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Co-Implementation of Tillage, Precision Nitrogen, and Water Management Enhances Water Productivity, Economic Returns, and Energy-Use Efficiency of Direct-Seeded Rice

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Abstract: The sustainability of conventional rice (*Oryza sativa* L.) production systems is often questioned due to the over-mining of groundwater and environmental degradation. This has led to the development of cost-effective, resource-efficient, and environmentally clean rice production systems by optimizing water and nitrogen (N) use. Hence, a 2-year field study (2019 and 2020) was conducted at the ICAR–Indian Agricultural Research Institute, New Delhi, to assess the effect of precision N and water management strategies on growth, land, and water productivity, as well as energy-use efficiency in scented direct-seeded rice (DSR). Two crop establishment methods, conventional-till DSR (CT-DSR) and zero-till DSR (ZT-DSR) along with three irrigation scenarios (assured irrigation (irrigation after 72 h of the drying of surface water), irrigation at 20% depletion of available soil moisture (DASM), and 40% DASM+Si (80 kg ha^{-1})) were assigned to the main plots; three N management options, a 100% recommended dose of N (RDN): 150 kg ha^{-1}; Nutrient Expert®(NE®)+leaf color chart (LCC) and NE®+soil plant analysis development (SPAD) meter-based N management were allocated to sub-plots in a three-time replicated split-plot design. The CT-DSR produced 1.4, 11.8, and 89.4, and 2.4, 18.8, and 152.8% more grain yields, net returns, and net energy in 2019 and 2020, respectively, over ZT-DSR. However, ZT-DSR recorded 8.3 and 10.7% higher water productivity (WP) than CT-DSR. Assured irrigation resulted in 10.6, 16.1 16.9, and 8.1 and 12.3, 21.8 20.6, and 6.7% higher grain yields, net returns, net energy, and WP in 2019 and 2020, respectively, over irrigation at 20% DASM. Further, NE®+SPAD meter-based N management saved 27.1% N and recorded 9.6, 18.3, 16.8, and 8.3, and 8.8, 21.7, 19.9, and 10.7% greater grain yields, net returns, net energy, and WP over RDN in 2019 and 2020, respectively. Thus, the study suggested that the NE®+SPAD-based N application is beneficial over RDN for productivity, resource-use efficiency, and N-saving (~32 kg ha^{-1}) both in CA-based and conventionally cultivated DSR. This study also suggests irrigating DSR after 72 h of the drying of surface water; however, under obviously limited water supplies, irrigation can be delayed until 20% DASM, thus saving two irrigations, which can be diverted to additional DSR areas.

Keywords: conservation agriculture; direct-seeded rice; irrigation scenarios; leaf color chart; SPAD meter; water productivity; precision nitrogen management

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1. Introduction

Conventional rice (*Oryza sativa* L.) cultivation faces a quadruple challenge of poor economic returns, high energy use, labor paucity, and environmental pollution [1,2]. Labor, energy, and water-intensive conventional transplanted rice (CTPR) systems are not profitable ventures as nursery raising and transplanting account for 30–40% of total expenses [3,4]. Repeated tilling and puddling in conventional rice systems deteriorate soil health [5,6] and accelerate greenhouse gas (GHG) emissions [7,8]. Puddling disintegrates soil particles, reduces hydraulic conductivity, and creates compact layers in the root zone, which offset the growth and yield of the post-rice crops [9]. Rice is a water-guzzling crop and has the highest water requirement among the cultivated cereal crops [7]. Cultivation of transplanted rice causes excess mining of groundwater, leading to water scarcity and a rise in the cost of pumping water [10]. Nearly, rice accounts for nearly 27% of the world's total freshwater withdrawal [11]. Furthermore, CTPR involves a huge amount of input energy, including the growth of the seedlings, puddling, transplanting in the main field, irrigation (pumping), fertilizer, and weed management [6,12]. Repeated tillage operations and overuse of irrigation water and nutrients (especially N apart from manual labor) contribute to a major chunk of total input energy in puddled transplanted rice [8]. Crop productivity and profitability are positively correlated with energy-use efficiency and are inversely related to energy intensiveness and greenhouse gas intensity [2,13]. If the energy in rice production is used judiciously by optimizing the use of tillage, water, and N, it will help to 'cope-up' environmental pollution by reducing greenhouse gas (GHG) emissions and other hazardous effects, apart from providing a sustainable and economically viable rice production system in the future [14].

Hence, there is a dire need to develop a water-, energy-, and resource-efficient rice production system to achieve global food security without jeopardizing environmental sustainability. Minimum soil disturbance, along with precise water and nutrient management, would help in natural resources, such as water, as well as in labor, energy, and time-saving, without compromising rice productivity and economic profitability [2,13]. Direct-seeded rice (DSR) is a resource–conservation technology that reduces energy, water, labor-use, and GHG emissions, and offers a myriad of benefits over CTPR [8,15]. Generally, DSR is raised by conventional tillage (CT), which involves repeated tillage operations to obtain a fine seedbed for crop seeding [16]. Owing to high energy involvement, repeated tillage accelerates soil erosion, production costs, and GHG emissions [6,17]. Hence, there is a need to devise conservation-effective minimum soil disturbance protocols for DSR, which will save energy and restore the soil ecosystem services.

Current faulty N management practices in CTPR lead to imbalanced N use, causing poor N-and water-use efficiency (WUE), resulting in sub-optimal economic returns and negative effects on the soil, environment, and human health [18]. In CTPR, a major portion of applied N is lost through leaching, denitrification, and volatilization, resulting in poor N use (~30–40%) [16]. Poor synchrony between soil N supply and crop demand, apart from the inappropriate splitting of N and the use of excess N, results in heavy N losses [19]. Hence, for obtaining optimum grain yield and quality with increased NUE and higher economic returns concurrently maintaining environmental quality, N optimization for DSR is inevitable. Hence, appropriate and conservation effective N management is highly warranted in environmentally friendly and profitable rice production [6]. Development of modern tools, such as the leaf color chart (LCC), Green Seeker, soil plant analysis development (SPAD) meter, and Nutrient Expert®(NE®) enable real-time N management with better synchrony between soil N supply and crop demand, thereby better utilization of applied N and higher crop growth, yield, NUE, net returns, considerable savings of fertilizer input, and less GHG emissions compared to the blanket application of fertilizers in rice production systems [1,20,21]. Thus, the need-based variable-rate nutrient application approach has great potential in increasing crop growth, yield, and NUE by overcoming the problem of over- and under-fertilization.

Conventional transplanted rice is grown in puddled soils with continuous water impounding, which leads to poor WUE and causes groundwater declines [8]. Puddling in CTPR alone consumes almost 30% of the total water used in rice production [9]. Owing to high water use, ~17–22 Mha rice areas will face acute water scarcity by 2025 [22]. Therefore, to overcome emerging water scarcity challenges, it is imperative to search/develop alternative water-efficient rice production systems that require less water than conventional flooded rice without yield penalty [11] and improved WUE [23]. The water requirement of DSR is substantially less compared to the CTPR system. DSR has been reported for potential water savings at the field level, but cultivation in non-puddled soil, longer irrigation intervals, and smaller quantities of water applied in each irrigation, result in moisture- and nutrient stresses to the crop, particularly for N, P, Fe, and Mn. The multi-nutrient and water stresses not only reduce crop productivity but also reduce nutrient uptake and produce quality [7]. However, keeping the root zone soil wet throughout the growing season by following a proper irrigation schedule can help address the issues of water and nutrient stresses to a great deal. A literature review showed that scheduling irrigation in DSR at pre-determined moisture levels led to better growth, higher yields, lower cultivation costs, higher net returns, and water productivity (WP) over the traditional way of irrigating crops [8,24,25]. However, research is lacking on precision N and water management options with the application of water stress mitigating material, such as Si in *basmati*-based DSR, particularly under a conservation agriculture (CA) system. Hence, we hypothesized that precision nitrogen and water management under conservation effective tilling in the DSR system will increase crop productivity, input-use efficiency, and economic returns. Thus, the present study was conducted with the objectives to find out the effects of (1) precision N and water management options on crop yield, profitability, and resource-use efficiency of DSR, and (2) different conservation effective N and water management methods on energy-use patterns in DSR. The findings of the present research will help researchers and policy planners in designing environmentally safe rice production systems in South Asia.

2. Materials and Methods

2.1. Experimental Site and Treatments Details

A field experiment was conducted on precision N management in CA-based DSR under different irrigation scenarios at the ICAR–Indian Agricultural Research Institute (28°38′ N; 77°09′ E; 229 m at mean sea level), New Delhi, India, for two consecutive years, 2019 and 2020. The climate of the experimental site is sub-tropical and semi-arid, with ~570 and ~623 mm rainfall (80% received during July–September) during the crop periods of 2019 and 2020, respectively. The monthly mean maximum and minimum air temperatures were 33.9 and 34.7 °C, and 24.6 and 23.7 °C in 2019 and 2020, respectively. The experimental field soil was sandy loam in texture and low to medium in fertility (Table 1). The main plot treatments comprised two crop establishment methods viz. conventional till-DSR (CT-DSR) and zero-till DSR (ZT-DSR) and three irrigation scenarios (assured irrigation, irrigation at 20% depletion of available soil moisture (DASM), and irrigation at 40% DASM+Si (80 kg Si ha^{-1}); while sub-plot treatments were composed of three N management options viz. 100% recommended dose of N (RDN): 150 kg ha^{-1}; NE®+LCC and NE®+SPAD meter-based N management. The experiment was laid out in a three-time replicated split plot design. As it is understood that 40% DASM would cause significant yield losses and Si plays an important role in improving water relations in plants, and helps plants overcome water stress apart from improving the many physiological functions of the plants, Si (80 kg ha^{-1}) was added to 40% DASM irrigation. Thus, 40% DASM+Si combination was compared with 20% DASM and adequate irrigation treatments.

Table 1. Initial soil characteristics of the experimental soil (0–15 cm depth) of the field.

S. No.	Parameters	Analytical Values	Method Employed
1	Available Nitrogen	176.2 kg ha^{-1}	Alkaline permanganate method [26]
2	Available Phosphorus	11.6 kg ha^{-1}	0.5 M $NaHCO_3$, pH = 8.5 [27]
3	Available Potassium	272.5 kg ha^{-1}	Ammonium acetate method [28]
4	Organic Carbon	0.41%	Rapid titration method [29]
4	pH	8.3	1:2.5 Soil: water suspension [30]
5	Soil Texture	Clay loam	International pipette method [31]

2.2. Crop Culture

The CT plots were prepared by 2-plowing with a cultivator followed by a harrowing to obtain a fine seed bed. However, in ZT plots, the glyphosate (translocated general weed killer) herbicide at 1.0 kg active ingredient (a.i.) ha^{-1} was applied 10 days before sowing to kill the weeds. Semi-dwarf *basmati* (scented) rice genotype (Pusa *Basmati* 1509) was sown by a seed drill at 30 kg ha^{-1} in the first week of July and the last week of June in 2019 and 2020, respectively. Immediately after sowing, pendimethalin at 1000 g a.i. ha^{-1} was sprayed manually by using a knapsack sprayer with a spray volume of 750 L ha^{-1}. After sowing, in ZT plots, 3.5 t ha^{-1} crop residue was maintained. The crop was fertilized as per the treatments, 150 kg ha^{-1} N was used as RDN, while in precision N management options, the N dose was calculated using NE®, which was 119 kg N and 28 kg P_2O_5 and 54 K_2O kg ha^{-1}. One-third of N and a full dose of P_2O_5 and K_2O, as computed by NE®, were applied as a basal dose at the time of the sowing by urea, single super phosphate, and muriate of potash; while the rest of N was applied when the LCC and SPAD ratings fell below their critical values (LCC: 3 and SPAD $\leq$ 37). Silicon was applied at the rate of 80 kg ha^{-1} through calcium silicate in the specified treatment, intended to impart tolerance to the crop against water stress at the time of sowing. After the establishment of the crop, irrigation was given as per treatment. Table 2 provides the number and depth of irrigation applied.

Table 2. Description of water management options.

Irrigation Regimes	No. of Irrigation				Depth of Each Irrigation Water (mm)		Total Irrigation Water Applied (mm)			
	CT-DSR		ZT-DSR		CT-DSR	ZT-DSR	CT-DSR		ZT-DSR	
	2019	2020	2019	2020			2019	2020	2019	2020
Irr.–Assured	15	14	13	12	50	50	750	700	650	600
Irr. at 20% DASM	13	12	11	10	55	55	715	660	605	550
Irr. at 40% DASM+Si_{80}	9	8	8	7	60	60	540	480	480	420

During both years depth of the water application was the same.

The amount of irrigation water was measured using a water flow meter. To maintain the weed population below the threshold level, bispyribac-Na at 25 g a.i. ha^{-1} was applied 20 days after sowing (DAS) of the crop, which was supplemented with hand-weeding 45 DAS. Need-based pesticides were also used to control diseases and pests during both years of experimentation.

2.3. Data Collection

To determine the number of tillers, m^{-2} at the flowering stage, two spots of 50 cm $\times$ 50 cm areas were randomly chosen from each plot; from there, tillers were counted manually and then summed up. The average value was expressed in m^{-2}. Further, samples from 50 cm $\times$ 50 cm areas from each plot were taken by cutting the plants just above the ground surface to determine dry matter accumulation (DMA), then left there for 2–3 days for sun-drying, thereafter oven-dried at 70 ± 2 °C until the constant weight was achieved and weighed through an analytical balance (expressed as g m^{-2}) [32]. The leaf area was measured from the same sample using a leaf area meter (Model LICOR 3100, LICOR Inc. Lincoln, NE, USA); the leaf area index (LAI) was calculated by dividing the leaf area by the ground area. Effective tillers were counted manually by placing a quadrant of 50 × 50 cm^2 at two places in each plot and the average value was expressed as no. m^{-2}. Randomly, 10 panicles from each plot were taken and used for determining panicle-length, panicle-weight, grain $panicle^{-1}$, and 1000-grain weight. The crops were manually harvested from the net plot, leaving aside a border of 0.6 m from each side in each plot, left in the field for 3–5 days for sun-drying, tagged carefully, and weighed with a portable swing balance to determine biological (grain plus straw) yield. For the calculation of biological yield and straw yield, the residue left in the field was also taken into account. Given the yield calculation, after threshing from each net plot, the grain yield was calculated (t ha^{-1}) and subtracted from the biological yield (t ha^{-1}) to obtain the straw yield (t ha^{-1}) using standard procedures. The harvest index was computed by dividing the grain yield by the biological yield and expressed in terms of percentage (%).

2.4. Economic Budgeting and Water Productivity Estimation

The cost of cultivation (COC) and gross returns of each treatment were computed based on the current market prices of the inputs and economic products of crop (in each year of the study). The net return for each treatment was determined by subtracting the cost of cultivation from the respective gross return. The benefit–cost ratio (B:C ratio) was calculated by dividing the gross return by the respective cost of cultivation. Production efficiency (PE) and monetary efficiency (ME) were calculated by dividing the grain yield and net returns by crop duration, respectively.

Water productivity (WP) was computed based on the formula given by [33].

$$\text{Water productivity} = \frac{\text{Grain yield}\left(\text{kg ha}^{-1}\right)}{\text{Water use }(\text{Effective rainfall} + \text{irrigation water})}$$

2.5. Energy Estimation

Key energy indicators were assessed using the input energy used in the production of DSR in the form of human energy, use of machinery and other equipment on the farm, fuel (diesel oil/petrol), fertilizers, pesticides, residue, and seed, and water inputs. All the inputs used in the production process were converted into energy terms by multiplying with their corresponding energy equivalent values. The energy equivalents of each input and output are given in Table 3. The energy of total biomass (grain plus straw) was calculated by multiplying the grain and straw yield by their respective energy equivalents. The total energy input was the sum of the energy of all inputs, and the total energy output was the sum of the energy of all outputs (grain and straw). Net energy was obtained by subtracting energy input from total energy output. Energy-use efficiency was calculated by dividing total energy output by total energy input. Energy profitability was calculated by dividing net energy by total energy input and specific energy was calculated by dividing input energy by grain yield.

2.6. Statistical Analysis

All the data were analyzed as per the standard procedure for "Analysis of Variance" (ANOVA) as described by [32]. The significance of treatments was tested by the 'F' test at a 5% level of probability. Duncan's multiple range test (DMRT) was used to compare the treatment means. The statistical analyses were performed via SAS software packages (SAS 9.3; SAS Inst. Inc., Cary, NC, USA).

Table 3. Energy equivalents for various input and output energy forms.

	Component	Unit	Energy Equivalent Coefficient (MJ unit^{-1})	Source
	Inputs			
1	Seed	kg	14.7	[34]
2	Human labor			
	Male	h	1.96	[35]
	Female	h	1.57	[36]
3	Machinery			
4	Tractors	h	62.80	[37]
5	Others	H	62.70	[37]
6	Fuel (Petrol)	L	46.30	[38]
	Chemical fertilizers			
7	N	kg	66.14	[35]
8	P_2O_5	kg	12.44	[35]
9	K_2O	kg	11.15	[35]
10	Micronutrients	kg	20.9	[39]
11	Herbicides	L	238.32	[36]
12	Irrigation	M^3	1.02	[40]
	Output			
13	Rice			
	Main product	kg	14.7	[34]
	By-product	kg	14.7	[34]

3. Results

3.1. Growth and Yield Attributes

Conventional till-DSR accumulated 2.6 and 3.0% higher dry matter compared to ZT-DSR in 2019 and 2020, respectively. However, concerning LAI, CT-DSR was statistically at par with ZT-DSR in 2019 but significantly higher in 2020. Yield attributes were not influenced significantly by establishment methods during both study years. However, CT-DSR produced higher effective tillers m^{-2} and yield attributes, such as panicle-length, panicle-weight, grains panicle^{-1}, and 1000-grain weight over ZT-DSR in both years (Table 4).

Table 4. Dry matter accumulation, leaf area index, and yield attributes of DSR influenced by establishment methods and precision N management options under various irrigation regimes.

Treatments	Dry Matter Accumulation at Harvest (g m^{-2})		LAI at Flowering		Effective Tillers (no. m^{-2})		Panicle Length (cm)		Panicle Weight (g)		Grains Panicle^{-1}		1000-Grain Weight (g)	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Crop establishment methods														
CT-DSR	783.3 ^{a}	627.2 ^{a}	4.35 ^{a}	3.96 ^{a}	324 ^{a}	299 ^{a}	24.6 ^{a}	23.5 ^{a}	2.13 ^{a}	1.96 ^{a}	70.5 ^{a}	64.6 ^{a}	24.4 ^{a}	23.0 ^{a}
ZT-DSR	763.1^{b}	608.4 ^{a}	4.22 ^{b}	3.85 ^{b}	316 ^{b}	294 ^{b}	24.1 ^{a}	23.1 ^{a}	2.04 ^{a}	1.86 ^{a}	68.3 ^{a}	62.8 ^{a}	24.0 ^{a}	22.7 ^{a}
Irrigation regimes														
Irr. –Assured	882.9 ^{a}	708.9 ^{a}	4.50 ^{a}	4.23 ^{a}	336 ^{a}	314 ^{a}	24.8 ^{a}	24.4 ^{a}	2.33 ^{a}	2.17 ^{a}	74.1 ^{a}	68.4 ^{a}	25.0 ^{a}	23.8 ^{a}
Irr. at 20% DASM	792.5 ^{b}	631.4 ^{b}	4.29 ^{b}	4.01^{b}	326 ^{b}	300 ^{b}	24.5 ^{a}	23.5 ^{b}	2.07 ^{ab}	1.92 ^{b}	69.3 ^{b}	64.4 ^{b}	24.2 ^{b}	23.1 ^{b}
Irr. at 40% DASM+Si_{80}	644.2 ^{c}	513.1^{c}	4.07 ^{c}	3.47 ^{c}	298 ^{c}	276 ^{c}	23.8 ^{b}	21.9 ^{c}	1.87 ^{b}	1.65 ^{c}	64.8 ^{c}	58.3 ^{c}	23.4 ^{c}	21.6 ^{c}
N management options														
RDN	743.6 ^{c}	594.7 ^{c}	4.14 ^{b}	3.71 ^{b}	312 ^{b}	286 ^{b}	23.9 ^{b}	22.8 ^{b}	2.00 ^{b}	1.80 ^{b}	62.6 ^{c}	57.1 ^{c}	23.6 ^{b}	22.3 ^{b}
NE®+LCC	769.3 ^{b}	615.9 ^{b}	4.33 ^{a}	3.99 ^{a}	322 ^{a}	298 ^{a}	24.5 ^{a}	23.5 ^{a}	2.04 ^{ab}	1.94 ^{a}	70.0 ^{b}	64.2 ^{b}	24.4 ^{a}	23.0 ^{a}
NE®+SPAD	806.7 ^{a}	642.7 ^{a}	4.40 ^{a}	4.04 ^{a}	326 ^{a}	305 ^{a}	24.7 ^{a}	23.6 ^{a}	2.23 ^{a}	2.00 ^{a}	75.6 ^{a}	69.9 ^{a}	24.5 ^{a}	23.2 ^{a}

Note: Means followed by similar lower-case letters within a column for a particular set of treatments are not significantly different at the 5% level of significance.

Among the irrigation regimes, assured irrigation led to higher DMA and LAI, effective tillers, m^{-2}, and other yield-contributing parameters, followed by irrigation at 20% DASM and irrigation at 40% DASM+Si (Table 4). The amount of DMA in assured irrigation was

11.4 and 12.3% higher in 2019 and 2020, respectively, over irrigation at 20% DASM. Among irrigation regimes, assured irrigation led to a higher number of effective tillers m^{-2} (3.1%, 4.6% in 2019 and 2020, respectively) over irrigation at 20% DASM. A similar trend was followed by over irrigation at 40% DASM, where assured irrigation resulted in a higher number of effective tillers m^{-2} (12.8% in 2019 and 13.8% in 2020). Among the precision N management options, NE®+SPAD meter-based N management was found best in terms of LAI, DMA, effective tillers, $m^{-2,}$ and other yield attributes, over NE®+LCC-based N management and RDN (Table 4). NE®+SPAD meter-based N management resulted in more effective tillers m^{-2} (4.5 and 6.6% in 2019 and 2020, respectively) over RDN, and similarly, NE®+LCC-based N management resulted in higher effective tillers m^{-2} (3.2% and 4.2% in 2019 and 2020, respectively). Among the yield attributes, an important yield attributing character panicle weight was, on average, found at ~5% higher under CT-DSR over ZT-DSR, 12% higher in assured irrigation, over irrigation at 20% DASM and 11.3% higher under NE®+SPAD meter-based N management over RDN.

3.2. Productivity

Conventionally-tilled DSR resulted in higher grain yields (3.8 and 3.0 t ha^{-1} in 2019 and 2020, respectively) and straw yields (5.0 and 4.0 t ha^{-1} in 2019 and 2020, respectively) over ZT-DSR (Figure 1). The yields (grain and straw) were significantly affected by irrigation regimes where assured irrigation resulted in a higher yield (4.28 t ha^{-1}, 3.46 t ha^{-1} in 2019 and 2020, respectively), over irrigation at 20% DASM (3.87 t ha^{-1}, 3.08 t ha^{-1} in 2019 and 2020, respectively), and irrigation at 40% DASM+Si (Figure 2). Nutrient expert®guided N management with LCC, the SPAD meter was found to be superior for grain and straw yields compared to the blanket application of RDN (Figure 3). Harvest index was found higher in ZT-DSR between two planting methods (Figure 4), and in LCC, the SPAD meter-based N over blanket application of RDN (Figure 5). However, NE®+SPAD meter-based N management proved to be the best for yield enhancement (3.89 and 3.10 t ha^{-1} in 2019 and 2020, respectively) as well as HI compared to NE®+LCC and RDN, though it was at par with NE®+LCC (Figure 6).

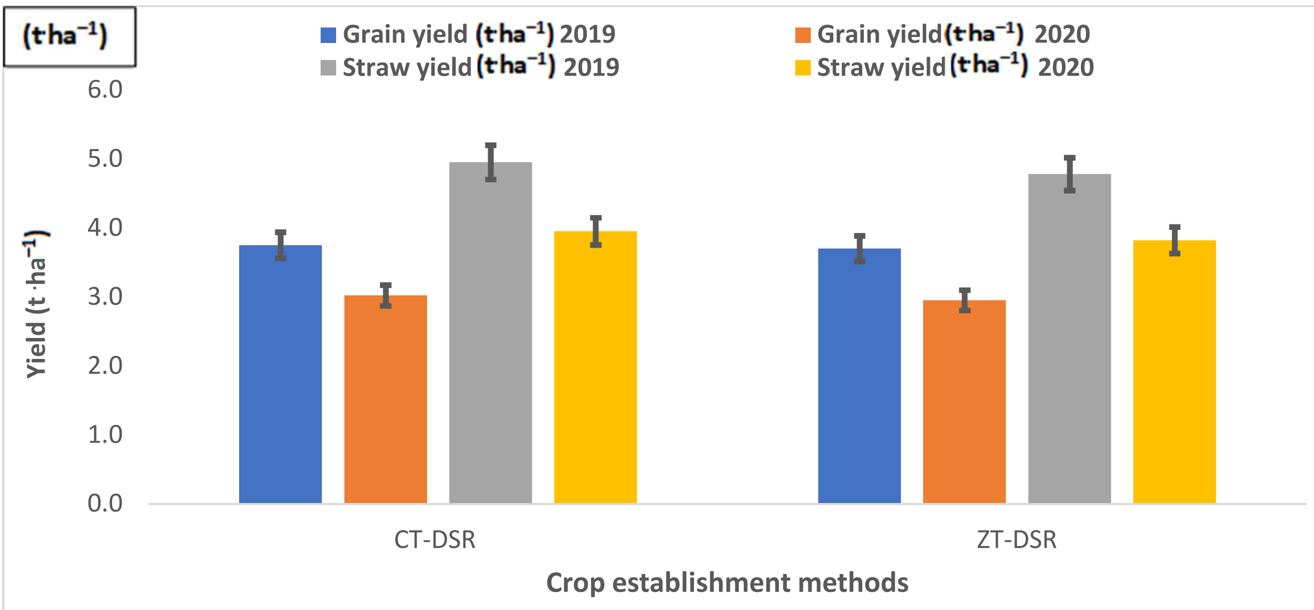

Figure 1. Effect of crop establishment methods on grain and straw yield of direct-seeded *basmati* rice.

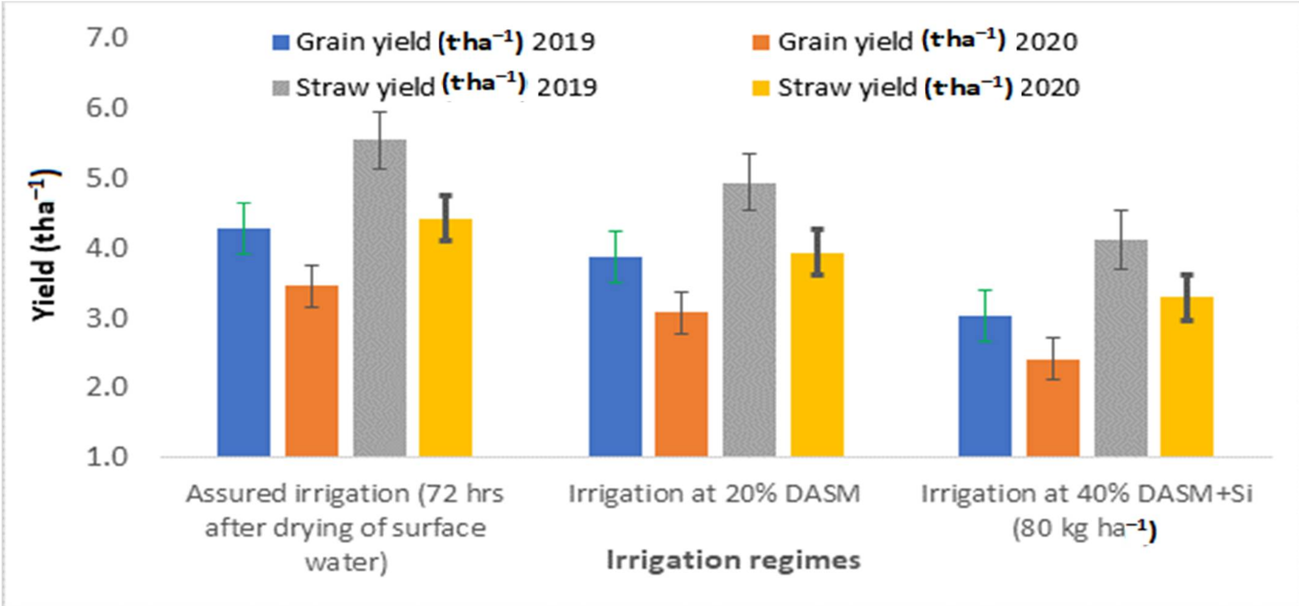

Figure 2. Effect of irrigation regimes on grain and straw yield of direct-seeded *basmati* rice.

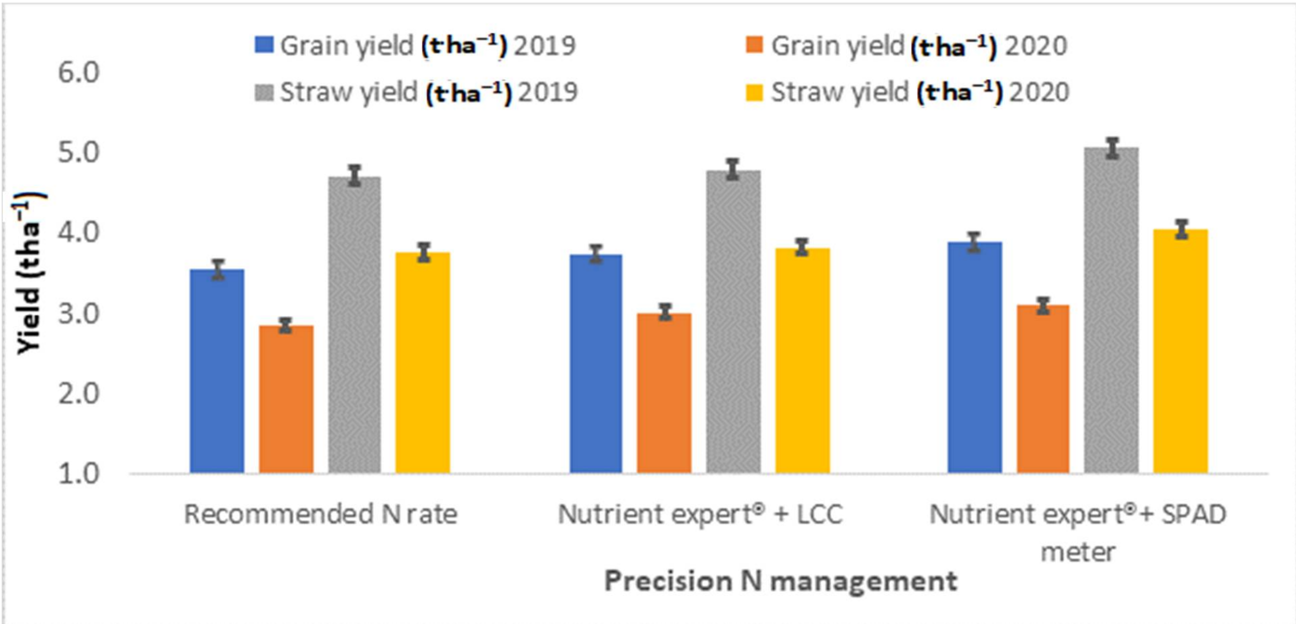

Figure 3. Effect of precision nitrogen management on grain and straw yield of direct-seeded *basmati* rice.

3.3. Crop Establishment Methods × Irrigation Regimes Interactions

The interaction effects of CEMs and irrigation regimes were significant for the grain yield. CTDSR with assured irrigation resulted in the highest grain yield (4.4 and 3.6 t ha^{-1} in 2019 and 2020, respectively), which was significantly higher than all combinations of ZTDSR and irrigation regimes. Although CTDSR and ZTDSR were alike under irrigation at 20% DASM, under-stressed irrigation (irrigation at 40% DASM+Si) ZTDSR recorded an average of 10.4% higher grain yield than CTDSR; this difference was significant (Table 5).

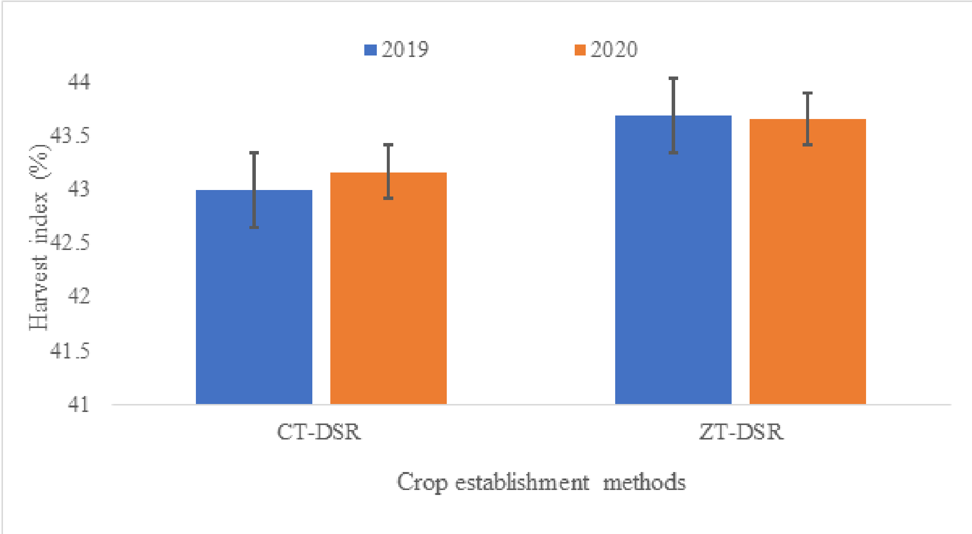

Figure 4. Effect of crop establishment methods on the harvest index of direct-seeded *basmati* rice.

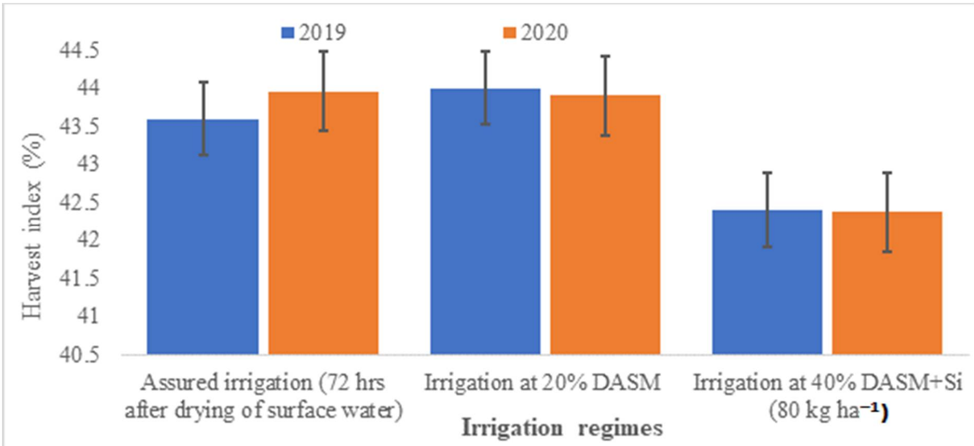

Figure 5. Effect of irrigation regimes on the harvest index of direct-seeded *basmati* rice.

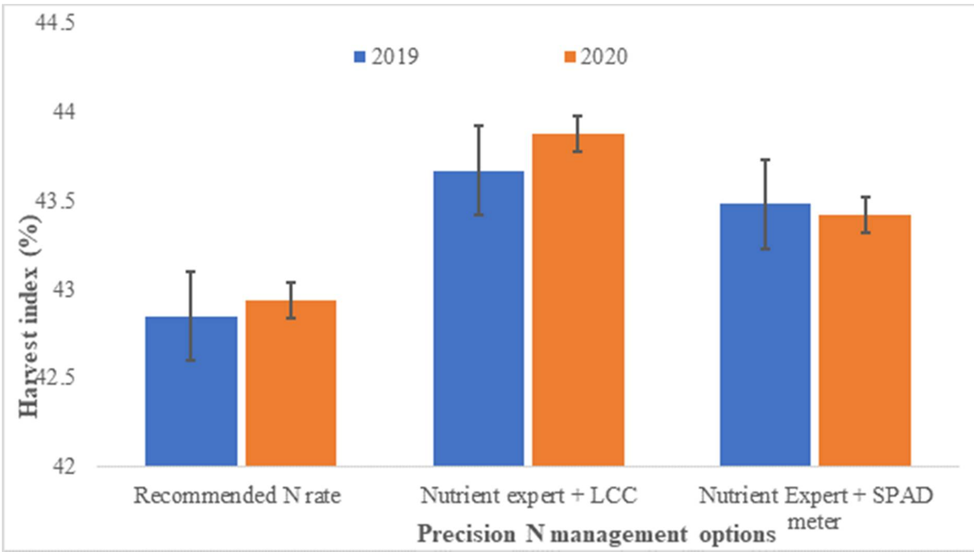

Figure 6. Effect of precision nitrogen management on the harvest index of direct-seeded *basmati* rice.

Table 5. Interaction effect of crop establishment methods and irrigation regimes of the grain yield of direct-seeded *basmati* rice.

Irrigation Regimes/Crop Establishment Methods	Grain Yield (t ha^{-1})			
	2019		2020	
	CT-DSR	ZT-DSR	CT-DSR	ZT-DSR
Irr.–Assured	4.43 ^{a}	4.13 ^{ab}	3.63 ^{a}	3.29 ^{b}
Irr. at 20% DASM	3.95 ^{bc}	3.79 ^{c}	3.14 ^{bc}	3.02 ^{c}
Irr. at 40% DASM+Si$_{80}$	2.88 ^{e}	3.19 ^{d}	2.30 ^{e}	2.53 ^{d}

Note: Means followed by similar lower-case letters within a column for a particular set of treatments are not significantly different at the 5% level of significance.

3.4. Precision N Management × Irrigation Regimes Interactions

The interaction effects of precision N management options and irrigation regimes were significant for straw yields of DSR. The Nutrient expert®+SPAD meter-based N application with assured irrigation resulted in the highest straw yield (5.32 and 4.25 t ha^{-1} in 2019 and 2020, respectively), which was significantly higher than all combinations of RDN and irrigation regimes, and Nutrient expert®+ LCC plots applied with either irrigation at 20% DASM or irrigation at 40% DASM+Si. On average, the percent increase in the straw yield due to NE®+SPAD-based N-scheduling over RDN was 10.9% when the crop received assured irrigation and 16.8% when the crop was irrigated at 20% DASM. Under stress-irrigation (40% DASM+Si), straw yields were generally low and remained similar among all N-management options (Table 6).

Table 6. Interaction effect of N-management options and irrigation regimes on straw yield of direct-seeded *basmati* rice.

N-Management Options/Irrigation Regimes	Straw Yield (t ha^{-1})					
	2019			2020		
	Irr.–Assured	Irr. at 20% DASM	Irr. at 40% DASM+Si$_{80}$	Irr.–Assured	Irr. at 20% DASM	Irr. at 40% DASM+Si$_{80}$
RDN	5.32 ^{bc}	4.58 ^{de}	4.26 ^{ef}	4.25 ^{b}	3.65 ^{cde}	3.40 ^{def}
NE®+LCC	5.38 ^{b}	4.88 ^{cd}	4.15 ^{ef}	4.30 ^{ab}	3.89 ^{bc}	3.31 ^{ef}
NE®+SPAD	5.91 ^{a}	5.35 ^{b}	3.96 ^{f}	4.71 ^{a}	4.27 ^{b}	3.16 ^{f}

Note: Means followed by similar lower-case letters within a column for a particular set of treatments are not significantly different at the 5% level of significance.

3.5. Economic Profitability

Zero-tilled direct-seeded rice involved USD 71.1 and USD 65.1 ha^{-1} higher COC over CT-DSR in 2019 and 2020, respectively (Table 7). Gross return, net return, and B:C were significantly higher in CT-DSR over ZT-DSR. Further, CT-DSR recorded higher ME (USD 8.2 and USD 5.6 ha^{-1} day^{-1} in 2019 and 2020, respectively) and PE (33.2 and 27.3 kg ha^{-1} day^{-1} in 2019 and 2020, respectively) over ZT-DSR. Among irrigation regimes, assured irrigation recorded the highest COC, gross return, net return, and B:C followed by irrigation at 20% DASM and 40% DASM+Si. Similarly, assured irrigation fetched the highest ME (ave. USD 8.2 ha^{-1} day^{-1}) and PE (34.6 kg ha^{-1} day^{-1}) followed by irrigation at 20% DASM and 40% DASM+Si (Table 5). Minimum COC (USD 699.8 and USD 685.1 ha^{-1} in 2019 and 2020, respectively) was incurred with NE®+SPAD, which was equal to the NE®+LCC and a maximum (USD 706.3 and USD 691.8 in 2019 and 2020, respectively) with the RDN. However, the higher gross return (USD 1650.7 ha^{-1} in 2019 and USD 1312.4 ha^{-1} in 2020) and net return (USD 950.9 ha^{-1} in 2019 and USD 627.4 ha^{-1} in 2020), and B: C (2.35, 1.91 in 2019 and 2020, respectively) were recorded with NE®+SPAD followed by NE®+LCC and RDN (Table 7). Both the precision N management options showed significantly higher ME and

PE over RDN. However, the NE®+SPAD meter recorded higher ME (USD 7.1 ha^{-1} day^{-1}) and PE (31.2 kg ha^{-1}) than NE®+LCC (Table 7).

Table 7. Profitability and resource-use efficiency of DSR as influenced by establishment methods and precision N management options under various irrigation regimes.

Treatments	COC (USD ha^{-1})		Gross Returns (USD ha^{-1})		Net Returns (USD ha^{-1})		B:C Ratio		Monetary Efficiency (USD ha^{-1} day^{-1})		Production Efficiency (kg ha^{-1} day^{-1})	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Crop establishment methods												
CT-DSR	666.4	654.8	1595.2 ^{a}	1281.1 ^{a}	928.9 ^{a}	626.3 ^{a}	2.38 ^{a}	1.95 ^{a}	8.2 ^{a}	5.6 ^{a}	33.2 ^{a}	27.3 ^{a}
ZT-DSR	737.5	719.8	1568.4 ^{a}	1247.2 ^{a}	830.9 ^{b}	527.4 ^{b}	2.12 ^{b}	1.73 ^{b}	7.4^b	4.8 ^{b}	32.8 ^{a}	26.6^b
Irrigation regimes												
Irr. –Assured	729.6	714.8	1814.0 ^{a}	1461.9 ^{a}	1084.4 ^{a}	747.1^a	2.50 ^{a}	2.05 ^{a}	9.6 ^{a}	6.7 ^{a}	37.9 ^{a}	31.2 ^{a}
Irr. at 20% DASM	702.6	688.1	1637.0 ^{b}	1301.2^b	934.4 ^{b}	613.1 ^{b}	2.34 ^{b}	1.90 ^{b}	8.3 ^{b}	5.5 ^{b}	34.2 ^{b}	27.8 ^{b}
Irr. at 40% DASM+Si_{80}	673.6	658.9	1294.5 ^{c}	1029.2 ^{c}	620.9 ^{c}	370.3^c	1.92 ^{c}	1.56 ^{c}	5.5 ^{c}	3.3^c	26.9 ^{c}	21.8 ^{c}
N management options												
RDN	706.3	691.8	1509.9 ^{b}	1207.2 ^{b}	803.6 ^{b}	515.4 ^{b}	2.14 ^{b}	1.75 ^{b}	7.1^b	4.6^b	31.4 ^{b}	25.6 ^{b}
NE®+LCC	699.8	685.1	1584.8 ^{ab}	1272.8 ^{a}	885.0 ^{ab}	587.7 ^{a}	2.26 ^{ab}	1.86 ^{a}	7.8 ^{ab}	5.3 ^{a}	33.1 ^{ab}	27.2 ^{ab}
NE®+SPAD	699.8	685.1	1650.7 ^{a}	1312.4 ^{a}	950.9 ^{a}	627.4 ^{a}	2.35 ^{a}	1.91 ^{a}	8.4 ^{a}	5.7 ^{a}	34.4 ^{a}	27.9 ^{a}

Note: Means followed by similar lower-case letters within a column for a particular set of treatments are not significantly different at the 5% level of significance.

3.6. Water Productivity

Higher water productivity (WP), 0.39 for 2019 and 0.31 kg m^{-3} in 2020, was found with ZT-DSR over CT-DSR (Figure 7). Among irrigation regimes, assured irrigation recorded the highest WP (0.40 and 0.32 kg m^{-3} in 2019 and 2020, respectively) followed by irrigation at 20% DASM (0.37 and 0.30 kg m^{-3} in 2019 and 2020, respectively) and the lowest with irrigation at 40% DASM+Si (0.34 and 0.27 kg m^{-3} in 2019 and 2020, respectively) (Figure 8). The highest WP was found with NE®+SPAD meter (0.39 and 0.31 kg m^{-3} in 2019 and 2020, respectively) followed by NE®+LCC (0.37 and 0.30 kg m^{-3} in 2019 and 2020, respectively) and the lowest with RDN (0.36 and 0.28 kg m^{-3} in 2019 and 2020, respectively) (Figure 9).

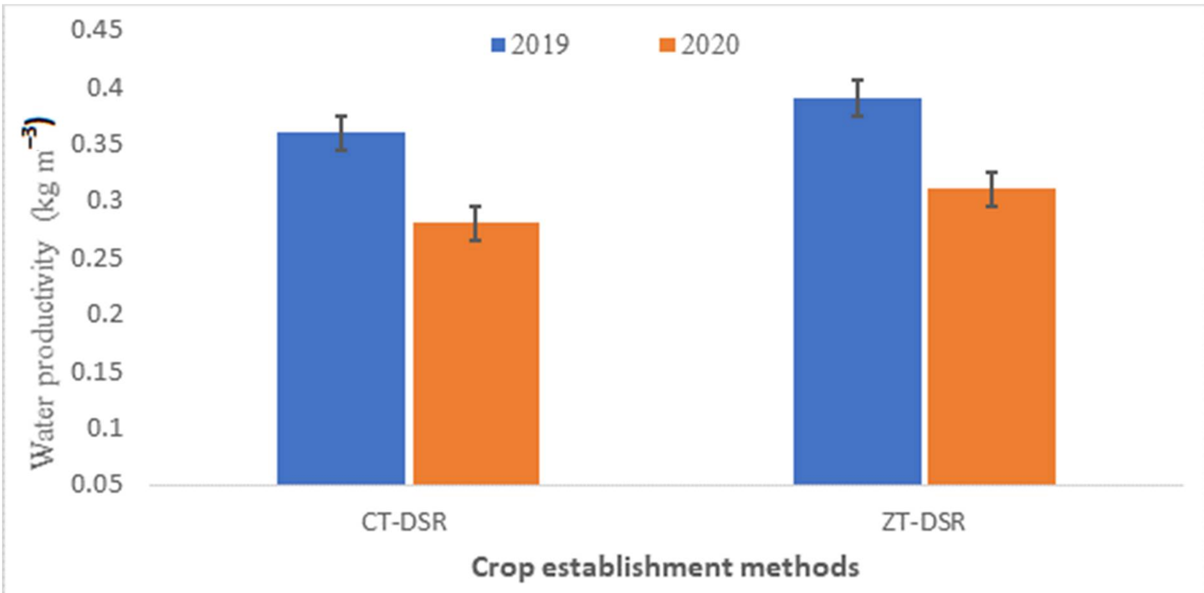

Figure 7. Effect of crop establishment methods on water productivity of direct-seeded *basmati* rice.

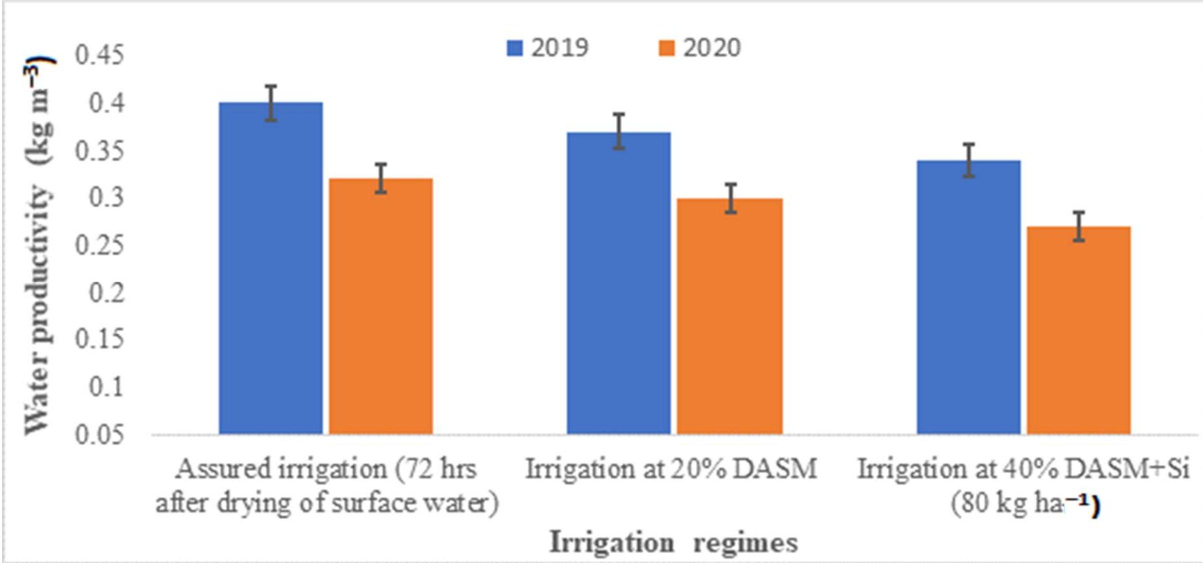

Figure 8. Effect of crop establishment methods on water productivity of direct-seeded *basmati* rice.

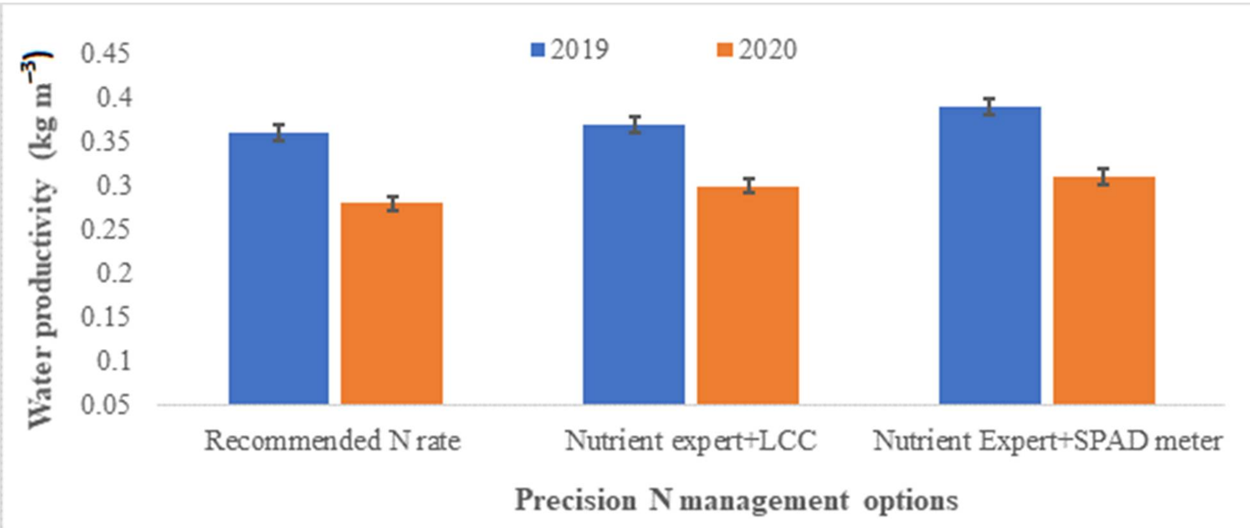

Figure 9. Effect of precision nitrogen management on water productivity of direct-seeded *basmati* rice.

3.7. Energy Dynamics

Zero-tilled direct-seeded rice accrued 43,173.7 and 11.8 MJ and 43,172. 8 and 14.9 MJ more energy input and specific energy over CT-DSR in 2019 and 2020, respectively (Table 6). Energy output (117,035.8 and 93,818.6 MJ in 2019 and 2020, respectively), net energy (97,489.6 and 74,870.8 MJ in 2019 and 2020, respectively), energy-use efficiency (6.0 and 5.0), and energy profitability (5 and 4) were higher in CT-DSR (Table 8). Among irrigation regimes, assured irrigation recorded higher energy input (41,362.1 and 40,814.8 MJ in 2019 and 2020, respectively), energy output (132,128.0 and 106,140.1 MJ in 2019 and 2020, respectively), net energy (90,767.0 and 65,325.2 MJ in 2019 and 2020, respectively), energy-use efficiency (4.5 and 3.7), and energy profitability (3.5 and 2.7) followed by irrigation at 20% DASM and irrigation at 40% DASM+Si. Higher specific energy (13.3 and 16.4 MJ in 2019 and 2020, respectively) was found with irrigation at 40% DASM+Si followed by irrigation at 20% DASM and assured irrigation (Table 8). Minimum energy input (40,427.5 MJ) was incurred with NE®+SPAD, which was equal to the NE®+LCC, and the maximum (42,543.5 MJ) with the RDN. However, specific energy was higher (12.3 and 15.2 MJ in 2019 and 2020, respectively) with RDN, energy output (120,596 and 96,151 MJ in 2019 and

2020, respectively), net energy (80,169.1 and 56,323.8 MJ in 2019 and 2020, respectively), energy-use efficiency (4.2 and 3.4), and energy profitability (3.2 and 2.4) were maximum with NE®+SPAD, followed by NE®+LCC and RDN.

Table 8. Energy budgeting of DSR as influenced by establishment methods and precision N management options under various irrigation regimes.

Treatments	Total Energy Input (MJ ha^{-1})		Total Energy Output (MJ ha^{-1})		Net Energy (MJ ha^{-1})		Energy-Use Efficiency		Energy Profitability		Specific Energy (MJ kg^{-1} ha^{-1})	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Crop establishment methods												
CT-DSR	19,546	18,948	117,036 [a]	93,819 [a]	97,490 [a]	74,871 [a]	6.00 [a]	4.96 [a]	5.00 [a]	3.96 [a]	5.44 [b]	6.55 [b]
ZT-DSR	62,719	62,121	114,195 [a]	91,048 [a]	51,476 [b]	28,927 [b]	1.82 [b]	1.47 [b]	0.82 [b]	0.47 [b]	17.28 [a]	21.48 [a]
Irrigation regimes												
Irr. –Assured	41,362	40,815	132,128 [a]	106,140 [a]	90,767 [a]	65,325 [a]	4.46 [a]	3.68 [a]	3.46 [a]	2.68 [a]	9.95 [c]	12.24 [c]
Irr. at 20% DASM	40,950	40,352	118,578 [b]	94,516 [b]	77,629 [b]	54,164 [b]	4.05 [b]	3.31 [b]	3.05 [b]	2.31[b]	10.82 [b]	13.38 [b]
Irr. at 40% DASM+Si_{80}	41,085	40,436	96,140 [c]	76,644 [c]	55,056 [c]	36,209 [c]	3.23 [c]	2.65 [c]	2.23 [c]	1.65 [c]	13.30 [a]	16.42 [a]
N management options												
RDN	42,543	41,945	111,169 [c]	88,912 [c]	68,625 [c]	46,967 [c]	3.53 [c]	2.90 [c]	2.53 [c]	1.90 [c]	12.30 [a]	15.17 [a]
NE®+LCC	40,427	39,829	115,082 [b]	92,236 [b]	74,654 [b]	52,407 [b]	4.02 [b]	3.32 [b]	3.02 [b]	2.32 [b]	11.12 [b]	13.71[b]
NE®+SPAD	40,427	39,829	120,596 [a]	96,152 [a]	80,169 [a]	56,324 [a]	4.19 [a]	3.43 [a]	3.19 [a]	2.43 [a]	10.65 [c]	13.17 [b]

Note: Means followed by similar lower-case letters within a column for a particular set of treatments are not significantly different at the 5% level of significance.

4. Discussion

4.1. Growth, Yield Attributes, and Yields

There was a gradual increase in the leaf area as the crop progressed towards maturity, the maximum being at the flowering stage. The leaf area (photosynthetic area) is the principal site for absorbing the solar radiation. Dry matter accumulation is largely decided by the leaf area. Table 4 clearly reflects this observation; the treatments with larger leaf areas also show larger dry matter production. As the dry matter accumulation is linearly related to the leaf area and tiller production; its maximum values were observed at the harvest stage [7,41,42]. Dry matter accumulation was significantly influenced by establishment methods in 2019 only. However, CT-DSR resulted in higher LAI and 2.6 and 3.1% higher DMA over ZT-DSR in 2019 and 2020, respectively. This could have converged to an adequate crop stand resulting from a fine seed bed (tilth) obtained by repeated tillage operations, which led to a congenial soil environment for germination and the emergence of rice seedlings and better crop growth apart from less weed growth over ZT-DSR [19,43]. Additionally, the provision of assured irrigation led to a maximum LAI and 11.4 and 12.3% greater DMA over irrigation at 20% DASM and 37.1 and 38.2% over irrigation at 40% DASM+Si in 2019 and 2020, respectively. Rice is a semi-aquatic crop; thus, higher LAI and DMA with assured irrigation could be possible due to higher crop growth and development as favored by proper root and shoot growth due to higher nutrient uptake and photosynthetic rate in response to more favorable moisture regimes. The results can be justified by the findings of [44,45], who found that more frequent irrigations created a congenial rhizosphere environment favorable for better absorption, translocation, and assimilation of nutrients, which, in turn, helped the plants to boost their growth, along with a higher photosynthetic rate. Irrigation at 20% DASM and irrigation at 40% DASM+Si resulted in lower DMA and LAI due to improper crop growth and development resulting from moisture stress created by the application of irrigation at longer intervals.

Application of RDN led to lower LAI and DMA in comparison with a NE®+SPAD meter-based N application due to various losses in the rice field and lesser availability to crops. The NE®+SPAD meter-based N application resulted in higher LAI and accumulated 8.3% greater dry matter over RDN due to synchronization of crop needs and the supply of N and, thus, better crop growth due to greater nutrient availability [46,47]. Need-based N supplementation by regular monitoring of the leaf greenness index using the SPAD meter maintained an optimum level of N inside the plant tissue. Higher effective tillers and yield attributes with CT-DSR were ascribed to improvement in growth parameters, better root growth, and its proliferation as favored by better soil conditions, apart from the absence of soil sickness that stemmed the higher yield attributes in CT-DSR over ZT-DSR [4,48]; lower effective tillers and yield attributes under ZT-DSR might have been due to more weed infestation and poor crop establishment and soil sickness. The supply of assured irrigation resulted in the highest number of effective tillers and panicle-length, panicle-weight, grains panicle^{-1}, and 1000-grain weight followed by irrigation at 20% DASM and 40% DASM+Si. This could have been possible due to the maintenance of adequate moisture regimes by more frequent irrigation, which created a favorable soil–water environment; consequently, better solubilization, uptake, and assimilation of both soil and applied nutrients led to better crop growth and more DMA, thereby supplying more photosynthates toward the sink, resulting in the formation of larger yield attributes [49,50]. However, applying water at longer intervals imposed water stress on plants and affected crop growth and development [19], which up to some extent might have been counteracted by Si by enhancing the water uptake and transport by regulating stomatal behavior and transpirational water loss, accumulating solutes and osmoregulatory substances, and inducing plant defense, associated with signaling events (consequently maintaining whole plant water balance) [17]. It still lowered the leaf water potential [22], reduced cellular growth [51], leaf expansion and tillering, closing of stomata [52], led to a reduced photosynthetic rate [53], radiation-use efficiency, reduced nutrient uptake [54], and hampered the transport of photosynthates towards developing sink, contributing to poor yield attributes.

Amongst N management options, NE®+SPAD meter-based N management resulted in the formation of the highest number of effective tillers, and longer and heavier panicles with a higher 1000-grain weight, followed by NE®+LCC. However, both the treatments were significantly superior to RDN. This could be possible due to greater nutrient uptake as N regularly matched crop needs [55,56]. Further, lower yield attributes with the application of RDN could be due to a greater loss of the applied N and, thereby, lower uptake owing to a lack of synchrony between crop demand and nutrient supply, resulting in lesser absorption, translocation, and assimilation of applied N and, thus, lesser formation of yield attributes. Grain and straw yields and HI were not significantly influenced by establishment methods in any of the study years. However, CT-DSR caused 1.4 and 2.4%, and 1.7 and 2.7% larger grain and straw yields in 2019 and 2020, respectively. Higher grain and straw yields and HI with CT-DSR could be ascribed to the higher number of effective tillers (2.5 and 1.7% in 2019 and 2020, respectively) per unit area and improved panicle-length, grains panicle^{-1}, and 1000-grain weight as compared with ZT-DSR. The authors of [19] also found that ZT-DSR produced the lowest grain yield due to more crop–weed competition as compared to CT-DSR.

On average, assured irrigation caused 11.4 and 12.3% higher grain and straw yield, respectively, over irrigation at 20% DASM. Further, irrigation at 20% DASM accrued 23.8% higher grain yield and 23.5% higher straw yield, over irrigation at 40% DASM+Si. Assured irrigation and irrigating crops with mild stress (irrigation at 20% DASM) created comparatively better soil–water conditions compared to irrigation at 40% DASM+Si, which enabled rice plants to grow profusely, by providing a beneficial micro-climate due to enhanced solubility of native and applied macro- and micronutrients, such as N, iron (Fe), and manganese (Mn) in the soil, and further, the higher absorption, translocation, and assimilation by the plants that led to higher DMA, more effective tillers, and better yield attributes—all of these altogether contributed to higher grain, straw yield, and HI [7,57].

The N application by NE®+SPAD led to an enhancement of 8.5% in grain yield and 8.1% in straw yield over RDN; the NE®+LCC-based N supply also stood taller than RDN for grain as well as straw yield. Higher yield and HI with NE®guided the N application supplemented either by LCC or SPAD, attributed to the balanced application of nutrients mediated by NE®, which made the nutrient recommendation consider the native nutrient supply capacity of the soil, the nutrient balance at the cropping system level, and the yield target, which ensured that all limiting crop nutrients were applied in the right dose and at right time [58] to feed crops with nutrients when needed [59]. Further, greater availability of N at distinct physiological phases led to more N uptake by rice plants, which resulted in the greater formation of yield attributes and better assimilation of photosynthates toward grains and finally contributed to higher grain and straw yields [7]. Lower grain and straw yields with RDN might have been attributed to the fact that a major portion of applied N was lost through different processes due to a mismatch between crop needs and the nutrient supply.

The CEMs × irrigation regime interaction effects revealed that the combination of CTDSR and assured irrigation resulted in significant yield enhancements over all combinations of ZTDSR and irrigation regimes, barring the ZTDSR × assured irrigation combination in 2019. This could be due to the combined effect of optimum plant population and lower weed growth, especially during initial growth stages and maintenance of proper soil moisture in the crop root zone throughout the crop period. CTDSR and ZTDSR though stood alike when irrigations were applied at 20% DASM; however, under-stressed irrigation (irrigation at 40% DASM+Si), ZTDSR superseded CTDSR, yielding on average 10.4% higher grain; this difference was significant (Table 5). These results imply that ZT in DSR was more beneficial under water stress conditions where crop residues retained on the soil surface offer several benefits, including moisture conservation, temperature regulation, and higher microbial activity, compared to under-optimal or near-optimal irrigation conditions [4,15,22].

Again, precision N management × irrigation regime interaction effects showed that the combination of Nutrient expert®+SPAD meter and assured irrigation resulted in greater straw yield enhancement over all combinations of RDN and irrigation regimes; the average increase in straw yield due to NE®+SPAD-based N-scheduling over RDN was 10.9% when the crop received assured irrigation and 16.8% when the crop was irrigated at 20% DASM. This could be ascribed to the combined effect of the adequate and timely supply of both N and water during the entire crop period. Under-stressed irrigation (40% DASM+Si), N-management options were not very expressive as straw yields were in general very low and remained similar among all N-management options.

4.2. Economics: Cost of Cultivation, Gross Return, Net Return, and B:C

ZT-DSR accrued 10.7 and 9.9% more COC over CT-DSR in 2019 and 2020, respectively. The higher cost of cultivation in ZT-DSR was ascribed to the additional costs incurred on herbicide (glyphosate) and residue and their application costs, though fewer costs were involved in the sowing of the crops [22]. However, CT-DSR fetched 11.8 and 18.8% more net returns over ZT-DSR in 2019 and 2020, respectively, which was ascribed to the maximum revenue generated from grain and straw yield with this treatment. Maintenance of saturated soil conditions through relatively frequent irrigations (at 72 h of the drying of surface water) incurred ~4% higher COC over irrigation at 20% DASM as the former irrigation schedule involved more expenditure on irrigation water and its application. The lowest COC with irrigation at 40% DASM+Si was mainly due to a cut in the irrigation number; thus, a smaller cost of irrigation and its application. Further, assured irrigation fetched, on average, 15 and 17% greater gross and net returns, respectively, with over irrigation at 20% DASM; this resulted from the higher revenue gained from grain and straw yields. The lowest gross and net returns and the lowest B:C were recorded with irrigation at 40% DASM+Si due to the lowest grain and straw yields in this irrigation treatment. The NE®-guided N application supplemented either by the LCC or SPAD meter involved lower COC owing to a saving of ~32 kg N ha^{-1}. Further, the NE®+SPAD meter-based N application resulted in 9.3 and 18.3% and 8.7 and 21.7% more gross and net returns over RDN, in 2019 and 2020, respectively. Similarly, the NE®+LCC-based N application caused 5.0 and 10.1% and 5.4 and 14.0% higher gross and net returns in 2019 and 2020, respectively, over RDN due to higher grain and straw yields. Several researchers have also reported that precision N management fetches larger monetary gains (gross returns, net returns, and B:C) over the blanket application of RDN [60,61]. RDN incurred higher costs as explained by more investments in supplying N; lower gross and net returns were attributed owing to lower returns from the grain and straw yields.

4.3. Resource-Use Efficiency: Water Productivity, Monetary Efficiency, and Energy-Use Efficiencies

Water productivity was, on average, 9.5% higher in ZT-DSR compared to CT-DSR, possibly due to lower water use and soil–water conservation due to minimizing evaporation of water, as checked by the residue cover [62]. Irrigating DSR 72 h after drying of surface water caused a 7.4% rise in WP over irrigation at 20% DASM and an 18% increase over irrigation at 40% DASM+Si. Similarly, irrigation at 20% DASM yielded higher (9%) WP over irrigation at 40% DASM+Si. This was due to the higher yield with irrigation at 72 h of the drying of surface water and efficient use of applied water, particularly with irrigation at 20% DASM. Nutrient expert®+SPAD meter-guided N scheduling led to 8.5% higher WP over RDN. The highest WP with the NE®+SPAD meter was due to the higher grain yield, resulting from better crop growth, and higher root biomass production, which might have led to better water and nutrient absorption, owing to balanced nutrition compared with an imbalanced application of RDN [63,64].

Monetary efficiency was significantly influenced by establishment methods; CT-DSR led to a 15.3% higher ME. The PE was not affected significantly by the establishment methods; however, CT-DSR showed a marginal edge (2.1%) over ZT-DSR. Lower values of PE and ME under ZT-DSR resulted from the lower grain yield and net return, respectively [14,16]. Assured irrigation caused an 11.5% increase in PE and 19% in ME over irrigation at 20% DASM, chiefly due to higher grain yield and net return, respectively, compared to irrigation at 20% DASM. The lowest PE and ME were observed with irrigation at 40% DASM+Si due to the lowest grain yield and net return. Precision N management was found to give higher ME and PE over RDN. The NE®+SPAD meter-based N application enhanced PE by 9.3% and ME by 20% over RDN, mainly due to higher grain yield and consequent higher net return; it was closely followed by NE®+LCC [46].

ZT-DSR accrued more than 200% higher energy than CT-DSR; the higher energy in ZT-DSR was ascribed to additional energy incurred from residue and herbicide (glyphosate) and their application despite the fact that the lower amount of energy was involved in the sowing of the crops. However, CT-DSR fetched 89.4 and 229.6; 509.75% and 158.8; and 237.4 and 742.6% higher net energy, energy-use efficiency, and energy profitability over ZT-DSR in 2019 and 2020, respectively, which might be due to the maximum energy generated from grain and straw yield with this treatment [19]. However, ZT-DSR fetched on average 222.8% more specific energy than CT-DSR primarily due to the lower grain yield from this treatment. Maintenance of saturated soil conditions through irrigation at 72 h after drying of the surface water incurred over 1% more energy over irrigation at 20% DASM as there was more energy expenditure on irrigation water and its application. Relatively higher energy with irrigation at 40% DASM+Si over irrigation at 20% DASM was due to the additional energy resulting from the application of Si, though lesser energy was involved in irrigation water. Further, relatively frequent irrigation scheduled at 72 h of the drying of surface water fetched 11.4, 17.0, 10.1, and 13.4% and 12.3, 20.6, 11.8, and 16.0% more energy output, net energy, energy-use efficiency, and energy profitability over irrigation at 20% DASM in 2019 and 2020, respectively, which was due to the higher energy gained from grain and straw yield [2,19]. The lowest energy output, net energy, energy-use efficiency, and energy profitability were with irrigation at 40% DASM+Si due to the lower energy resulting from grain and straw yield. Further, irrigation at 40% DASM+Si recorded 33.66 and 34.15% greater specific energy over assured irrigation due to the lower grain yield. The NE®-guided N application supplemented either by the LCC or SPAD meter accrued lower energy owing to the saving of energy ~ 2116 MJ ha^{-1}. Further, the NE®+SPAD meter-based N application resulted in 8.48, 16.8, 18.7, and 26.1% and 8.1, 19.9, 18.3, and 27.9% more energy output, net energy, energy-use efficiency, and energy profitability over RDN in 2019 and 2020, respectively. Similarly, the NE®+LCC-based N application returned 3.5, 8.8, 13.9, and 19.4% higher energy output, net energy, energy-use efficiency, and energy profitability in 2019 and 3.7, 11.6, 14.5, and 22.1% in 2020, respectively, over RDN due to the higher energy resulting from the grain and straw yield [61]. The RDN incurred higher energy as explained by more energy investment into supplying N, and lower energy output, net energy, energy-use efficiency, and energy profitability attributed to lower energy gained from grain and straw yields. However, on average, RDN recorded 13% higher specific energy over both the NE®+SPAD meter-based and NE®+LCC-based N applications due to the lower gain yield from the former.

5. Conclusions

This study proves the hypothesis that precision nitrogen and water management under conservation effective tilling in the DSR system will increase crop productivity, input-use efficiency, and economic returns. The findings support the following conclusions.

Direct-seeded rice (*Basmati* var. Pusa *Basmati* 1509) can be grown with ZT without any significant yield penalty in the trans-Indo-Gangetic plains of India.

Under adequate water supply, it is advisable to irrigate DSR at 72 h of the drying of surface water; however, under obviously limited water supplies. Irrigation can be delayed to 20% DASM, saving two irrigations, which can be diverted to additional DSR areas.

The NE®+SPAD-based N application was beneficial over RDN in terms of growth, productivity, resource-use efficiency, energy, and N-saving (~32 kg ha^{-1}), both in CA-based and conventionally cultivated DSR.

The current findings suggest that precision N management options along with appropriate water management practices can be recommended to the farmers in trans-Indo-Gangetic plains of India to obtain a higher yield, productivity, and resource-use efficiency from the CA-based DSR system. Further, in water-scarce zones, rice cultivation can be recommended with intermittent water applications at 20% DASM and precision N management as an alternate irrigation schedule instead of conventional methods to harness more yield, profits, and resource-use efficiency from a given (limited) amount of water.

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Abbreviations

AI	active ingredients
CTPR	conventional puddled transplanted rice
CT	conventional tillage
COC	cost of cultivation
DAS	days after sowing
DASM	depletion of available soil moisture
DMA	dry matter accumulation
DSR	direct seeded rice
GHGs	greenhouse gases
INR	Indian rupees
LCC	leaf color chart
LAI	leaf area index
ME	monetary efficiency
MJ	megajoule
NUE	nitrogen use efficiency
PE	production efficiency
RDN	recommended dose of nitrogen
SPAD	soil plant analysis development meter
WP	water productivity
WUE	water-use efficiency
ZT	zero tillage

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