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Tillage, Water and Nitrogen Management Strategies Influence the Water Footprint, Nutrient Use Efficiency, Productivity and Profitability of Rice in Typic Ustochrept Soil

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Abstract: The current study was conducted to assess how optimal tillage water and nitrogen management system are adopted to reduce various field inputs, to improve water footprint (WF), nutrient use efficiency (NUE), rice productivity and profitability. The W_1 (CS to a depth of 5 cm) achieved significantly higher total water footprint (TWFP) compared to all other irrigation strategies. When N_1 (control) and N_2 (80 kg N ha^{-1}) was used, the highest TWFP was observed. The rice transplanted on wide raised beds (WBed-TPR) (0.71 kg m^{-3}) yielded the greatest water productivity (WP_{IRRI}), followed by reduced tillage transplanted rice (RT-TPR) and conventional tillage puddled transplanted rice (CT-TPR). The physiological NUE values ranged from 33.3 to 50.6 kg grain/kg N absorption, the values decreasing as the N doses rose. According to the findings, WBed-TPR and RT-TPR plots similarly drank more moisture from the deeper profile layer than CT-TPR practice. In plots of CT-TPR and WBed-TPR, the yield contributing characteristics of rice all increased, while grain yield increased by 16.8% and 10.6% over NBed-TPR technique, respectively. Finally, CT-TPR reported with maximum cultivation costs, followed by NBed-TPR and the lowest in RT-TPR plots, although WBed-TPR had the highest net profit, B: C ratio.

Keywords: rice; water footprint; nutrient use efficiency; productivity; profitability

1. Introduction

Rice (paddy) is a staple food crop that feeds more than half of the world's population and provides approximately 19% of the world's nutritional energy [1]. Food production will need to increase by roughly 60% to meet global food demand in 2050 according to estimates [2]. Freshwater demands for food production are expected to rise dramatically in the coming decades as a result of population expansion, urbanisation and economic development [3]. Agriculture, on the other hand, consumes the most land and freshwater, accounting for about 37.5% of the world's land area [4] and 85% of global freshwater consumption [5]. Water is an important aspect of sustainable development and plays a key role in today's environmental concerns. Water scarcity, on the other hand, is becoming a global issue [6].

Water footprint is recognized as a technique for assessing the relationship between agricultural production, water resources and environmental consequences in order to improve water use efficiency, watershed sustainability, water impact mitigation and water resource management [7–9]. In India, the water footprint of per unit rice production and percolation was 1403 (m^3 t^{-1}) and 432.9 (m^3 t^{-1}), respectively. Thailand has a higher per capita water footprint (547 m^3 cap^{-1} yr^{-1}) than India (239 m^3 cap^{-1} yr^{-1}) [10,11], with water footprints related to rice consumption of 63, 364 and 250, 305 (Mm^3 yr^{-1}), respectively. According to Chapagain and Hoekstra [12], India's rice cultivation had a total water footprint of 2020 m^3 t^{-1} and a percolation volume of 1403 m^3 t^{-1}, whereas Pakistan claimed the highest water footprint (2874 m^3 t^{-1}). Water footprints in crop production must be reduced to make effective use of the available water by replacing conventional faulty crop establishment and irrigation techniques with new RCTs, and the saved water could then be used on to the other competitive sectors [13]. Rice production has become a challenge due to changing global weather trends and reduced per capita availability of surface and ground water quantum. Different components of soil water balance such as evaporation, transpiration, seepage, percolation and drainage, must be calculated in order to determine which component should be prioritized for enhancing the water use efficiency and productivity under a specific irrigation management system [14,15]. Footprints of water can be used to assess, directly and indirectly, groundwater resource requirements [16,17]. They are described as the ratio of the volume of consumptive water usage to the quantity of produce obtained.

Reduction tillage benefits a variety of soil qualities, but excessive and unnecessary tillage activities have the reverse effect, causing soil degradation. As a result, there is a lot of focus right now on changing from extreme tillage to conservation tillage to control erosion [18,19]. Traditional tillage activities change the bulk density and moisture content of the soil, altering its structure. In addition, conventional tillage produces in a finer and looser-setting soil structure, whereas conservation and no-tillage methods preserve the soil [20]. Conversely, conservation tillage increases soil quality indicators over time [21]. Another issue is the degradation of soil (land) health, which is particularly prevalent in intensive agriculture, such as that practiced in northwest India. Poor agronomic management, water logging, acidification, salinization and alkalinization, among others, lead to land degradation, low input use efficiency, water productivity, etc.

Nitrogen (N) is one of the most important inputs for rice growth and development, although soil N availability is often a constraint [22]. As a result, the application of nitrogen fertilizer has been a major component in increasing crop production over the last five decades, whereas excessive nitrogen fertilizer may not lead to crop benefits but may cause serious environmental and economic problems [23]. Rapid nitrogen losses in the soil flood water system due to ammonia volatilization, denitrification, surface runoff and leaching lead to lower nitrogen usage efficiency (NUE) when high N fertilizer input is used. As a result, major environmental issues such as soil acidification, air pollution and water eutrophication have occurred [22,24]. New strategies to increase yields while maintaining or decreasing optimally applied N are urgently needed to achieve higher crop productivity and NUE under well-fertilized conditions [25]. Depending on the soil quality and socioeconomic scenario, farmers in northern India apply 80 to 150 kg N ha^{-1}. However, in order to increase rice farmer income, more research into a sustainable N rate with various irrigation management options is still needed in the region [26]. Keeping this in mind, the aforementioned research study was conducted to investigate tillage, water and nitrogen management strategies for enhancing water footprint, nitrogen use efficiency, productivity and profitability of wet rice under *Typic Ustochrept* soil.

2. Materials and Methods

2.1. Investigational Location

The investigation was initiated during 2016 at the Sardar Vallabhbhai Patel University of Agriculture and Technology's Meerut research farm situated at 290 04′ N latitude, 770 42′ E longitude, 237 meters above mean sea level in Uttar Pradesh, India. The investigation location was reported with semi-arid sub-tropical climate with an average yearly temperature of 16.8 °C. For the years 2016 and 2017, data on climatic parameters such as rainfall (mm), mean maximum and minimum temperatures, evaporation, air velocity and relative humidity were collected at the meteorological observatory of the Sardar Vallabhbhai Patel University of Agriculture and Technology Meerut (U.P.). The average maximum weekly temperature in 2016 and 2017 ranged between 27.7 and 35.9 °C, while the average minimum weekly temperature ranged between 11.9 and 26.1 °C, according to the meteorological data depicted graphically in Figure 1. In both years, there is a modest increase in mean daily temperature in June, reaching as high as 2.1 °C, and then a gradual decrease, reaching as low as 33.6 and 32.8 °C in October 2016 and 2017, respectively. The mean relative humidity is highest in July and lowest in June. During the crop period, minimum evaporation was recorded 10.5 mm in the second week of November and maximum evaporation was recorded at 52.3 mm in the fifth week of June in 2016 and minimum evaporation was recorded at 7.9 mm in the second week of November and maximum evaporation was recorded at 52.4 mm in the fourth week of June in 2017. The maximum temperature was highest in the fifth week of June during 2016 and the fourth week of June during 2017. Rainfall was recorded at 427.7 mm and 607.5 mm during the crop period in 2016 and 2017. The most prevalent soil type found at the test location is Typic Ustochrept. Before applying treatments, surface soil samples were collected and analyzed. The basic properties are poor accessible nitrogen, low in organic carbon, accessible phosphorus, accessible potassium medium and alkali in response.

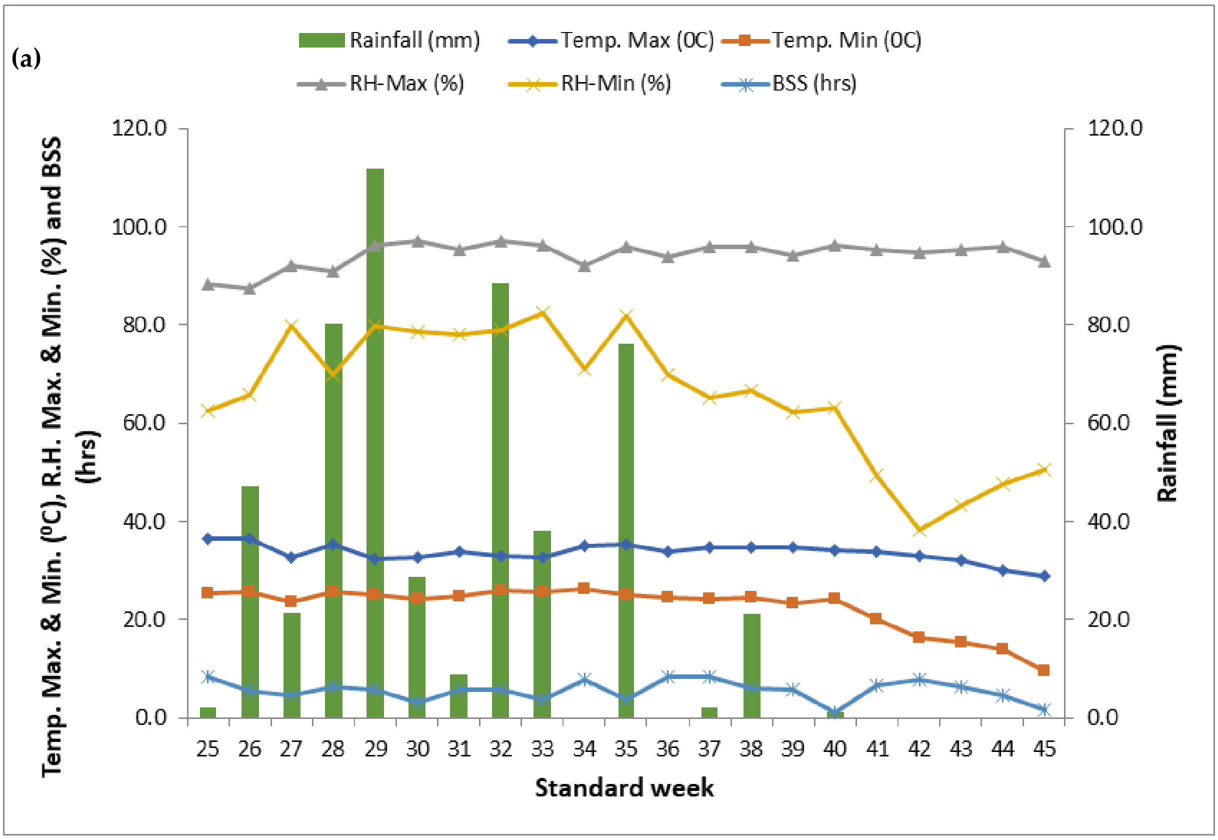

Figure 1. *Cont.*

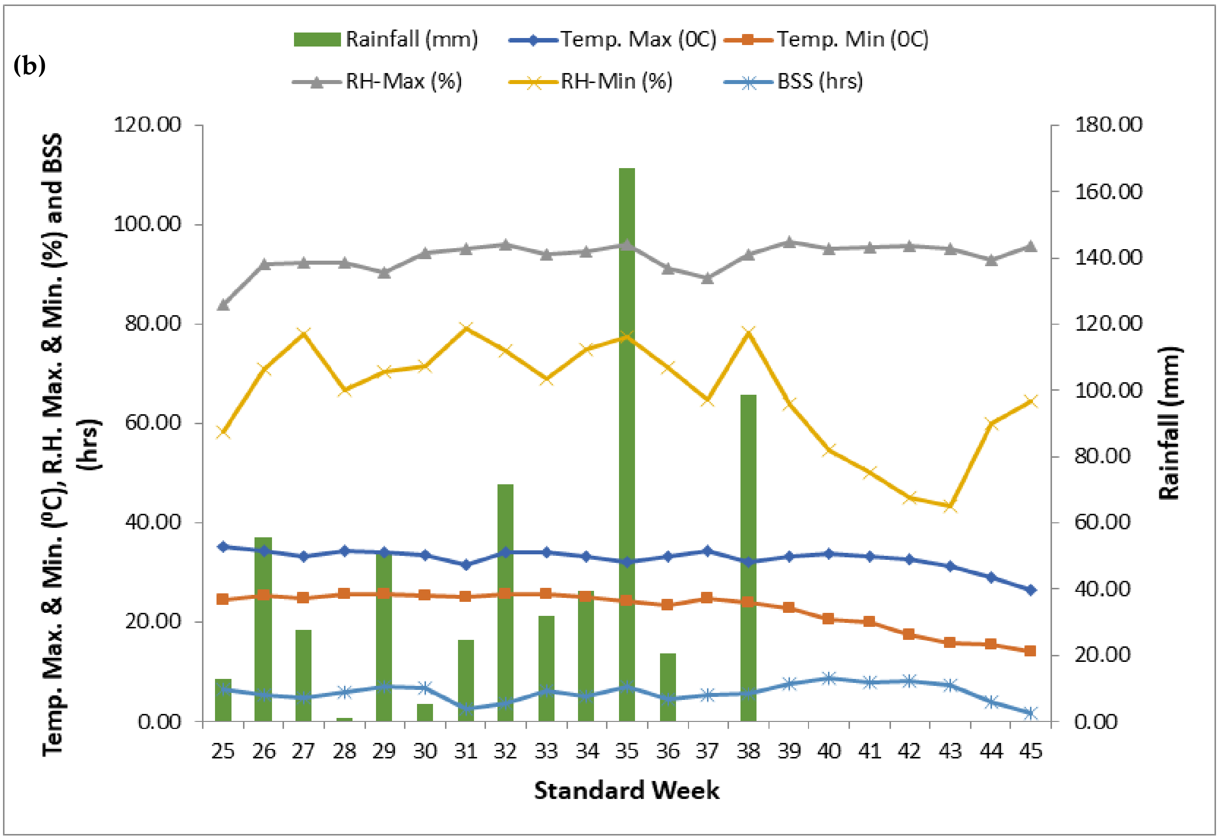

Figure 1. Mean weekly agro-meteorological data during the crop growing *kharif* season: (**a**) 2016 and (**b**) 2017.

2.2. Experimental Invent and Organization

A detailed description of different tillage systems is required to compare the effect of tillage techniques on environmental performance [27]. There are four different tillage crop establishing methods: T_1 is transplanted rice after reduced tillage (RT-TPR), T_2 is transplanted rice on narrow raised beds (N Bed-TPR), T_3 is transplanted rice on wide raised beds (W Bed-TPR) and T_4 is conventional tillage puddled transplanted rice in main plots (CT-TPR). There were three water management/alternate wetting drying (AWD) practices: W_1 is continuously submerged (CS) of 5 cm depth, W_2 is irregular submergence (IS) of 5 cm and irrigation after 2 days of water vanishing from the surface and W_3 is alternating submergence of 5 cm and irrigation after 5 days of water vanishing from the soil surface allotted to sub-plots; five nitrogen levels: N_1 is N0P0K0 (control), N_2 is 80 kg N ha^{-1}, N_3 is 120 kg N ha^{-1}, N_4 is 160 kg N ha^{-1} and N_5 is 200 kg N ha^{-1} allotted to sub-subplots in a split-split-plot design and replicated three times.

Treatments were layered on the same plot every year to evaluate their cumulative effect. The gross and net plot sizes were 8 m $\times$ 3.2 m and 6.0 m $\times$ 2.0 m, respectively. In traditional tillage, there were three tillage operations. The primary tillage took place during the pre-monsoon season (April/May), while the second took place 20–25 days later, in May/June. The third tillage was carried out in June with a tractor-drawn cultivator at a deeper depth (>15 cm). Nitrogen was applied in accordance with the protocols. Except for N_1, all treatments received soil application 60 kg phosphorus (P), 40 kg potassium (K) and 25 kg zinc (Zn) ha^{-1} in the form of di-ammonium phosphate, potash sulphate and 21 percent zinc sulphate, respectively. P, K and Zn, as well as 1/3 of nitrogen, were all applied at the time of transplanting and seed bed preparation. In terms of treatment, the remaining nitrogen fertilizer dose was split in half at the time of booting (3 weeks after transplantation) and panicle commencement (6 weeks after transplantation). On 1 July, three-week-old nursery seedlings were manually plucked and replanted into the main field with a distance of 20 cm from row to row. When the crop reached physiological maturity, watering was stopped two weeks before harvest and the crop was harvested.

2.3. Weed Management

For the rest of the growing season, the plots would remain weed-free. Butachlor at 1300 ga.i.ha^{-1} should be applied 2 days after transplanting (DAT), followed by a spray treatment of bispyribac sodium (Nomne gold) at 25 ga.i.ha^{-1} one month later. Additionally, weeds were manually removed in the transplanted rice plots to keep it weed-free.

2.4. Water Footprints

The total amount of water used for producing agricultural goods is known as water footprint (WFP) [28]. The unit is commonly stated in m^3 t^{-1} or L kg^{-1}.

$$\mathrm{WFP_{total}} = (\mathrm{WFP_{green}}) + (\mathrm{WFP_{blue}}) + (\mathrm{WFP_{grey}}) = \frac{\mathrm{CWUgreen} + \mathrm{CWUblue} + \mathrm{CWUgrey}\left(\mathrm{m^3\ ha^{-1}}\right)}{\text{Economic yield of the crop}\left(\mathrm{t\ ha^{-1}}\right)} \tag{1}$$

Water productivity ($\mathrm{WP_{I+R}}$) (kg m^{-3}) was computed as follows

$$\mathrm{WP_{I+R}} = \frac{\text{Grain yield}}{\text{Irrigation water applied} + \text{Rainfall received by the crop}} \tag{2}$$

Rice Water Footprints

Under conventional systems, total water inputs for the rice–wheat cropping sequence involved total water required to meet various components of soil water balance with extra water required for puddling, especially for rice. However, only evapotranspiration (ET) and evaporation (E) during land preparation were taken into consideration for water footprint calculations, and attempts mostly were made to reduce E. As a result, the amount of water evaporated to produce a specific set of yields equals the WFP (m^3 t^{-1}) of rice–wheat production. Percolation is not considered a watershed loss, but it was left out of the farm-wide water footprint estimation because it occurs during crop development and field preparation. On the other hand, the crop's grey WF due to N pollution was calculated and merged with the blue and green WF.

2.5. Nutrient Use Efficiency

The nitrogen harvest index (NHI) measures the ability of a crop to divide total N intake among different plant parts [29]. As a result, the NHI was defined as the ratio of seeds to total biomass nitrogen intake. The nitrogen usage efficiency (NUE) is categorized in various methods. The total N uptake by seed and straw as well as the amount of applied N as fertilizer are used to calculate the apparent N recovery (NUE) for various N treatments (Equation (3)). The term "nitrogen yield efficiency" (NYE) or "agronomic nitrogen efficiency" is preferred to characterize how well N inputs are used in relation to the amount of nitrogen applied [30]. Equation (4) [31] was used to compute the NYE in various N treatments using the applied nitrogen as fertilizer and seed yield. Equation (5) also determined the physiological nitrogen efficiency (NPE).

$$\mathrm{NUE} = \frac{\mathrm{Nui} - \mathrm{Nuc}}{\mathrm{Nfi} - \mathrm{Nfc}} \tag{3}$$

$$\mathrm{NYE} = \frac{\mathrm{Yi} - \mathrm{Yc}}{\mathrm{Nfi} - \mathrm{Nfc}} \tag{4}$$

$$\mathrm{NPE} = \frac{\mathrm{Yi} - \mathrm{Yc}}{\mathrm{Nui} - \mathrm{Nuc}} \tag{5}$$

where NUE, Nuc, Nfi, Nfc, Yi and Yc represents nitrogen use efficiency, total N uptake by seed and straw (kg ha^{-1}), applied N (kg ha^{-1}), rice grain yields in N treatments and control (kg ha^{-1}), respectively.

2.6. Statistical Investigation

The SPSS application, which runs on Windows, was used to conduct the statistical analysis (Version 10.0, SPSS, 1996, Chicago, IL, USA). For analysis of variance, the SPSS technique was utilized to establish the statistical significance of treatment effects. Duncan's multiple range test was used to compare the means using the least significant difference (LSD) method. Statistically significant values are considered at a probability level of 5%.

3. Results and Discussion

3.1. Soil Moisture Studies

Results revealed that surface soil pertaining to 0–15 cm of soil mined a higher proportion of the moisture as compared to the other three layers, viz., 15–30, 30–60 and 60–90 cm, where 60–90 cm extracted the least moisture (Figure 2).

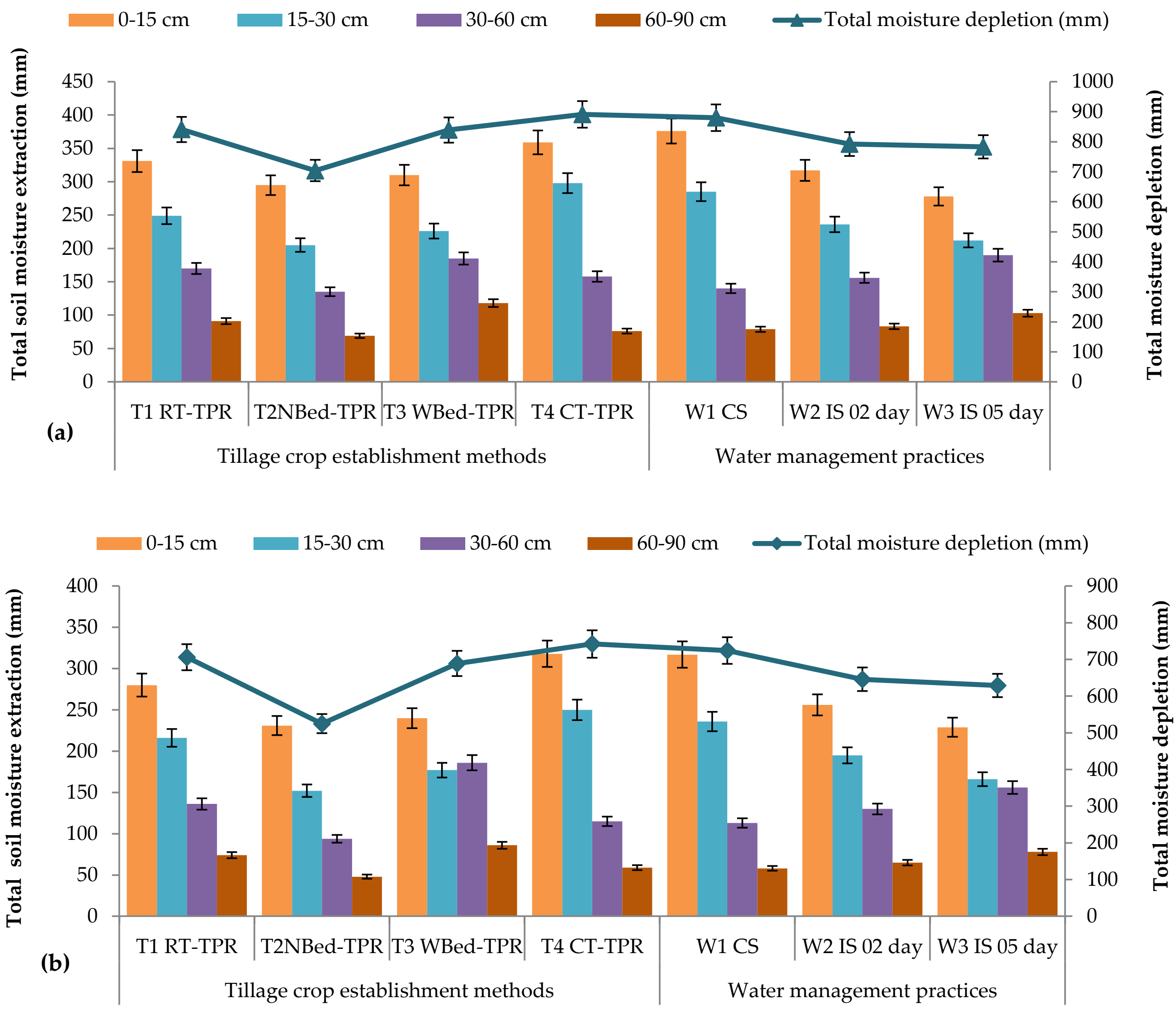

Figure 2. Tillage, water and nitrogen interactive effects on water extraction patterns in soil profile in both years: (**a**) 2016 and (**b**) 2017.

Moisture extraction from the surface layer (0–15 cm) was slightly increased using conventional tillage and reduced tillage techniques. Similarly, the moisture extraction was marginally reduced as the profile depth and furrow irrigated raised beds increased during 2016 and 2017, respectively. Furthermore, rice transplanted on wide raised beds and in reduced tillage plots had higher moisture removal from deeper profile layer than rice transplanted using the conventional method. Throughout the experimentation period, moisture mined from 0–15 cm rose marginally as irrigation frequency increased. Similarly, as the profile depth and irrigation frequency increased in both years, moisture extraction reduced marginally of W_1's water management technique decreased moisture extraction as profile depth increased. During the experimentation, however, moisture extraction was increased in profile depth for W_2 and W_3 treatments compared to W_1 treatment.

In 2016 and 2017, the seasonal variation in average profile moisture in all treatments ranged from 27.1 to 21.4% and 27.9 to 19.7%, respectively, which might be due to the variation in tillage practices adopted to establish the crop and receive rainfall. However, under irrigation, the soil upper profile was recharged to field capacity, but its moisture content decreased over time due to evapotranspiration losses, which are dependent on the weather parameters such as air maximum temperatures.

In both years, the lowest moisture content was found at the time of crop maturity, which could be because irrigation was stopped three weeks before harvesting. Furthermore, well-fertilized plots, i.e., N_4 or N_5 treatment, had lower moisture than the control plots with no fertilizers, etc., which could be attributed to better crop growth and higher transpiration losses in the previous plots. Similar observations are also reported by [32].

The amount of moisture extracted from various soil profile layers decreased as profile depth increased, which could be due to reduced root mass density (RMD) as we moved down the profile (Figure 2). However, in reciprocate of this, surface soil layers received better moisture, nutrients, and RMD, which further extracted higher soil moisture. No doubt, weather parameters also affected these quantum volumes. In both years, moisture was extracted from the 30–60 cm layer at around 19.9%, with 39.8 and 29.8% of water used from the 0–15 and 15–30 cm layers, respectively. Measuring moisture usage cm^{-1} of soil depth in the 0–15 cm layer can further support this argument. when compared to deeper layers, such as the 30–60 cm layer, T_1 and T_3 treatments had respective values of 0.35 and 0.23 cm cm^{-1} in T_2 treatment and 0.29 cm cm^{-1} in T_4 treatment. When irrigation scheduling mode was used, moisture removal from the upper layers increased by 1–2%, with a decline in similar values in the deepest soil layers. The reason for the recorded observation might be that the previous layers received higher solar radiation, which further resulted in higher ET losses than the respected lower layers, as also explained by [33–35].

However, moisture in the soil profile was reported to be around 40% higher during transplanting time than harvesting time, which might be due to the fact that transplantation was carried out in flooded conditions during both years. The enhancements in profile moisture content seen from the peaks under various tillage practices were linked to moisture conservation due to irrigation frequency application as per treatments.

Furthermore, during both years of experimentation, T_4 treatment at a deeper depth remained on the lower side as compared to T_1 and T_3 treatments, respectively, with the exception of peaks, where recharging of the profile by irrigation or rainfall made constant soil profile moisture. The average soil moisture content of the typical till crop was 1.5% lower than that of the broad raised bed plots throughout the crop season, excluding after the recharging of the soil profile by irrigation or rainfall.

3.2. Footprints and Productivity of Irrigation Water

During both years, T_4 treatment had the highest total water footprint (TWFP) with a value of 1894.4 and 1899.6 m^3 t^{-1} whereas T_1, T_3 and T_2 plots reported 1738.0, 1697.0 and 1659.6 and 1834.0, 1738.0 and 1659.6 m^3 t^{-1}, respectively. The irrigation technique of W_1 treatment had a TWFP of 1785.2 m^3 t^{-1} in 2017 and 1821.9 m^3 t^{-1} in 2018. That was significantly higher than all other irrigation strategies and statistically equivalent to W_2 treatment. During both years of the study, however, W_3 treatment had the lowest TWFP of 1709.3 and 1744.3 m^3 t^{-1}. The highest TWFP was reported in 2016 and 2017 when "control" fertilizer was not used and only 80 kg N ha^{-1} was broadcast in N_1 and N_2 treatments during both years, with values of 1817.0, 1776.3 and 1825.2 and 1807.2 m^3 t^{-1}, respectively. Furthermore, N_3, N_4 and N_5 plots recorded the lowest TWFP of 1768.3, 1743.6 and 1631.5 m^3 t^{-1} in 2017 and 1774.0, 1766.0 and 1741.3 m^3 t^{-1} in 2018. Hence, from control plots to fertilized plots, TWFP was reduced to better crop growth and higher transpiration losses, which only met with the used higher irrigation water quantum, which clearly explains why TWFP was lower in fertilized plots as compared to control plots. In addition, T_4 plots were recorded with significantly higher values of TWFP as compared to T_1, T_2 and T_3 plots during both experimental years (Tables 1 and 2).

Table 1. The impact of various treatments on footprints and productivity of applied irrigation water in the 2016 year.

Treatments	BWFP (m^3 t^{-1})	GWFP (m^3 t^{-1})	Gr WFP (m^3 t^{-1})	TWFP (m^3 t^{-1})	PERC_V (m^3 t^{-1})	TWU_V (m^3 t^{-1})	WP_{IRRI} (kg m^{-3})	WP_{TCW} (kg m^{-3})	WP_{ETC} (kg m^{-3})
Tillage crop establishment methods									
T_1 (RT-TPR)	1627	108.8	2.2	1738.0	1288	2919.2	0.68	0.42	0.37
T_2 (NBed-TPR)	1554	105.3	0.7	1659.6	1325	2646.5	0.65	0.40	0.39
T_3 (WBED-TPR)	1588	107.2	1.8	1697.0	1303	2804.5	0.70	0.43	0.44
T_4 (CT-TPR)	1782	109.7	2.7	1894.4	1265	3080.8	0.66	0.38	0.42
LSD ($p \leq 0.05$)	78.70	1.38	0.03	24.52	17.56	37.88	0.08	0.04	0.04
Water management practices									
W_1 (CS)	1674	109.1	2.2	1785.2	1315	3135.3	0.61	0.39	0.36
W_2 (IS 02 day)	1638	107.5	1.9	1747.3	1296	2846.5	0.63	0.39	0.43
W_3 (IS 05 day)	1601	106.8	1.6	1709.3	1274	2606.5	0.64	0.42	0.44
LSD ($p \leq 0.05$)	63.67	1.81	0.03	29.88	22.54	51.08	0.08	0.07	0.07
Nitrogen levels									
N_1 (Control)	1709	106.4	2.1	1817.0	1366	3006.3	0.46	0.54	0.32
N_2 (80 kg N ha^{-1})	1667	107.2	2.0	1776.3	1355	2984.7	0.49	0.41	0.38
N_3 (120 kg N ha^{-1})	1659	107.8	1.9	1768.3	1342	2958.2	0.53	0.39	0.52
N_4 (160 kg N ha^{-1})	1633	108.4	1.8	1743.6	1223	2717.1	0.56	0.35	0.64
N_5 (200 kg N ha^{-1})	1521	109.2	1.7	1631.5	1189	2647.5	0.55	0.34	0.63
LSD ($p \leq 0.05$)	NS	NS	0.06	52.75	38.71	86.12	0.07	0.08	0.13

BWFP, GWFP, Gr WFP stood for blue, green and grey water footprints while TWFP, PERC_V, TWU_V, WP_{IRRI}, WP_{TCW} and WP_{ETC} stands for total water footprint, percolation water volume, total water use volume, water productivity, water productivity of total crop water needs and water productivity as evapotranspiration only.

The ratio of percolation losses to grain yields was reported to be the highest in the control plots with no broadcasted N fertilizers, while it was reduced to 1366 and 1355 m^3 t^{-1} in 2017 and 1434 and 1423 m^3 t^{-1} in 2018 reported for the N_1 and N_2 treatments, respectively. During the years 2016 and 2017, N_3, N_4 and N_5 plots reported 1342, 1223 and 1189 m^3 t^{-1} and 1410, 1292 and 1258 m^3 t^{-1}, respectively.

The highest grain yield was attributed to a lower volume of percolation water with higher fertilizer doses, but decreased infiltration volume was mostly due to shorter standing water duration under N_4 and N_5 treatments. Because of the continuous submergence under the previous treatment, the WFs are reported to be greater for W_1 (3135.3 and 3048.3 m^3 t^{-1}) than for W_2 (2846.5 and 2877.6 m^3 t^{-1}) and W_3 (2606.5 and 2745.7 m^3 t^{-1}) than for W_2 (2846.5 and 2877.6 m^3 t^{-1}) and W_3 (2606.5 and 2745.7 m^3 t^{-1}) (Tables 1 and 2). These results indicate that agricultural administration (tillage crop establishment methods and irrigation techniques) had a greater impact on the water footprint and amount of water infiltration than the agro-climate in which the crop was grown. Through improved agro-management techniques, this opens up the option of improving production and water productivity. It is also determined that the optimal use of fertilizers has the potential to improve yield and, as a consequence, reduce water footprints in rice cultivation in the region.

Table 2. The impact of various treatments on footprints and productivity of applied irrigation water in 2017 year.

Treatments	BWFP (m^3 t^{-1})	GWFP (m^3 t^{-1})	Gr WFP (m^3 t^{-1})	TWFP (m^3 t^{-1})	PERC_V (m^3 t^{-1})	TWU_V (m^3 t^{-1})	WP_{IRRI} (kg m^{-3})	WP_{TCW} (kg m^{-3})	WP_{ETC} (kg m^{-3})
Tillage crop establishment methods									
T_1 (RT-TPR)	1718	113.9	2.4	1834.0	1370	2946.5	0.69	0.41	0.41
T_2 (NBed-TPR)	1548	109.5	1.9	1659.6	1397	2683.5	0.67	0.39	0.42
T_3 (WBED-TPR)	1624	111.8	2.3	1738.0	1356	2837.1	0.72	0.42	0.44
T_4 (CT-TPR)	1781	115.5	2.9	1899.6	1330	3094.9	0.68	0.38	0.42
LSD ($p \leq 0.05$)	17.16	1.41	0.03	22.84	18.16	38.90	0.05	0.04	0.06
Water management practices									
W_1 (CS)	1706	114.1	2.1	1821.9	1386	3048.3	0.40	0.39	0.42
W_2 (IS 02 day)	1667	112.8	2.3	1782.3	1364	2877.6	0.42	0.39	0.45
W_3 (IS 05 day)	1631	111.2	2.6	1744.3	1340	2745.7	0.43	0.42	0.46
LSD ($p \leq 0.05$)	23.73	1.90	0.05	30.70	23.75	51.4	NS	NS	NS
Nitrogen levels									
N_1 (Control)	1713	111.3	2.4	1825.2	1434	3040.4	0.41	0.53	0.32
N_2 (80 kg N ha^{-1})	1695	112.1	2.3	1807.2	1423	3017.2	0.42	0.41	0.33
N_3 (120 kg N ha^{-1})	1660	112.7	2.2	1774.0	1410	2989.6	0.54	0.38	0.34
N_4 (160 kg N ha^{-1})	1652	113.3	2.1	1766.0	1292	2738.8	0.58	0.35	0.38
N_5 (200 kg N ha^{-1})	1626	114.1	2.5	1741.3	1258	2666.7	0.57	0.36	0.35
LSD ($p \leq 0.05$)	41.25	NS	0.07	53.43	40.76	86.74	0.08	0.07	0.08

BWFP, GWFP, Gr WFP stood for blue, green and grey water footprints while TWFP, PERC_V, TWU_V, WP_{IRRI}, WP_{TCW} and WP_{ETC} stands for total water footprint, percolation water volume, total water use volume, water productivity, water productivity of total crop water needs and water productivity as evapotranspiration only.

WP_{IRRI} was lower in T_1 (0.69 kg m^{-3}) and T_4 (0.68 kg m^{-3}) treatments, while it was the highest in T_3 (0.71 kg m^{-3}) treatment (Tables 1 and 2). Despite having a 9.5% lower production, T_3 treatment had a 7.5% higher WP_{IRRI} than T_4 treatment. WP values of T_3 plots were recorded on the higher side as compared to T_4 plots, though yields were reported to be significantly different in the above plots. From control to N fertilized plots, the corresponding values of WP_{IRRI} jumped to 0.44, 0.46, 0.54, 0.57 and 0.56 kg m^{-3}, respectively, for N_1, N_2, N_3, N_4 and N_5. Furthermore, in T_4, T_2, T_1 and T_3 treatments, the respective values of WP were recorded as 0.38, 0.40, 0.41 and 0.42 kg m^{-3}. The reason for better WP is assumed to be poor vegetation and hence less transpiration loss in these plots. As a result, WPTCW yields were comparable to the other three tillage crop establishment treatments, whereas T_2 treatment yields were lower. Although the expected water productivity was comparable to that of N_3, N_4 and N_5 treatments, the WPTCW grew gradually as the nitrogen dose was increased. A similar pattern was observed when water productivity was evaluated only on the basis of evapotranspiration (Tables 1 and 2) as recorded earlier by [36–39].

3.3. Nitrogen Use Efficiency

Under various tillage, water and nitrogen treatments, ANUE values ranged from 13.5–24.1%. Over the course of the N treatments, alternate wetting and drying treatments (W_2 and W_3) had a higher ANUE than continuous submergence (W_1). The average ANUE was also found to be higher (24.1%) at N_2 treatment, but not at higher doses of N (14.6% at N_5 treatment). In water management treatments, the NHI was quite consistent, ranging from 47.7 to 50.7%. The level of significance for NHI was similarly inconsistent between N treatments (Figure 3).

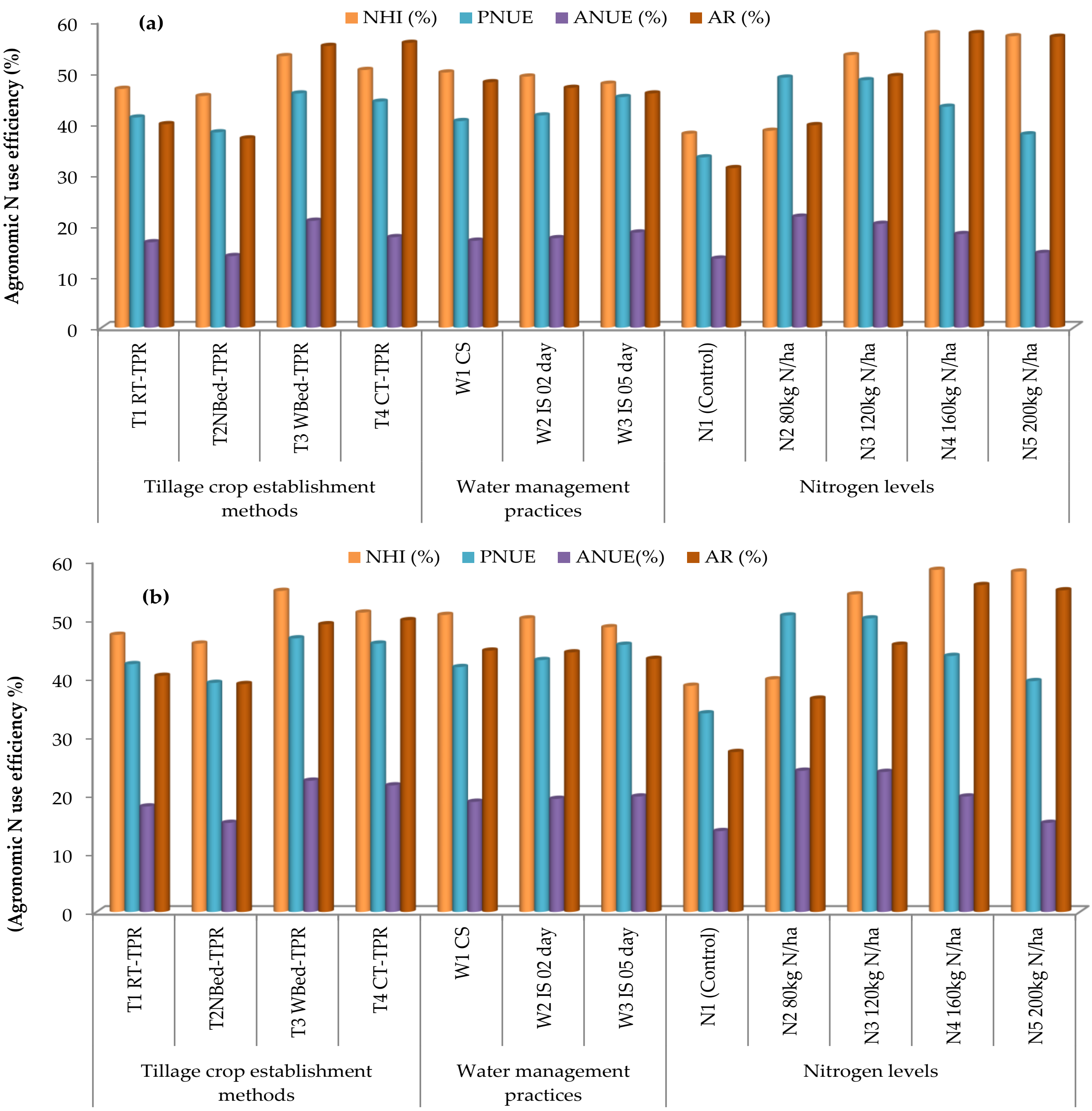

Figure 3. Tillage, water and nitrogen interactive effects on nitrogen use efficiency parameters in both years: (**a**) 2016 and (**b**) 2017.

The PNUE limits ranged from 33.3 to 50.6 kg grain kg^{-1} N uptake, with decreasing values as the N dosages increased (Figure 3). As N doses increase, PNUE values tend to decrease due to higher N uptake and higher N concentrations in both the grain and straw. However, the PNUE values in W_1, W_2 and W_3 treatments were similar and statistically insignificant. Different N and water management procedures resulted in AR values ranging from 27.3 to 57.6%. Because of the larger grain output, the AR was higher at N_4 treatment. This was due to the greater yield difference between the N_1 and N_4 treatments (about 1.92 t ha^{-1}).

3.4. Yield Contributing Characteristics and Yield

Tillers m^{-2}, effective tillers m^{-2}, spike length and spikelets per panicle^{-1} and number of grains per panicle^{-1} all varied with tillage strategies, with the T_4 treatment having significantly more effective tillers m^{-2} than all other land configurations. During the years of study, however, T_3 treatment recorded considerably greater yield in contributing metrics than the other treatments, compared to T_1 and T_2, during testing, respectively (Figures 4 and 5).

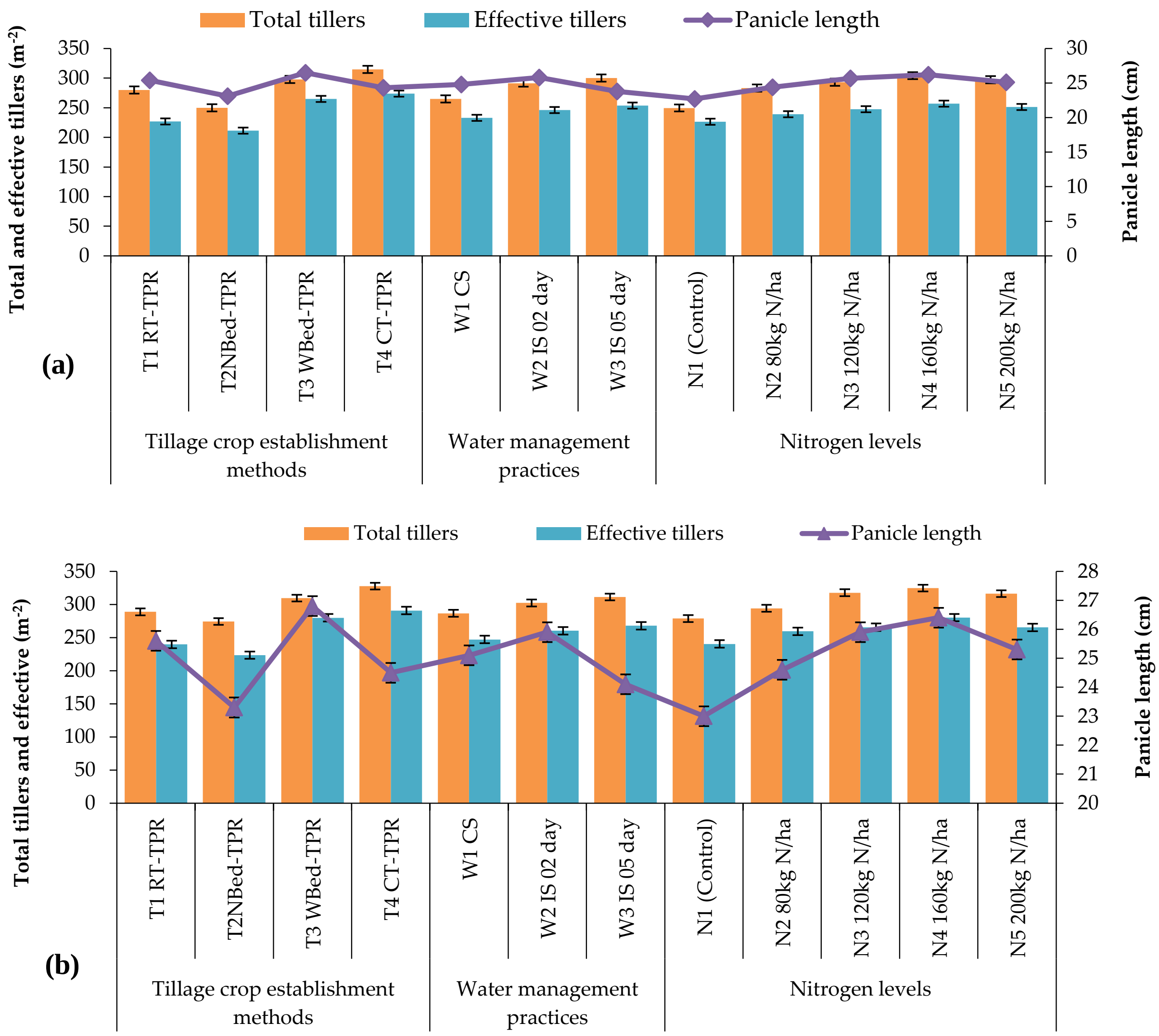

Figure 4. Interactive effects of tillage, water and nitrogen on total and effective tillers and panicle length of rice in both years: (**a**) 2016 and, (**b**) 2017.

Irrigation management differences were also shown to be significant in terms of average effective tillers m^{-2}. During both years of study, W_2 and W_3 treatments produced significantly higher yield contributing parameters than W_1 treatment. Differences in nitrogen management were also discovered to be significant in terms of yield contributing parameters. In 2016 and 2017, the N_1 and N_2 treatments produced significantly lower yield contributing parameters than the rest of the nitrogen management. In both the years of study, N_4 treatment produced significantly higher yield contributing parameters than all other treatments except N_3 treatment (Figures 4 and 5). This was due to a 25.2 and 25.9% increase in the quantity of grains per panicle, respectively, during the research years. Similarly, the increase in test weight during the experiment was between 25.8 and 26.2%. The current study's findings on the interactive effects of tillage, water and nitrogen on total and effective tillers, panicle length, spikelets, and grains/panicle and 1000 grain weight of rice were also corroborated by previous studies [39–43].

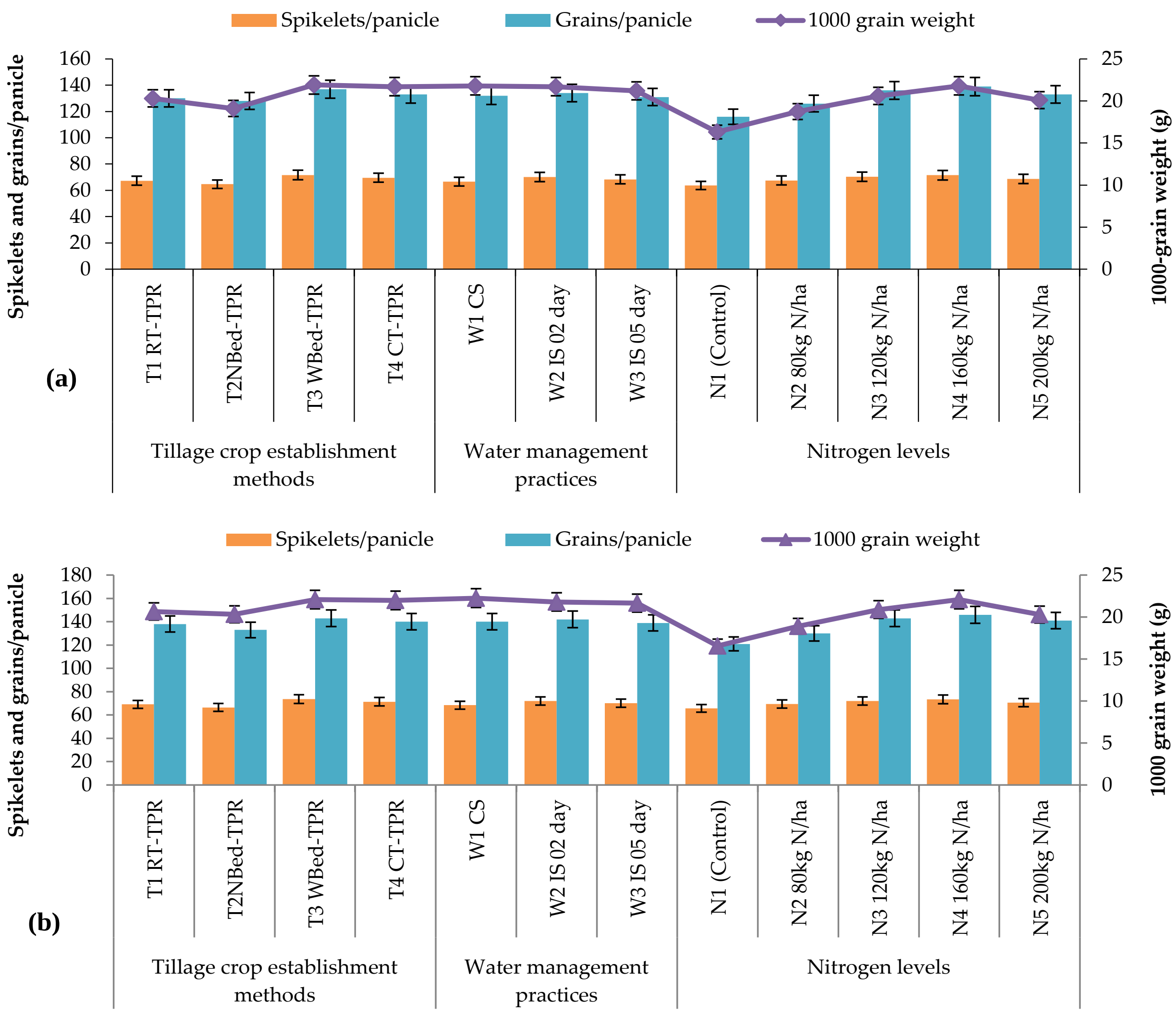

Figure 5. Interactive effects of tillage, water and nitrogen on spikelets and grains/panicle and 1000 grain weight of rice in both years: (**a**) 2016 and, (**b**) 2017.

During the study period, T_4 treatment (rice transplanted on wide raised beds) yielded the highest grain and straw yield (48.10 and 64.7 q ha^{-1}) and T_3 treatment (rice transplanted on narrow raised beds) (45.2 and 60.9 q ha^{-1}) remained statistically similar (Figure 6). The decline in grain and straw yield due to unpuddled tillage, i.e., reduced tillage and narrow raised bed practices, was 16.1, 9.8; 10.6, 3.9 and 17.2, 11.9, 12.1, 6.6% compared to T_4 and T_3 practices, respectively. However, rice transplanted on widespread raised beds of 4.1% recorded a significant increase in yield compared to the reduced tillage options.

Yields pertaining to grain and straw are reported to be significantly influenced by the interactive effects of water and N management. During both experimental years, W_1 treatment (continuously submerged to a depth of 5 cm) had a significantly higher grain yield (45.92, 46.89 and 63.16, 63.97 q ha^{-1}) when compared to all other water management treatments (Figure 6a,b). Moreover, W_2 treatment (intermittent submergence of 5 cm and irrigation after 2 days of disappearance of water from soil surface) was significantly superior to W_3 treatment (intermittent submergence of 5 cm and irrigation after 5 days of disappearance of water from soil surface), which recorded minimum grain yield during the years of study.

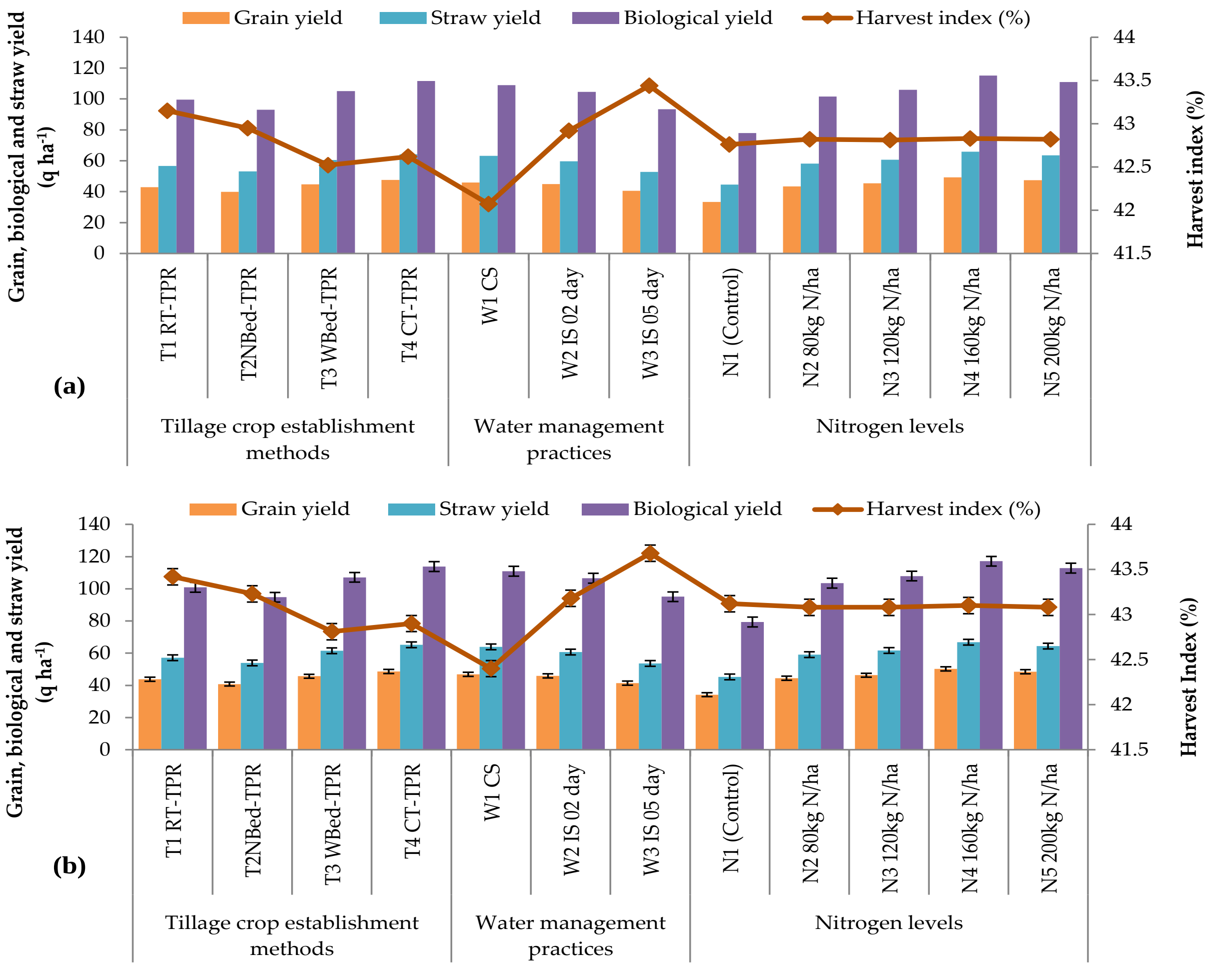

Figure 6. Interactive effects of tillage, water and nitrogen on grain, biological and straw yield, and harvest index (%) of rice in both years: (**a**) 2016 and (**b**) 2017.

Furthermore, grain yields of 49.30, 50.26 and 65.93 and 66.88 q ha^{-1} were significantly improved in the N_4 treatment, which remained statistically comparable to the N_5 treatment. The yield of N_3 treatment (120 kg N ha^{-1}) was much higher than that of N_2 and N_1 "control" treatments (Figure 6a,b). During the experimentation, the same yield behavior was observed for biological yield.

Due to favorable weather conditions, crop performance was somewhat higher in 2017 than in 2016. On the other hand, inorganic nitrogen sources may provide increased nutritional availability, allowing for improved growth and development. Because there were more nutrients accessible for crop growth, N_4 treatment (160 kg N ha^{-1}) had significantly greater grain (62.3 and 61.8%), straw (34.9 and 35.5%) and biological yield (36.1 and 48.7%) than N_1 treatment (Figure 6a,b). Poor nutrition had a greater impact on grain yield, as evidenced by [40–46], resulting in a significant drop in harvest index.

The harvest index is a critical criterion for evaluating how well dry matter is partitioned to the crop's economic component. In irrigation and nutrient management treatments, all the treatments proved higher than W_3 and N_1 treatments during both years of study. However, all treatments were comparable to one another. There was no discernible trend in terms of planting techniques on the harvest index. However, during the experimental period, the T_1 treatment had the largest harvest index while the T_4 treatment had the lowest (Figure 6a,b).

3.5. Profitability

The year 2017 was reported with better profitability indices such as rice grain yield with reduced cultivation costs compared to 2016 (Figure 7). Various tillage operations increase total farming costs, gross income, net profit and B:C ratio due to better grain yields and hence gross income than the cost of cultivation. Of all the tillage techniques, the T_3 treatment had the highest net profit, gross income and B:C ratio. This could be owing to the better proficiency of FIRB systems compared to other tillage methods, as well as a better production gain when compared with other treatments. Among the various nitrogen doses, N_4 treatment had the highest net profit, gross income and B:C ratio. This could be attributed to the N_4 treatment's superior efficiency compared to the other N treatments, as well as the better rice grain yield hike compared to other treatments. As also reported by [47,48], lower nitrogen doses may not have satisfied crop requirements during the great growth period when bigger levels were required, causing crop growth and output to suffer.

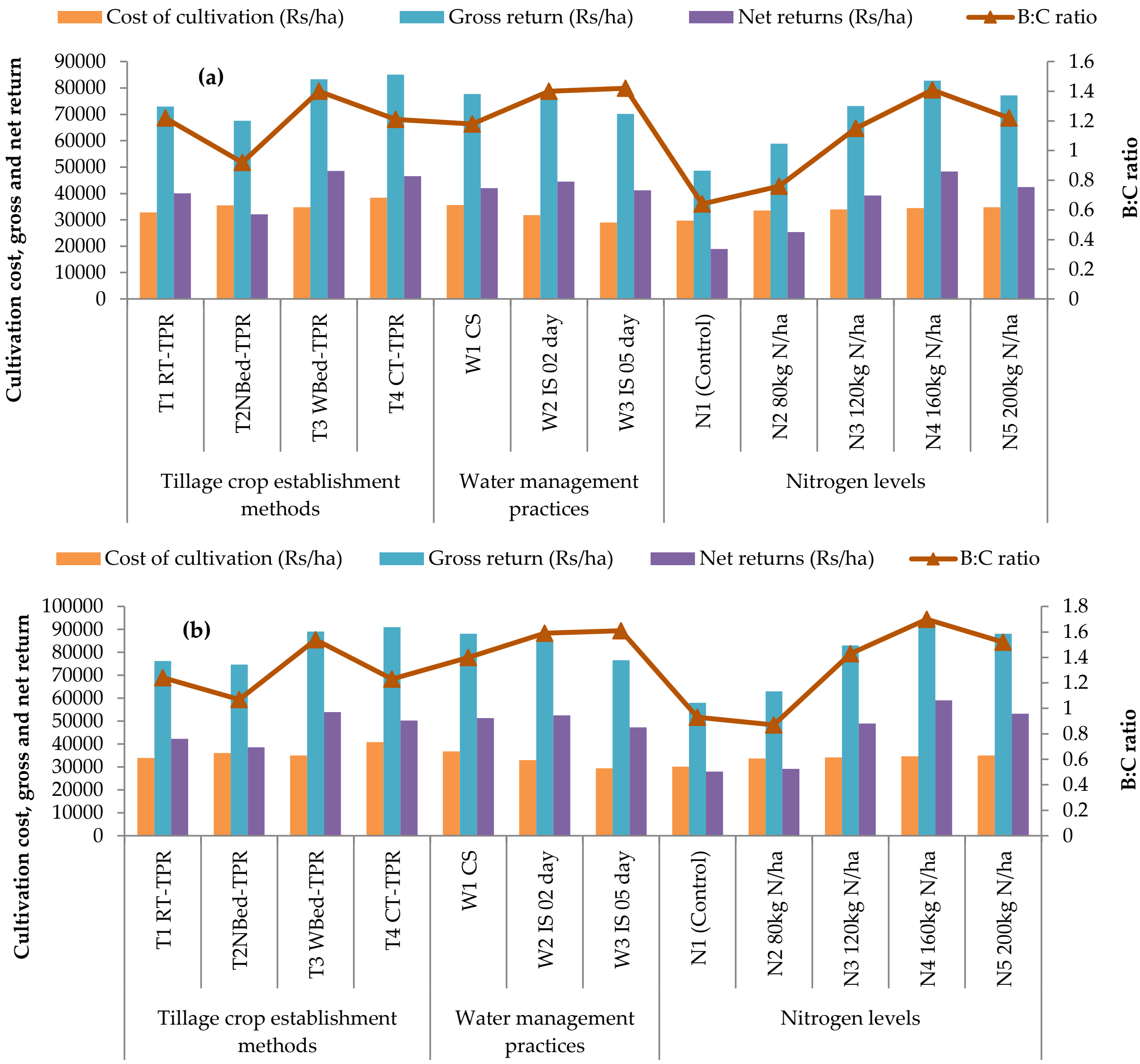

Figure 7. Interactive effects of tillage, water and nitrogen on the profitability of rice in both years: (**a**) 2016 and (**b**) 2017.

4. Conclusions

Finally, a two-year study covering tillage, water and nitrogen interactive effects on wet rice conclude that puddling is the most popular and commonly utilized crop establishment technique on the Indo-Gangetic Plain of India. However, it causes significant limits to production and sustainability of rice–wheat systems. Puddling is not necessary to produce high grain yields, according to two years of research in western Uttar Pradesh, India. Transplanting in unpuddled wide raised beds may be a viable option, and farmers can accept them if they are provided with the right information and recommendations. Rice transplanting under unpuddled wide raised beds is cost effective and can match conventional planting yields if weed control is accomplished. According to the findings, water footprints, crop water productivity and yield attributes of rice crops grown with optimal tillage, water and nitrogen management strategies improved significantly. In addition, if irrigation scheduling is reworked to accommodate these tactics, irrigation water can be saved. Hence, computation of the water balance parameters as affected by tillage, water and nitrogen management strategies to grow rice must be discovered for texturally divergent soils and under various agro-climatic conditions. Green water is important in rice cultivation and there is a lot of room to enhance water productivity by increasing yield levels within the existing water balance. The plots under WBed-TPR had significantly higher nutrient use efficiency, rice productivity and profitability than NBed-TPR and RT-TPR plots. The findings indicate that conservation tillage would enhance grain quality and yield while also being environmentally friendly. Although nitrogen fertilizer increases the probability of intensive agriculture, it does so at the expense of environmental protection. This study indicates that optimum tillage, water and nitrogen management strategies or technologies appear to be viable solutions for long-term rice productivity. However, local governments should encourage farmers to manage water and nutrients based on conservation tillage to improve their water footprint, profitability and crop quality and increase their crop water productivity for the long term.

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