets. **(i)** The red lines indicate negative links (trade-offs), and dotted lines indicate that the indicator-level data is not available for the targets; whereas (ii) black lines indicate positive links (synergies) between different targets. **(iii)** The photograph shown here is of the adoption of the double transplantation method for rice cultivation as employed by local women farmers in Varanasi district in eastern UP, north India. . (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Gangetic areas like Narayanpur than drylands like Rajgarh, and therefore DT can be considered as a promising practice for engaging more women in transplantation (owing to the inherent caring nature of women required for the transplantation of delicate seedings at the early stage) and thereby attaining UN-Sustainable Development Goals (SDGs) related to no poverty, zero hunger, gender equality, responsible consumption and production, and climate action at the local/regional level (Fig. 7A). The study also advocates, DT practice shows direct synergy with six SDG goals with their twenty-four specific targets (Table 5; Fig. 6A). Particularly for India, nine SDG targets (Table 5) remain in positive nexus with fifty-seven more SDG targets as shown in Fig. 7B. Hence, the DT practice hold plausible potential to impart overall sustainability for rice farming in India and elsewhere.

4. Conclusion

Rice is a staple food for almost half of the global population and, therefore, adaptive and resilient practices are imperative for enhancing rice production in times of human population explosion, climate change, and increasing incidence of pests and diseases. Moreover, rice production alone is accountable for almost 14% of the global fertilizer usage, including nitrogen, and thereby results in the emission of potent greenhouse gases. Therefore, adopting innovative practices is also crucial for reducing the chemical pollution from agricultural systems while conferring endurance to crop plants to cope with adverse conditions, including biotic and abiotic. In this context, a three-year study was conducted in the eastern part of Uttar Pradesh to know the extent of adoption of various adaptive practices employed for rice cultivation and also to standardize promising practices for further validation and large-scale popularization. The study results proved that among the four different practices (i.e., ST, ST + FYM, DT and DT + FYM), both DT and DT + FYM are more resilient, adaptive, resource-conserving, as well as ecologically and economically feasible cultivation practices for rice. Moreover, the large-scale adoption of DT practices will also pave the way for food security, livelihood security, and gender equality by providing employment opportunities to women farmers and thereby attaining the UN-SDGs at the local level. While subsidies are available for buying chemical fertilizers, it is high time to provide incentives to resource poor farmers for integrated farming (so that they could also rear animals for FYM).

The most interesting feature of DT is that it provides an opportunity to utilize the pre-monsoon rain for the early establishment of nurseries and subsequent protection from post-monsoon or offseason rain by early harvest of rice. In DT, nursery bed size is reduced by two-thirds in comparison to ST, thereby saving critical resources viz. land, water, time, labour, organic and inorganic input for nursery preparation and maintenance cost. Moreover, the input cost for the intermediary field in DT is compensated by the cost reduction in the nursery bed. Since a relatively small part (1/10th of the main field) is utilized for the second round of transplantation (i.e., DT), no extra land is needed for DT. Furthermore, as the stepwise transplantation increases the seedling multiplication rate, DT practices require only about half the seeds in comparison to ST, thereby saving the input (seed) cost. Furthermore, two-time transplantation in DT results in double hardening in rice compared to ST, and DT practices confer greater endurance and tolerance to rice against pests and diseases, flood submergence, and even lodging. Hence, DT practices can be considered suitable for flood-prone or low-lying rice production systems in countries in Asia. DT practices also resulted in gender equality, women empowerment, and local livelihood security as it provides more opportunities to women labourers (as more labour days are created) owing to greater care and attention is needed for plucking/uprooting and transplanting seedlings. DT practices resulted in a yield increase of up to 20% in comparison to conventional practices. Further field-scale validations are required for standardizing DT practices for different rice varieties in different agro-climatic regions (including uplands). Currently, few resource-poor or subsistence farmers have been found to adopt this DT practice. As a result, large-scale popularization is required to persuade all farmers (including small, medium, and large-land holding farmers) of the ecological, economic, and climatic importance of DT practices. Therefore, the adoption of innovative practices like DT in combination with the sustainable utilization of organic inputs is the need of the hour for improving climate adaptation in rice cultivation while achieving economic and ecological sustainability, local food security, and several UN-Sustainable Development Goals.

Ethical statement

The study does not have any animal or human trials and the prior informed oral consent of the farmers was obtained during the field survey.

Credit author statement

Conceptualization: PKD & PCA, Field works & Data Collection: PKD: Data analysis & First Draft: PKD: Editing: PKD, RC, AS, KKP, AKB, GSS, RKM, PCA, Reviewing & Final approval: PKD, RC, AS, KKP, AKB, GSS, RKM, PCA: Supervision: PCA, GSS, RKM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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