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# Tillage Crop Establishment and Irrigation Methods Improve the Productivity of Wheat (*Triticum aestivum*): Water Use Studies, and the Biological Properties and Fertility Status of Soil

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**Abstract:** The Crop Research Centre of Sardar Vallabhbhai Patel University of Agriculture and Technology in Meerut (U.P.), India, conducted field experiments in a randomised block design, comprising three replicates, one late sown variety (DBW-90), and eight treatments, viz.: T1 was a conventional flood irrigation (CFI); T2, furrow irrigated with gated-pipe raised beds (FIGPRB); T3, all furrow irrigation (AFI); T4, alternate furrow irrigation (Alt. FI); T5, wide bed furrow irrigation (WBFI); T6, skip furrow irrigated (SFI); T7, Sprinkler irrigation (SI); and T8, Zero-till flat-irrigated using gated pipe/controlled-flood irrigation (ZTFIGP). These field experiments were conducted during the Rabi seasons of 2017–2018 and 2018–2019. The purpose of this study was to evaluate the yield, water productivity, and soil health under different tillage crop establishment methods. Test weight, spike length, and productive tillers were all considerably enhanced in treatment T5, with the treatment's statistical significance being similar to that of treatments T8 and T2. Treatment T5 considerably outperformed the other treatments in terms of grain yield, straw yield, biological yield (44.32, 61.88, and 106.19 q $ha^{-1}$, respectively), as well as harvest index (41.73). Thirty to sixty centimetres of soil were mined for the most water, followed by fifteen to thirty centimetres, zero to fifteen centimetres, and sixty to ninety centimetres. Both water-use efficiency (2.86 q $ha^{-1}$ cm) and water productivity (1.91 kg $cm^{-3}$) were highest under T7 (Sprinkler irrigation). The maximum total NPK (113.69; 27.45; 127.33 kg $ha^{-1}$) was found in crops grown with wide bed furrow irrigation. The data also showed that treatment T6 (skip furrow irrigated) had the highest levels of accessible NPK in soil, followed closely by treatment T4 (alternate furrow irrigated). Treatment T8 (zero-till flat-irrigated using gated-pipe/controlled flood irrigation) had the highest bacterial, fungal, and actinomycete populations, followed by T5 (wide bed furrow irrigated) and T2 (furrow irrigated with gated-pipe/elevated bed). Our research showed that there may be more options for maintaining wheat crop water productivity and soil health under different agroecological conditions, including crop productivity, conservation tillage-based establishing methods, and irrigation regimes.

**Keywords:** wheat; tillage; establishment methods; yield; water productivity; soil health

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## 1. Introduction

Wheat (*Triticum aestivum* L.) can grow in a wide range of climates and soil types, from sandy loam to heavy black cotton, making it India's principal grain crop. Wheat may be grown at any altitude between sea level and 3658 m in the Himalayas, and from 11 degrees North latitude to 30 degrees North latitude. From the wet soils of the deltaic coastal areas to the dry soils of Rajasthan, it is cultivated in a wide range of environments and soil types [1]. Wheat is a healthy option because it is a rich source of carbohydrates, protein, and fat. Thiamine, niacin, iron, riboflavin, calcium, and fibre are just some of the minerals it has in abundance. India's most extensively cultivated crop, wheat, feeds 35% of the world's population. About 215.5 million hectares are used for wheat production worldwide, leading to a harvest of 764.5 million metric tons and a productivity of 3.39 t per $ha^{-1}$ [2]. India cultivates wheat on 29.65 million hectares of land, with a yearly production of 99.9 million metric tons (at a productivity of 3371 kg per hectare) [2]. About a third of the world's food grain supply comes from wheat. With 1.35 billion inhabitants, India is only slightly less populous than China (1.41 billion). In about seven years, it will have surpassed China's population and is expected to peak at roughly 1.7 billion by 2050. Therefore, wheat will probably continue to play a crucial role in reaching this. The ever-increasing human population makes steady wheat production a need.

It is crucial that agricultural water management be factored into irrigation schedules, as more than a third of the world's population will face absolute water scarcity by 2025 [3]. Global wheat output has to grow by 1.6% to 2.6% per year to meet demand, and this growth may be accomplished mostly through enhanced input utilisation efficiency. The Indo-Gangetic Plains are experiencing a rate of groundwater loss that ranges from 13 to 17 $km^3$ on an annual basis [4]. Two primary crop management practices can be implemented to increase the efficiency with which wheat inputs are used. Today, 70% of the world's freshwater is utilised in agriculture, although only 40% of the world's food is grown in irrigated soils. Aquifer water is used for about 10% of irrigation, which is an excessive and unsustainable amount [5]. It is generally agreed that adjusting irrigation systems for maximum efficiency saves water and improves crop yields and quality. Sprinkler irrigation should be implemented to minimise water loss, enhance water-use efficiency, and increase agricultural water yield. This method allows for the accurately application water during the presowing and subsequent watering stages. New hydro-physical features of the soil can be strongly influenced using soil tillage. As of late, there has been a lot of buzz about conservation tillage (sometimes known as "zero tillage") and the assertions that it invariably improves soil properties for plant development and water retention. Management strategies that prioritise resource conservation are gaining favour in the rice–wheat cropping system. This approach improves soil organic matter, moisture availability, aggregation, and water transmission capacity [3].

To improve the soil's microbial population, conservation agriculture practises such as zero tillage are preferable under a rice–wheat cropping system from both an economic and ecological standpoint. Zero-till farming has gained popularity among farmers in recent years [6,7] due to its ability to increase crop yields while reducing soil disturbance and protecting soil carbon. Conventional tillage methods are important to India's farming tradition and have made substantial contributions to India's food security. Before planting crops, CT entails a number of procedures, such as clearing the land of residue (either by removing it or by burning it) plough tillage (PT), harrowing, and levelling the ground. CT's effect on the soil's physicochemical and biological properties can have an effect on soil production and longevity [8]. Long-term mechanical disturbances of soil, such as those induced by inversion tillage or severe CT throughout the entire crop growing season, can lead to soil erosion and mycelium network damage [9]. Conventional tillage practices, such as improper straw management, can reduce soil organic carbon (SOC) storage and endanger sustainable crop production [10]. Higher C stocks in agricultural soils can be produced by returning crop residue to the soil [11], which is a key indicator of the soil's environmental quality, and agronomic sustainability [12]. In comparison to the traditional tillage system, the rice–wheat cropping system with zero tillage had a much greater population of bacteria, fungus, actinomycetes, microbial-C, microbial-N, and SOC sequestration. Avoiding tillage can have an impact on crop productivity and, by extension, food security [13]. Therefore, methods of soil and crop management that increase organic carbon and microbial biomass carbon (while keeping yields constant) are of importance. Soil microbial biomass variations as a result of changes in soil management and environmental stresses are indicative of changes in the chemical and physical properties of agricultural ecosystems. Since the soil microbiome is responsible for supplying nutrients to plants, it regulates the availability and production of nutrients in agroecosystems. The capacity of an ecosystem to sequester the carbon fixed during photosynthesis in soil organic matter is related to its net primary output [14]. Since appropriate irrigation practises improve soil health and maximise water consumption without reducing output, they are vital for wheat production, and must be implemented by farmers. Due to the diminishing ground water level caused by improper usage and over-extraction from the ground, this study on tillage crop establishment and irrigation methods in wheat was undertaken, as we know water is the most vital natural resource for humans, animals, and the production of food-producing crops. In light of these facts, wheat (*Triticum aestivum*) productivity, water use efficiency, nutrient uptake, and soil health in sandy loam soils in western Uttar Pradesh, India were investigated as a result of this interest by researchers at the SVPUA&T in Meerut, U.P.

## 2. Materials and Methods

### *2.1. Selected Site*

The study's research was conducted at the Crop Research Centre of the Sardar Vallabhbhai Patel University of Agriculture and Technology in Meerut, Uttar Pradesh (U.P.). Based in the centre of western Uttar Pradesh, Meerut has a subtropical climate and is 237 m above mean sea level. Its coordinates are 29°08′ N latitude and 77°41′ E longitude. The trial field was completely level, and it had well-developed irrigation and drainage systems already in place. The experimental soil was sandy loam in texture, low in available nitrogen and organic carbon, with a medium level of available phosphorus and potassium, while being alkaline in reaction.

### *2.2. Climate and Weather Condition*

This area experiences a semiarid, subtropical climate, with extremely hot summers and freezing winters. In the first year of the study, 2017–2018, the minimum mean temperature was recorded in the month of January 2018 at 4.80 °C (Figure 1A), and in the second year, 2018–2019, it was recorded in the month of December 2018 at 2.90 °C (Figure 1B). During both research years, the month of April saw the mean maximum temperature. During the crop seasons of 2018 and 2019, the mean relative humidity was found to be at its highest points in the months of January (95.7 and 96.7%, respectively) and its lowest points in the months of December (30.3 and 38.9%, respectively). In the first year of the experiment, the minimum evapotranspiration throughout the crop period was 1.7 mm in the month of December, and 1.3 mm in the month of January. In total, the crop years 2017–2018 and 2018–2019 saw rainfall totals of 20.5 and 127.5 mm, respectively (Figure 1A,B).

### *2.3. Treatments Description*

In total, there were nine different treatments, eight of which were different combinations of irrigation and tillage practises, and the ninth was a late-planted variety that was given the name DBW-90. The following treatments were utilised: T1, conventional flood irrigation (CFI); T2, furrow irrigated with gated-pipe raised beds (FIGPRB); T3, all furrow irrigation (AFI); T4, alternate furrow irrigation (Alt. FI); T5, wide bed furrow irrigation (WBFI); T6, skip furrow; T7, Sprinkler irrigation (SI); and T8, Zero-till flat-irrigated using gated pipe/controlled flood irrigation (ZTFIGP). A randomised block design (RBD) with three independent replications was used to conduct controlled flood irrigation (ZTFIGP) over the 2017–2018 and 2018–2019 growing seasons.

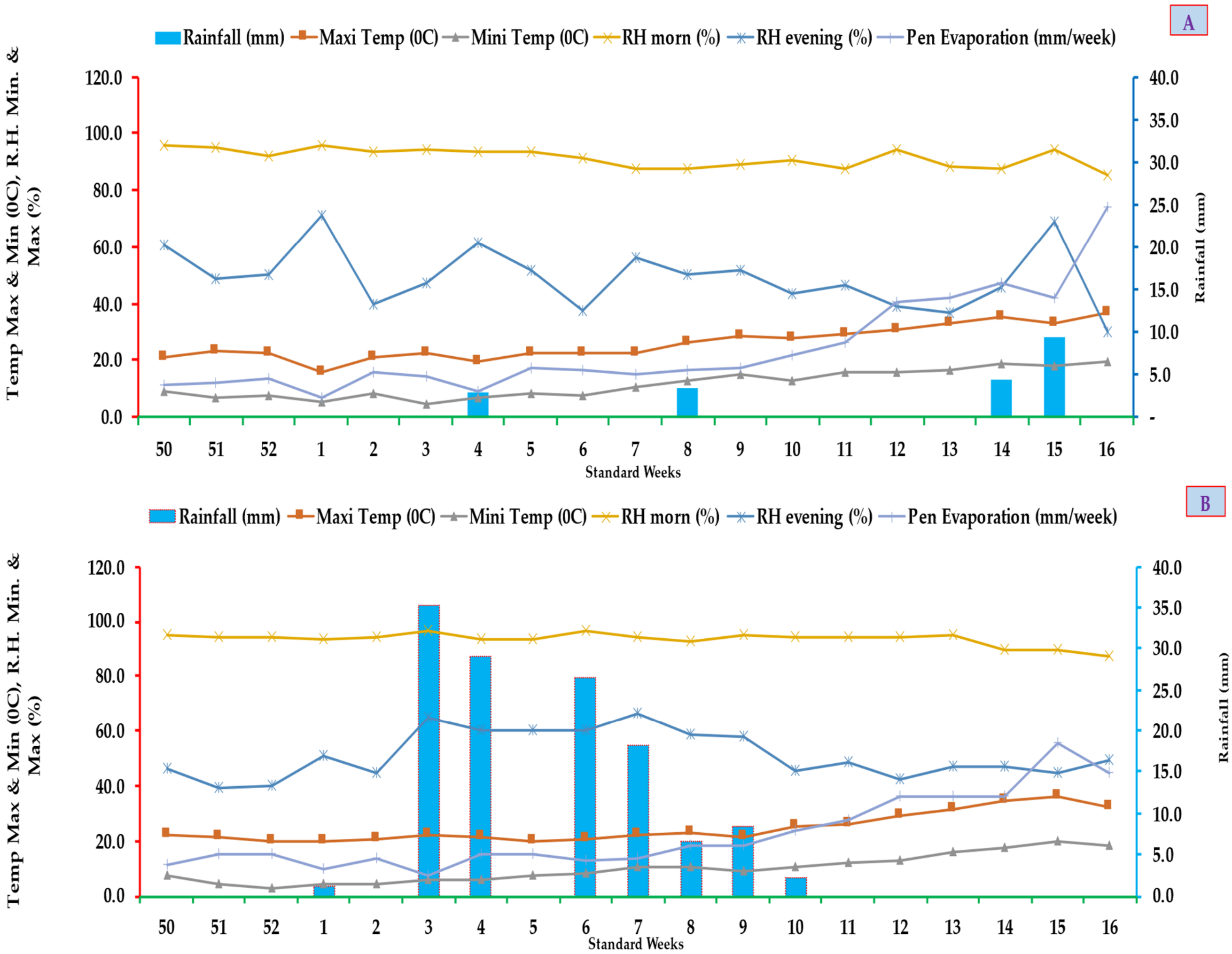


**Figure 1.** Mean weekly Agro-meteorological data during the crop growing *rabi* season for (**A**) 2017–2018 and (**B**) 2018–2019.

### 2.4. Cultural Practices

Wheat was planted using a seed drill equipped with a dry fertiliser attachment in rows 20 cm apart, after presowing irrigation and a CT method comprising two harrowings, three ploughings (using a cultivator), and then planking. Raised beds were constructed utilising a tractor-drawn multicrop raised bed planter outfitted with inclined plate seed metering systems while using furrow-irrigated raised-bed tillage (FIRB). Narrow beds were 40 cm wide, while broad beds were 100 cm wide. Irrigated furrows were 12 cm high and 30 cm wide at the top, and a 70 cm spacing was kept between the centres of neighbouring furrows. Wheat was planted in a staggered pattern of three rows per raised bed. The crops were planted utilising the ZT method, which involves minimal tilling of the ground, and the zero-till seed drill was utilised to achieve this. With this implement, farmers could sow seeds directly into narrow slots in the ground that were only a few millimetres wide, and four to seven cm deep.

### 2.5. Management of Fertilisers and Crops

All of the fields were fertilised with the proper ratio of nitrogen to phosphorus to potassium (150:60:60 kg ha$^{-1}$), in order to achieve optimal crop yield. At the time of planting, a full dose of phosphorus and potassium (as well as half the recommended dose of nitrogen) were applied using a seed-cum-fertiliser drill. Urea, DAP, and MOP were used together as a source of N, P, and K. The rest of the nitrogen was applied along with the urea at 25 and then at 55 days following planting. The herbicide Sulfosulfuron (postemergence) at 33.3 g a.i. per $ha^{-1}$ was applied to the standing crop at 30 days, and then one round of hand weeding was performed at 45 days to control the weed population. The soil used in the experiment was a sandy loam with medium levels of accessible phosphorus and potassium and a mildly alkaline pH.

### *2.6. Yield Attributing Characters and Yield (q ha$^{-1}$)*

For each net plot, we calculated the number of effective tillers per metre of row length in a random sample of marked rows, and then translated the results to $m^2$. The average length of each spike was determined by measuring ten spikes at random from each plot. Ten separate spikes were counted to provide an average for the number of grains per spike. By isolating the grains from the spikelets, the density of grains per unit of spikelet area could be calculated. The number of grains in a composite sample obtained from the harvest of each plot was counted using an automatic seed counter, and the weight of 1000 grains was reported in grammes.

The biological harvest from the whole net area of each plot was collected using miniature plot threshers. After harvesting the net plot area, wheat bundles were sun-dried for four days, and their final weights were converted to kilogrammes per hectare (ha) in order to calculate the biological yield (q $ha^{-1}$). Straw yield (in q $ha^{-1}$) was determined by subtracting the biological yield per net plot area from the grain yield. Grain yields were originally recorded in kilogrammes per hectare for the net plot area, but were converted to kilogrammes per hectare after being normalised to 14% moisture. The harvest index was determined by dividing the economic yield by the biological yield and then expressing the result as a percentage.

$$\text{Harvest index}(\%) = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

### *2.7. Water Use Studies*

#### 2.7.1. Consumptive Use of Water

The consumptive use was worked out from the loss in soil moisture, effective rainfall, and potential evapotranspiration for 2 days following irrigation. The seasonal consumptive use was calculated using the formula given below.

$$\mathrm{U} = \sum_{\mathrm{i}}^{\mathrm{n}} (\mathrm{Eo} \times 0.8) + (\mathrm{M}_1 - \mathrm{M}_2) + \mathrm{ER}$$

#### 2.7.2. Water-Use Efficiency (WUE)

The economic yield (kg $ha^{-1}$) was divided by the total amount of water used (cm) from the relevant plots to calculate the water-use efficiency (WUE) of various treatments.

$$\mathrm{WUE} = \frac{\text{Economic yield}\left(\text{kg ha}^{-1}\right)}{\text{Total consumptive use of water (cm)}} \text{kg ha}^{-1}\text{cm}^{-1}$$

#### 2.7.3. Water Productivity (WP)

By dividing the economic yield (kg $ha^{-1)}$ by the depth of irrigation water applied (cm) from separate plots, the WP of various treatments was calculated. It is expressed in kg $m^{-3}$.

$$\mathrm{WP} = \frac{\text{Economic yield}\left(\text{kg ha}^{-1}\right)}{\text{Amount of water applied (cm)}} \text{ kg m}^{-3}$$

### *2.8. Plant Analysis*

Nutrient concentrations in harvested grains and straw were examined and computed separately from estimates from selected plants in each plot. To evaluate dry matter production (i.e., grains and straw), representative samples of plants were dried in a hot air oven at 60 °C after harvest.

Dried samples were pulverised in a Wiley mill and kept in polythene bags for further examination.

#### 2.8.1. Nutrient Uptake (kg ha$^{-1}$)

In order to calculate nutrient uptake, we multiplied the grain yield and straw yield by the percentage of each nutrient they contained.

$$\text{Nutrient uptake (kg ha}^{-1}\text{) = Content (\%) in grains/straw} \times \text{grains/straw yield}$$

$$\text{Total uptake (kg ha}^{-1}\text{) = Uptake from grains + nutrient uptake from straw}$$

#### 2.8.2. Nutrient Harvest Index (NHI)

Nutrient harvest index (NHI) is the ratio of nutrient uptake in economic part of the crop plants to the total nutrient uptake in biological part of the crop plants. NHI of nitrogen, phosphorus and potassium were computed by using the formula given below:

$$\text{NHI} = \frac{\text{Nutrients uptake in grains}\left(\text{kg ha}^{-1}\right)}{\text{Total nutrients uptake}(\text{grains} + \text{straw})\left(\text{kg ha}^{-1}\right)}$$

### *2.9. Economic Nutrients Use Efficiency (ENUE)*

Economic Nutrients Use Efficiency is defined as the amount of INR (₹) invested on production of per kg grain yield. ENUE was calculated by using the formula given below:

$$\text{NHI} = \frac{\text{Grain Yield}\left(\text{kg ha}^{-1}\right)}{\text{₹ Invested on nutrient}}$$

### *2.10. Biological Properties*

The population of bacteria, fungi, and actinomycetes were counted using a serial soil dilution method. In the beginning and at the end, soil samples were taken from the field while receiving the designated treatments, and they were then screened using a 2 mm sieve. To create a representative sample, the samples were properly combined and blended. For the purpose of identifying and isolating live bacteria, fungus, and actinomycetes count, the serial dilution approach was used, which is outlined as follows: Set up the media to support the required microbiota. Fill sterile petri plates with the cooled (45 °C) and autoclaved medium. Permit the medium to set. Then, 9 mL of sterile water blank and 1 g of sieved (2 mm) soil should be shaken for 15 to 20 min. Prepare dilutions $10^{-2}$, $10^{-3}$, $10^{-4}$, $10^{-5}$, $10^{-6}$, $10^{-7}$, and $10^{-8}$ in serial order. Add 1 mL aliquots of various dilutions to the medium in Petri plates after it has cooled and solidified. To ensure that spores are distributed equally, rotate the plates for 3–4 days at 28 °C. Check the plate for colonies growing on the medium's surface. According to [15], the population counts of bacteria, fungi, and actinomycetes were determined using the dilution plate technique, with Martin's rose agar, Bengal agar, and Ken Knight's agar media, respectively.

### *2.11. Soil Fertility Status*

The fertility status of soil was estimated using the Walkley–Black wet oxidation Method [16] for organic carbon, the alkaline potassium permanganate method [17] for the available nitrogen, Olsen's method for the available phosphorus, and the 1 N NH4OAC extraction method [16] for the available potassium in soil after wheat harvesting.

### 2.12. Statistical Analysis

OPSTAT was utilised for the investigation's comprehensive analysis of variance (ANOVA). The statistical significance level used to compare the treatment means was $p$ 0.05.

## 3. Results

### 3.1. Yield Attributing Characters

The number of productive tillers $m^{-2}$ (i.e., tillers with fertile spike) is an important yield attribute, accounting for major variation in grain yield of wheat (Figure 2). Among the tillage crop establishment methods, the greatest number of productive tillers (283.50 $m^{-2}$) was recorded under $T_5$ compared to all other treatments, with the exception of $T_2$ and $T_8$ during experimentation. However, treatments $T_1$ and $T_7$ were recorded as being superior to the remainder of the treatments, and on par with each other. Treatments $T_3$, $T_4$, and $T_6$ were recorded to be on par with each other. Treatment $T_6$ produced the lowest number of productive tillers (252.50 $m^{-2}$) during our investigation. Tillage crop establishment methods exhibited a significant effect on spike length during this study. The spike length of wheat varied from 10.40 to 14.00 cm during experimentation. The maximum spike length (14.00 cm) of the wheat was recorded in $T_5$, which was higher than all other treatments except $T_8$ during study. However, $T_2$ and $T_7$ were superior to the rest of the treatments for this parameter. Treatments $T_1$, $T_3$ and $T_6$ were on par with each other during experimentation, while treatment T6 was found to exhibit the minimum spike length (10.40 cm).

Number of grains per spike$^{-1}$ is an important yield attribute, which directly affects the grain yield. The number of grains per spike$^{-1}$ registered significant variation during this study. Among the tillage crop establishment methods, a significantly greater number of grains (53 grains per spike$^{-1}$) was produced under treatment $T_5$ than under other treatments during experimentation, with the exception of $T_2$ and $T_8$. $T_1$ and $T_7$ were both equally effective, though well beyond the other treatments. The experimental results showed that Treatments $T_3$, $T_4$, and $T_6$ were all similar, with Treatment $T_6$ yielding the fewest grains (42 grains per spike$^{-1}$). An essential aspect of yield, test weight is the weight of 1000 grains divided by the weight of a single grain, so as to determine how effective the grain filling process was.

The difference in test weight of wheat varied significantly in relation to the tillage crop establishment method during both the years of study. The maximum test weight was recorded in treatment $T_5$ than all other treatments except $T_1$, $T_2$ and $T_8$. However, treatments $T_3$, $T_4$, $T_6$ and $T_7$ were on par with each other. Meanwhile, treatment $T_4$ recorded the lowest test weight during investigation.

### 3.2. Yield (q $ha^{-1}$)

The harvest index and yield (grain, straw, and biological, measured in q $ha^{-1}$) are shown for a variety of tillage methods in Figure 2. All treatments (except $T_5$, which produced a yield of 44.32 q $ha^{-1}$) reported significantly lower yields. Compared to the other treatments, both $T_1$ and $T_7$ were shown to be comparably effective. After $T_5$, the next highest grain yield was in Treatment 3 (30.10 q $ha^{-1}$), followed by Treatment 4 (29.01 q $ha^{-1}$), and Treatment 6 (28.29 q $ha^{-1}$). The production of wheat grains differed by 20.99% between $T_1$ and $T_5$, 17.79% between $T_8$ and $T_3$, and 16.21% between $T_3$ and $T_5$.

Wheat straw yield varied from 46.23 to 61.88 q $ha^{-1}$. While $T_2$ and $T_8$ had similar straw yields, $T_5$ had the highest yield (61.88 q $ha^{-1}$). There was a clear preference for $T_1$ and $T_7$ over the other therapies. While treatments $T_4$ and $T_6$ produced the most straw, treatment $T_3$ produced the least. However, $T_3$, $T_4$, and $T_6$ all functioned to about the same extent.

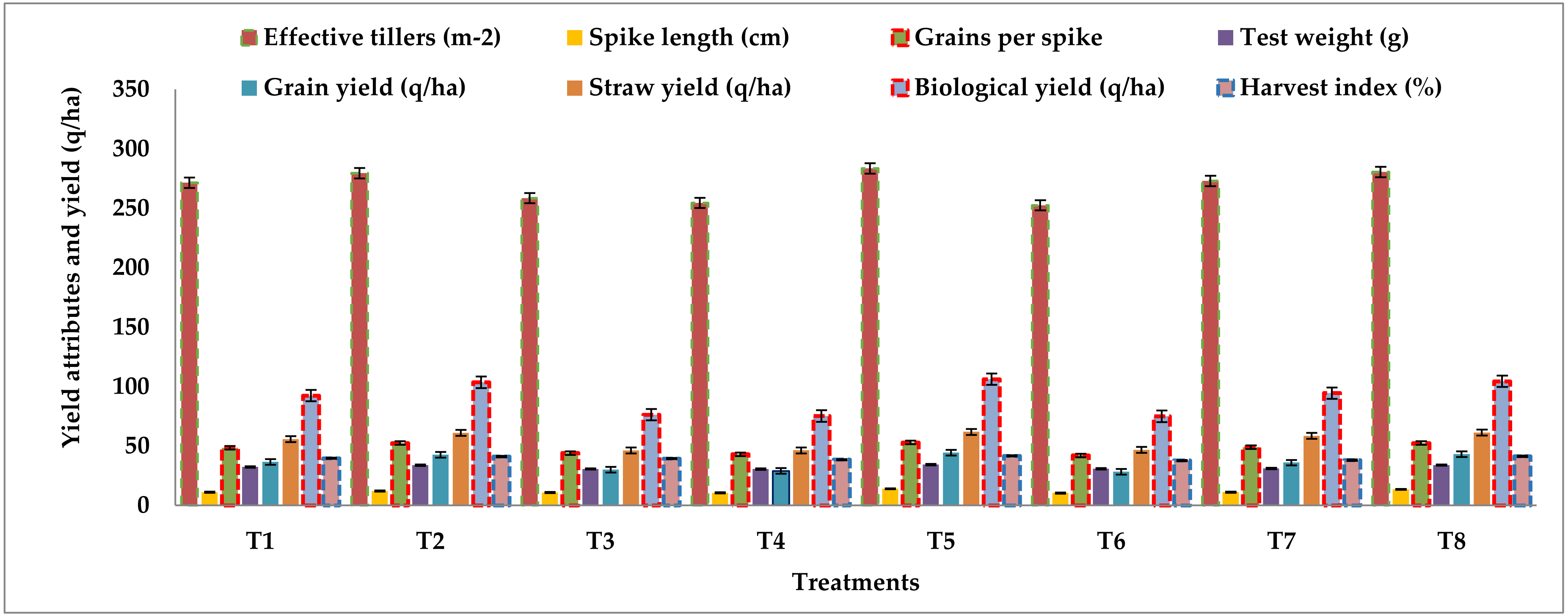


**Figure 2.** Impact of tillage and crop establishment practices on yield attributing characters and yield of wheat (2017–2018 and 2018–2019 pooled) (Bars represent standard error).

Tillage crop establishment with Treatment T5 was shown to be the most effective, followed by $T_8$ and $T_2$. $T_3$, $T_4$, and $T_6$ were all equivalent in every measurable way. The T6 treatment had the lowest observed biological yield, namely, 74.98 q $ha^{-1}$. Increases in grain, straw, and biological yield have all been linked to refinements in tillage methods. Increased growth and dry matter accumulation occurred because FIRB and Zero-till rapidly meet the crop's water needs. Grain output, as indicated with metrics like effective tiller count, grain count per spike, and test weight, grew at a higher pace for plants that grow at a faster rate. The treatment with the greatest harvest index was $T_5$, at 41.73 percent; however, treatments $T_8$ and $T_2$ were quite close behind. The harvest index ranged from 48.22% in Treatment $_7$, to 37.27% in Treatment 6. However, $T_1$, $T_3$, $T_4$, and $T_7$ all functioned similarly.

### *3.3. Water Input Studies*

Soil moisture extraction pattern within layers was analysed, and it was found that the greatest amount of water was extracted (absorbed) from the 30–60 cm layer during the experiment, followed by the 15–30 cm, 0–15 cm, and the 60–90 cm layers (Table 1). Land arrangement under furrow-irrigated raised-beds practises enhanced the moisture extraction from the surface layer (0–15 cm) in both study years. Similarly, a modest drop in moisture extraction was seen with increasing profile depth, with the largest decrease (1.93) happening in the 60–90 cm soil layer under spray irrigation practises, due to a moisture deficit at shallower depths. The data also showed that in both years of analysis, the FIRB and zero-till plots drank more heavily from the deeper profile layer than the typical flood irrigation practise plots did.

**Table 1.** Effect of tillage and crop establishment practices on soil moisture depletion, consumptive use, and water-use efficiency of wheat (2017–2018 and 2018–2019, pooled).

| Treatments | Soil Moisture Depletion | | | | Total Soil Moisture Depletion (cm) | Consumptive Use (cm) | Water-Use Efficiency (q $ha^{-1}$ cm) | Water Productivity (kg $cm^{-3}$) |
|---|---|---|---|---|---|---|---|---|
| | Depth of Soil (cm) | | | | | | | |
| | 0–15 | 15–30 | 30–60 | 60–90 | | | | |
| $T_1$ | 3.66 | 3.36 | 2.83 | 2.39 | 12.23 | 24.83 | 1.47 | 0.94 |
| $T_2$ | 2.27 | 3.18 | 3.57 | 2.78 | 11.79 | 21.10 | 2.02 | 1.46 |
| $T_3$ | 2.25 | 3.75 | 3.21 | 2.40 | 11.60 | 19.00 | 1.58 | 1.01 |
| $T_4$ | 2.23 | 3.48 | 2.68 | 2.30 | 10.68 | 16.88 | 1.72 | 1.14 |
| $T_5$ | 3.04 | 3.86 | 4.42 | 3.46 | 14.77 | 18.25 | 2.43 | 1.72 |
| $T_6$ | 2.13 | 3.31 | 2.37 | 2.22 | 10.02 | 16.05 | 1.76 | 1.23 |
| $T_7$ | 4.30 | 3.34 | 2.61 | 1.93 | 12.17 | 12.55 | 2.86 | 1.91 |
| $T_8$ | 3.25 | 4.11 | 2.57 | 2.93 | 12.86 | 18.95 | 2.28 | 1.40 |
| *Mean* | *2.89* | *3.55* | *3.03* | *2.55* | *12.00* | *18.45* | *2.01* | *1.31* |

Under plots where higher tillage procedures were used, crop water-use rose. Treatment $T_1$ used significantly more water than treatments $T_2$ and $T_5$, while treatment T5 used significantly less water. Treatment $T_7$ showed the highest water use efficiency, followed by $T_5$, $T_8$, and $T_2$. Researchers found that as production grew, water productivity grew as well. In both years, T1 had significantly lower water productivity compared to $T_7$, $T_5$, $T_2$, and T8. In terms of water output, the rankings were as follows: $T_7 > T_5 > T_2 > T_8 > T_6$.

### *3.4. Nutrient Uptake (kg $ha^{-1}$)*

#### 3.4.1. Nitrogen

Wheat's nitrogen level ranged from 1.52% in the grains to 1.74% in the straw, and from 0.59 to 0.59 percentage points. Among the tillage crop establishment treatments, significant maximum nitrogen percentage levels in grains (1.74%) and straw (0.59%) was recorded in treatment $T_5$, which was recorded as being statistically at par with treatment $T_8$ (Figure 3). However, treatment $T_2$ was recorded to be statistically superior, on a par with $T_7$ over rest of the treatments and across all parameters, with the exception of grain yield. However, the minimum nitrogen percentage contents in the grains (1.52%) and straw (0.48%) of the wheat were recorded in treatment $T_6$, followed by $T_4$, $T_3$ and $T_1$. Among the tillage crop establishment treatments, significant maximum nitrogen uptake in grains (76.9 kg ha$^{-1}$) and straw (36.8 kg ha$^{-1}$) of wheat was recorded in treatment $T_5$, followed by $T_8$ and $T_2$ (Figure 4). However, statistically speaking, $T_8$ and $T_2$ were on level with one another. Statistically speaking, $T_7$ and $T_1$ were equally the best treatments overall; however, for straw, $T_3$ was the worst. Furthermore, with treatment T6, nitrogen uptake was measured at 45.2 kg ha$^{-1}$ (grains) and 24.2 kg ha$^{-1}$ (straw), significantly lower than the uptake under treatment T4 (52.4 kg ha$^{-1}$ in grains, and 25.6 kg ha$^{-1}$ in straw). However, uptake of nitrogen into straw under treatments $T_6$ and $T_4$ were recorded as being statistically on par with each other during investigation.

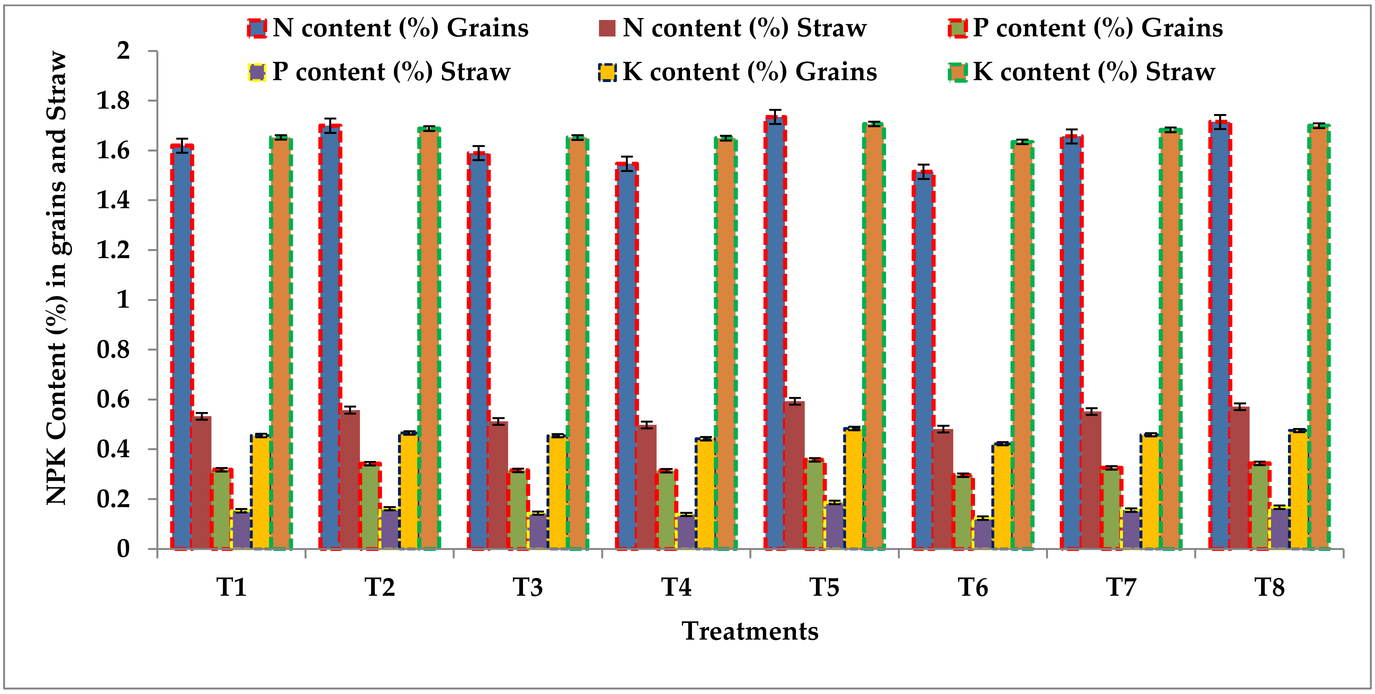


**Figure 3.** Nutrient (N, P, and K) content per cent in grains and straw of wheat affected by tillage crop establishment methods (Pooled data: 2017–2018 and 2018–2019) (Bars represent standard error bars).

The total nitrogen uptake varied from 69.4 to 113.7 kg ha$^{-1}$. Treatments $T_5$, $T_8$ and $T_2$ were recorded as having 27.97, 22.73, and 19.89% more total Nitrogen uptake as compared to treatment $T_1$ (Figure 5). However, treatment T6 was recorded as having the lowest total Nitrogen uptake (69.4 kg ha$^{-1}$), followed by $T_4$, $T_3$ and $T_7$ at values of 78.0, 83.4, and 92.3 kg ha$^{-1}$, respectively. The nitrogen harvest index of wheat was affected by tillage crop establishment practices. The maximum nitrogen harvest index was recorded in treatments $T_2$ and $T_8$, with the value of 0.7, which was recorded as being statistically on par with treatments $T_1$, $T_4$, $T_3$, and $T_6$ (Figure 6). However, the minimum nitrogen harvest index (with the value of 0.6) during the course of our investigation was recorded under treatment $T_7$, followed by $T_6$.

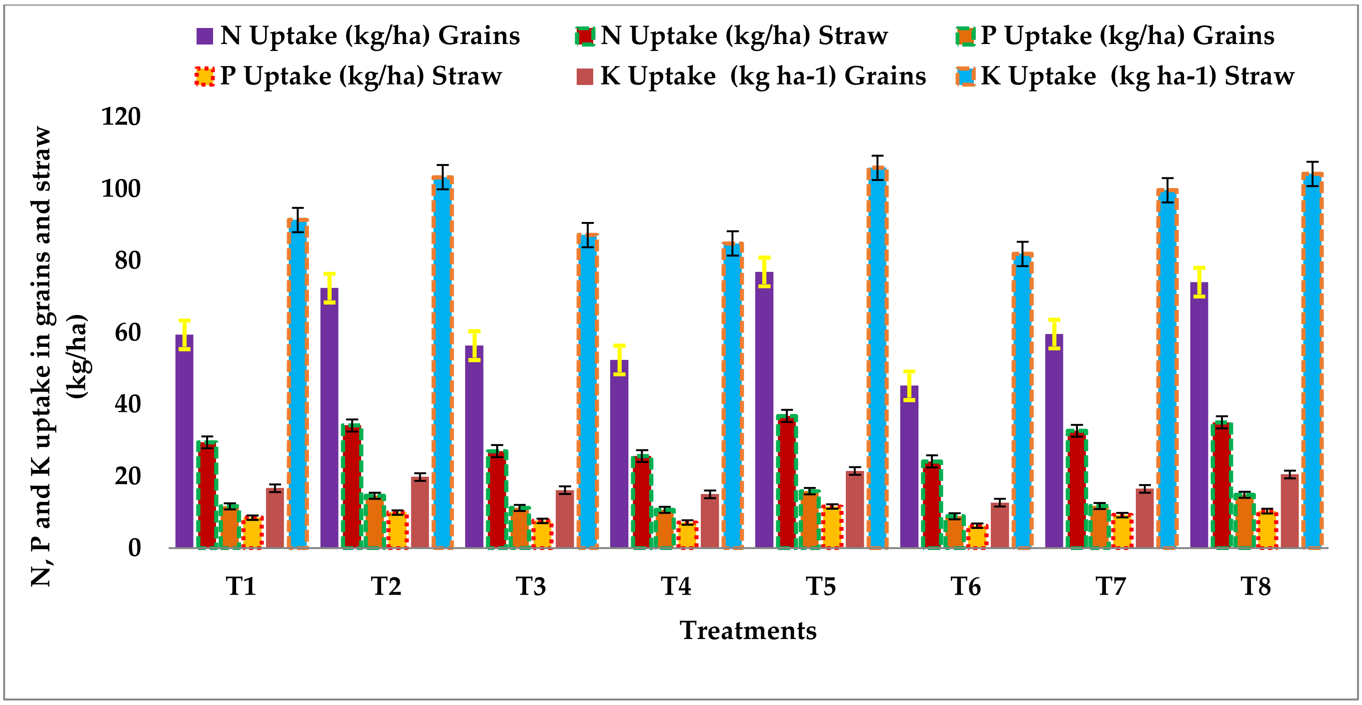


**Figure 4.** Nutrients (N, P, and K) uptake in grains and straw of wheat affected by tillage crop establishment methods (Pooled data: 2017–2018 and 2018–2019 (Bars represent standard error bars).

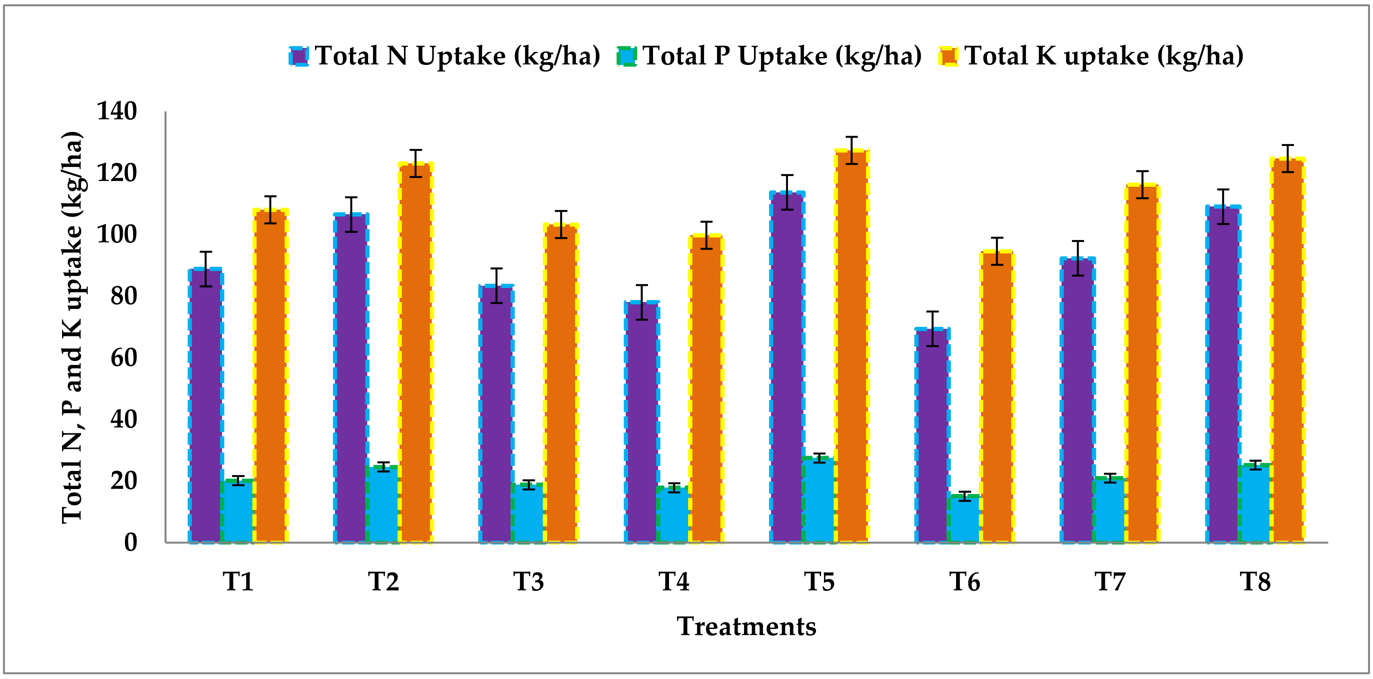


**Figure 5.** Effect of tillage crop establishment methods on total N, P, and K uptake in wheat (Pooled data: 2017–2018 and 2018–2019) (Bars represent standard error bars).

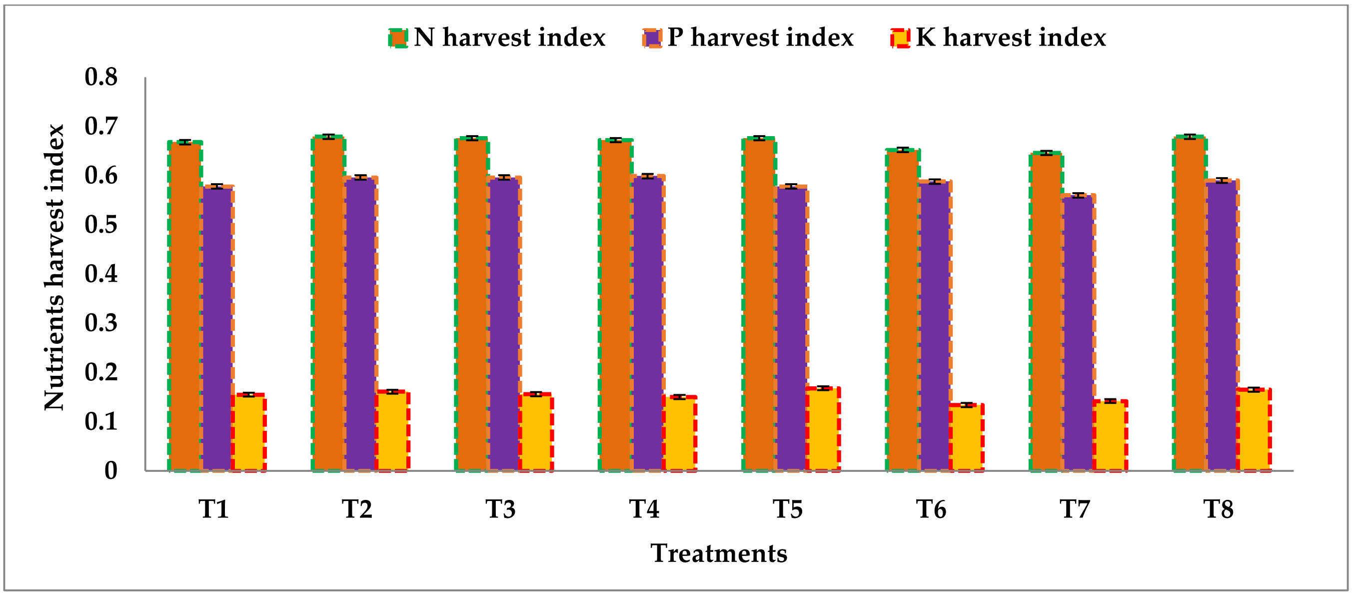


**Figure 6.** Nutrients (N, P, and K) harvest index of wheat influenced by tillage crop establishment methods (2017–2018 and 2018–2019, pooled) (Bars represent standard error bars).

### 3.4.2. Phosphorus

The percentage content, uptake, and harvest index of phosphorous were significantly affected by various treatments. Among the treatments, significant maximum Phosphorus percentage content in grains (0.36%) and straw (0.19%) of wheat were recorded in treatment $T_5$ (Figure 3). However, treatments $T_2$, $T_7$, and $T_8$ were found to be statistically superior over the rest of the treatments in case of wheat straw, being about on par with each other. However, significantly low percentages of phosphorus content in grains (0.30%) and straw (0.12%) were recorded under treatment $T_6$; this was followed by $T_4$, $T_3$, and $T_1$ with the value of 0.32, 0.14, and 0.32 per cent for grains, and 0.14, 0.32, and 0.15 per cent in straw, respectively. The uptake of phosphorus in the grains and straw of the wheat was affected by various treatments (Figure 4). Among the treatments, significant maximum phosphorus uptakes in the grains and straw of wheat were recorded in treatment $T_5$ compared to all other treatments, with value of 15.9 and 11.6 kg ha$^{-1}$. This was followed by $T_8$ and $T_2$, which were recorded as statistically superior over rest of the treatments and on par with each other. Likewise, treatments $T_7$ and $T_1$ were recorded on par with each other, and superior to $T_3$, $T_4$, and $T_6$. However, treatment $T_6$ recorded significantly low phosphorus uptakes, with the values of 8.87 and 6.22 kg ha$^{-1}$ in grains and straw, respectively.

Total phosphorus uptake varied from 15.1 to 27.5 kg ha$^{-1}$. Among the tillage crop establishment practices, significant maximum total phosphorus uptakes were recorded in treatment $T_5$ (27.5 kg ha$^{-1}$) compared to all other treatments, followed by $T_2$ and $T_8$ (Figure 5). However, the treatments $T_2$ (24.6 kg ha$^{-1}$) and $T_8$ (25.2 kg ha$^{-1}$) were recorded statistically superior over the rest of the treatments and on par with each other, followed by $T_1$ and $T_7$ which were also recorded on par with each other. However, treatment $T_6$ was recorded significant minimum total phosphorus uptakes, followed by $T_3$ and $T_4$. The phosphorus harvest index differed significantly due to treatments' effects. The phosphorus harvest index was highest in treatment $T_4$, then $T_2$, then $T_3$, then $T_8$, then $T_6$, then $T_5$, then Treatment$_1$ (Figure 6), and was ultimately lowest in treatment $T_7$.

### 3.4.3. Potassium

Among the treatments, significant maximum percentages of potassium content in the grains and straw of wheat were recorded in treatment $T_5$, with the values of 0.48 and 1.71 per cent; this was recorded as being statistically on par with treatments $T_2$ and $T_8$ (Figure 3). However, treatments $T_7$ and $T_1$ were recorded as being similarly statistically superior, being on par with each other, followed by $T_3$ and $T_4$. Meanwhile, the minimum per cent potassium content in the grains and straw of wheat were recorded in treatment $T_6$. As is evident from the data, potassium uptake in the grains and straw of wheat differed significantly due to treatments' effects (Figure 4). Significant maximum potassium uptakes in both grains (21.4 kg $ha^{-1}$) and straw (105.9 kg $ha^{-1}$) of wheat was recorded in treatment $T_5$ compared to all other treatments except $T_2$ and $T_8$, which were recorded as being statistically on par, with the exception of $T_2$ in the case of grains. However, treatments $T_7$, $T_3$ and $T_1$ were recorded as statistically superior (on par with each other) over rest of the treatments except wheat straw. Meanwhile, the minimum potassium uptake in the grains (12.7 kg $ha^{-1}$) and straw (81.9 kg $ha^{-1}$) were recorded in treatment $T_6$, followed by $T_4$. Among the treatments, significant maximum total potassium uptakes were recorded into treatment $T_5$ (127.3 kg $ha^{-1}$), which was recorded as being statistically on par with treatment $T_8$ (Figure 5). However, the treatment $T_2$ was recorded as statistically superior to the rest of the treatments, followed by $T_7$, $T_1$, and $T_3$. However, significantly low total potassium uptake was recorded into treatment $T_6$ (94.5 kg $ha^{-1}$), followed by $T_4$. Treatments $T_5$ and $T_8$ exhibited an increased total uptake of potassium compared to $T_1$ and $T_6$, with difference of 17.8, 34.7, and 15.4, 31.9 per cent, respectively, during course of investigation. Among the treatments, the maximum potassium harvest index was noted in treatment $T_5$, which was recorded as being statistically on par with treatments $T_2$ and $T_8$, all three being greater than the rest of the treatments (Figure 6). However, the treatments $T_1$, $T_3$, and $T_4$ were also recorded as possessing statistical superiority, being on par with each other over the remainder of the treatments. However, the minimum potassium harvest index of wheat was recorded in treatment $T_6$, followed by $T_7$.

### *3.5. Economic Nutrients Use Efficiency*

The economic nutrient-use efficiency of wheat was significantly affected by tillage crop establishment methods during course of investigation (Figure 7). All the treatments received equal amount of nutrient, which is why the investment (INR/ha) for nutrients across all treatments was the same. An economic nutrient-use efficiency is dependent upon obtaining the ratio of productivity to the amount of INR invested on the nutrients applied. Among the treatments, maximum economic nitrogen-use efficiency (ENUE) was observed in treatment $T_5$ (2.68), which was recorded as being statistically on par with treatments $T_2$ and $T_8$. After this, the treatments $T_1$ and $T_7$ were recorded as the next most statistically superior compared to the remainder of the treatments, being on par with each other. However, minimum ENUE was recorded under treatment $T_6$ (1.71), followed by $T_4$ and $T_3$. A significant maximum Economic Phosphorus Use Efficiency was observed in treatment $T_5$ (1.42) compared to all other treatments, with the exception of $T_2$ and $T_8$, which were recorded as being statistically on par. However, treatments $T_1$ and $T_7$ were recorded as being similarly statistically superior, on par with each other over rest of the treatments. The minimum EPUE was recorded in treatment $T_6$, followed by $T_4$ and $T_3$. Economic Potassium Use Efficiency (EPUE) varied from 1.49 to 2.33. Among the treatments, the maximum EPUE was recorded in treatment $T_5$ (2.33) over all other treatments, with the exception of $T_2$ and T8, which were recorded as being statistically on par with it. After those, the treatments $T_1$ and $T_7$ were recorded as the next most statistically superior, *on par* with each other over rest of the other treatments. Meanwhile, the minimum EPUE was recorded in treatment $T_6$, followed by $T_4$ and $T_3$.

### *3.6. Biological Properties of Soil*

Biological properties of soil were significantly influenced by tillage crop establishment methods during experimentation (Table 2). Among the treatments, the highest bacterial population was recorded under $T_8$ compared to other treatments. However, treatments $T_2$ and $T_5$ were recorded as superior to the remaining the treatments. Treatments $T_3$, $T_4$, $T_6$, and $T_1$ were recorded as being on par with each other, but treatment $T_7$ had the lowest recorded bacterial population during both years of study. Tillage crop establishment methods resulted in significant differences in the population of fungi after wheat harvesting. Treatment $T_8$ recorded the highest fungi population, followed by $T_5$. However, treatments $T_2$, $T_3$, and $T_4$ were recorded as similarly superior, being about on par with each other over rest of the treatments. The lowest fungi population was recorded in treatment $T_7$, followed by $T_6$ and $T_1$. The highest population of actinomycetes following the wheat harvest was noted in treatment $T_8$ compared to other treatments. However, treatments $T_2$ and $T_5$ were recorded as superior over remaining the treatments. Treatments $T_{1,}$ $T_4$, and $T_3$ were recorded as being on par with each other. The lowest population of actinomycetes was recorded during $T_7$, followed by $T_6$. Tillage crop establishment methods recorded significant differences in microbial carbon during the investigation. Treatment $T_8$ recorded the highest microbial biomass carbon (160.21 µg $g^{-1}$) compared to other treatments. However, treatments $T_2$ and $T_5$ were recorded as being similarly superior, being on par with each other. Treatments $T_3$ and $T_4$ were likewise recorded as being on par with each other. The lowest microbial-C during experimentation was recorded in treatment $T_7$, followed by $T_6$ and $T_1$. The microbial biomass nitrogen was significantly affected by tillage crop establishment methods. Maximum microbial nitrogen (23.40 µg $g^{-1}$) was recorded in $T_8$ compared to other treatments, followed by $T_5$ and $T_2$. In addition, treatments $T_3$ and $T_4$ were recorded as being on par with each other. The lowest microbial-N during experimentation was recorded in treatment $T_7$, followed by $T_6$ and $T_1$.

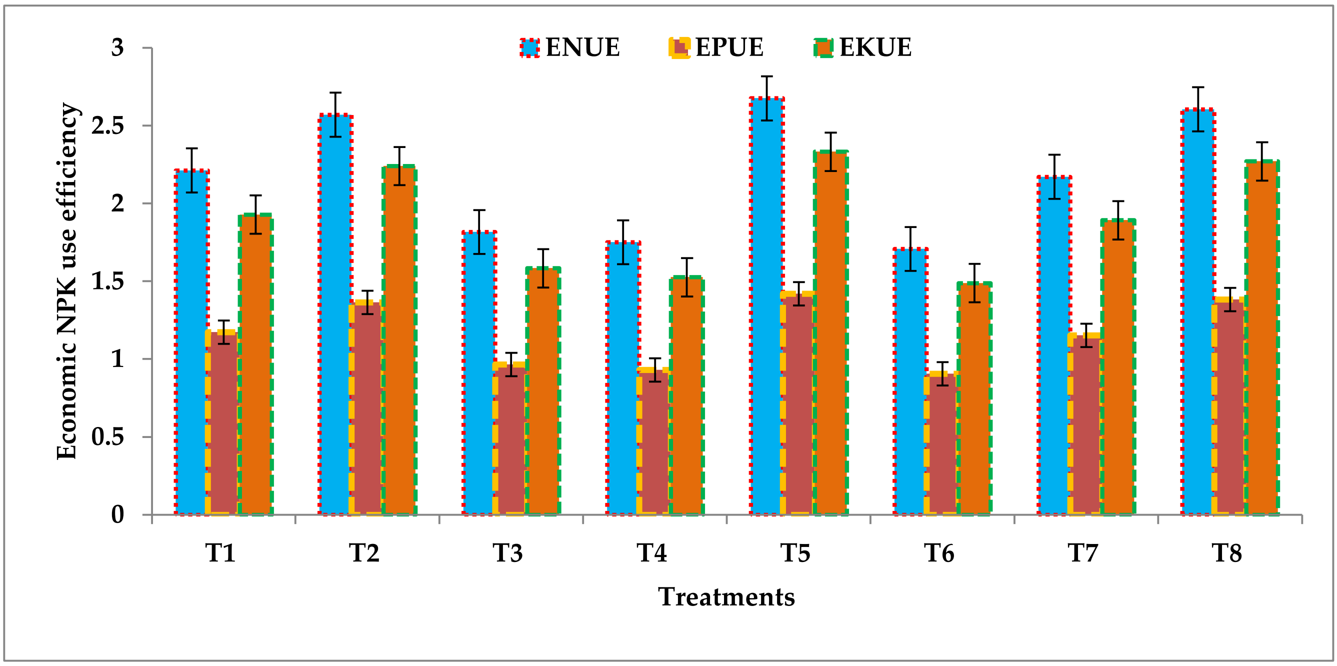


**Figure 7.** Economic Nitrogen, Phosphorus and Potassium Use Efficiency of wheat, as influenced by tillage crop establishment methods (pooled data: 2017–18 and 2018–19) (Bars represent standard error bars). ENUE: Economic Nitrogen Use Efficiency; EPUE: Economic Phosphorus Use Efficiency; and EKUE: Economic Potassium Use Efficiency. Nitrogen through Urea: 276 kg $ha^{-1}$ at INR 6 $kg^{-1}$, Phosphorus through DAP: 130 kg $ha^{-1}$ at INR 24 $kg^{-1}$ and Potassium through MOP: 100 kg $ha^{-1}$ at INR 19 $kg^{-1}$.

### *3.7. Fertility Status of Soil*

Data showed that the status of soil organic carbon percentage differed only insignificantly (Table 3). Treatment $T_8$ registered the highest organic carbon percentage compared to all other treatments. However, treatment $T_4$ recorded the lowest organic carbon content percentage during experimentation, followed by $T_6$, $T_7$, $T_3$, $T_2$, $T_5$, and $T_1$. The tillage crop establishment method registered a significant difference in the fertility status of soil during the investigation (Table 3). Among the treatments, the maximum available nitrogen (228.95 kg $ha^{-1}$) was recorded in $T_6$, compared to all other treatments. However, treatments $T_3$ and $T_4$ were recorded as superior to the remainder of the treatments. Treatments $T_1$, $T_2$, and $T_7$ were on par with each other over the rest of the treatments. Treatment $T_5$ recorded the minimum available nitrogen during the investigation, followed by $T_8$. The maximum available phosphorus (15.70 kg $ha^{-1}$) was recorded under $T_6$ compared to other treatments (except $T_4$). However, treatments $T_1$ and $T_3$ were similarly superior, being on par with each other. Treatments $T_2$, $T_5$, $T_7$, and $T_8$ were on par with each other, while treatment $T_5$ recorded the minimum available phosphorus. Treatment $T_6$ (skip furrow irrigated) recorded the maximum (209.62 kg $ha^{-1}$) available potassium compared to other treatments. However, treatment $T_5$ recorded the minimum available potassium than rest of the treatments during experimentation, followed by $T_8$, $T_2$, $T_7$, $T_3$, $T_4$, and $T_1$.

**Table 2.** Biological properties of soil as influenced by tillage crop establishment methods (2017–2018 and 2018–2019, pooled).

| Treatments | Biological Properties of Soil | | | | |
|---|---|---|---|---|---|
| | Bacteria ($10^5$ CFU $g^{-1}$) | Fungi ($10^4$ CFU $g^{-1}$) | Actinomycetes ($10^6$ CFU $g^{-1}$) | Microbial-C (μg/$g^{-1}$ Soil) | Microbial-N (μg/$g^{-1}$ Soil) |
| $T_1$ | 0.73 | 0.56 | 0.53 | 151.63 | 18.71 |
| $T_2$ | 0.77 | 0.62 | 0.57 | 156.03 | 20.88 |
| $T_3$ | 0.76 | 0.60 | 0.56 | 155.60 | 20.28 |
| $T_4$ | 0.75 | 0.57 | 0.54 | 154.57 | 19.62 |
| $T_5$ | 0.80 | 0.65 | 0.59 | 157.31 | 21.91 |
| $T_6$ | 0.72 | 0.52 | 0.50 | 147.80 | 17.38 |
| $T_7$ | 0.69 | 0.50 | 0.48 | 144.94 | 16.14 |
| $T_8$ | 0.84 | 0.66 | 0.62 | 160.21 | 23.40 |
| SEm± | 0.01 | 0.01 | 0.01 | 0.62 | 0.34 |
| CD ($p = 0.05$) | 0.02 | 0.02 | 0.02 | 1.80 | 0.98 |

**Table 3.** Effect of tillage crop establishment methods on fertility status of soil (2017–2018 and 2018–2019, pooled).

| Treatments | Organic Carbon (%) | Available Nutrients (kg $ha^{-1}$) | | |
|---|---|---|---|---|
| | | Nitrogen | Phosphorus | Potassium |
| $T_1$ | 0.49 | 215.17 | 12.94 | 206.37 |
| $T_2$ | 0.48 | 213.64 | 12.30 | 204.30 |
| $T_3$ | 0.49 | 219.10 | 14.15 | 205.72 |
| $T_4$ | 0.47 | 221.35 | 14.45 | 206.07 |
| $T_5$ | 0.49 | 204.52 | 10.99 | 200.84 |
| $T_6$ | 0.48 | 228.95 | 15.70 | 209.62 |
| $T_7$ | 0.49 | 213.68 | 12.64 | 205.03 |
| $T_8$ | 0.50 | 210.64 | 11.82 | 203.48 |
| SEm± | 0.001 | 1.33 | 0.44 | 0.94 |
| CD ($p = 0.05$) | NS | 3.88 | 1.27 | 2.74 |

## 4. Discussion

The rice plant height, number of tillers, dry matter accumulation, CGR, RGR, AGR, LAI, and NAR were recorded as being most significantly high in the wide-bed furrow-irrigated ($T_5$) treatment, being on par with both zero-till flat irrigated using gated pipes ($T_8$) and furrow irrigated with gated-pipe raised bed ($T_2$). It has been hypothesised that increased rates of dry matter production, translocation, and photosynthesis conversion were responsible. Better light penetration from bed seeding wheat resulted in stronger plants and more efficient photosynthesis, both of which boosted yields [18,19]. There were more spikes produced per square metre when there were more tillers present. Larger spikes and heavier grains resulted from a bigger proportion of biomass being assigned to spikes, which in turn resulted from a greater leaf area index, allowing the crop to absorb more solar energy for dry matter formation via photosynthesis. These results are discussed further in [20–25].

Of the studied yield attributes, productive tillers, grains spike$^{-1}$, spike length, and test weight were significantly increased in $T_5$, which was statistically on par with $T_8$ and $T_2$. The grains, straw, and biological yield, as well as the harvest index, were significantly higher under treatment $T_5$. The slow supply of moisture for longer times in order to enhance root and shoot growth of the crop is directly reflected in the source-to-sink transformation and boosting the metabolic activity of the crop plants. The yield per hectare rose as a result of the favourable effect of the increase in available moisture on per-plant productivity. Grain yield per plant increased as a result of an increase in moisture supply in three ways: the number of effective tillers, the number of grains per spike, and the test weight. Treatment $T_5$ (the wide-bed furrow-irrigated treatment) was recorded as producing 20.96, 10.99 and 14.94 per cent higher grain, straw, and biological yields, respectively, over $T_1$ (conventional flood irrigation). The same trend has been confirmed by several other investigations [26–30].

The significant impact that water had on the vegetative growth of the crop plant suggested that straw crop output may have increased as a result. Improved water distribution led to more vegetative growth, which in turn increased straw production. Straw production has reportedly followed a similar trend in other studies [22,31,32].

Due to the lack of surface moisture, conventional irrigation may be the leading cause of water loss. Many writers [33–35] have reported the same results.

The presence of soil moisture in the root zone of the crop increased root growth, which in turn enhanced nutrient uptake and boosted crop growth. Wide-bed furrow-irrigated treatment had the maximum recorded NPK content percentage and uptake in both grain and straw, as well as having the highest nutrient harvest index. Total NPK uptake was increased by approximately 27.97, 35.35, and 17.82 percent, respectively, in $T_5$ wide-bed furrow-irrigated wheat compared to $T_1$ conventional flood irrigation, which also boosted grain and biomass yield. The results are corroborated by the published research [35–40].

An increased porosity, increased availability of nutrients (especially P), and greater water availability in the soil profile available to be used by plants may have improved the soil's microbiological properties. These results are also affirmed in [41,42].

The maximum population of bacteria, fungi, and actinomycetes, microbial-C, and microbial-N were recorded in treatment $T_8$ (zero-till flat, irrigated using gated pipe/controlled-flood irrigation treatment) followed by $T_5$ (wide-bed furrow-irrigated treatment) and $T_2$ (furrow-irrigated with gated-pipe raised-bed treatment). The retention of previous crop residue in wheat under the rice–wheat cropping system on the surface of the soil (i.e., Conservation Agriculture, or Zero-till farming) maximised organic carbon level and microbial population, and minimised soil moisture loss, which helped the multiplication of microbes in the soil. Microbial development and, by extension, microbial circulation, are both influenced by the availability of organic matter in the soil [43]. Because of the decreased soil disturbance, the soil microbial biomass and activity were increased with full CA-based management using conservation-agriculture practices. Conservation agriculture may lead to higher microbial biomass nitrogen levels than conventional farming [44] due to the increased associated C inputs, residue retention, and decreased tillage.

The leached-down N, P, and K during treatment $T_5$ was the outcome of increased growth, yield, nutrient uptake, and soil moisture availability over a longer period of time. The findings of [35,37,38] were consistent with this.

## 5. Conclusions

This study recommends sowing wheat in a wide-bed furrow-irrigated system, or a zero-till flat-irrigated using gated-pipe/controlled-flood irrigation system for the best outcomes when growing rice and wheat together under irrigated conditions. Wide-bed furrow irrigation increased the total nutrient NPK uptake in wheat, while sprinkler irrigation maximised water-use efficiency, water productivity, and consumption. The zero-till and gated-pipe/controlled-flood irrigation treatment also had larger bacterial, fungal, and actinomycete populations, as well as higher microbial-C and microbial-N levels than traditional flood irrigation. Our research suggests that farmers should use conservation tillage-based establishing tactics and irrigation strategies to increase crop productivity, water- and nutrient-use efficiency, nutrient uptake, and soil fertility in wheat-growing regions, in order to maintain crop water productivity and soil health under different agroecological conditions.

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