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Plant Growth-Promoting Bacteria and Crop Residue in Rice–Wheat System Cultivated with Favorable Tillage Influence Crop Productivity, Nutrient Uptake, Soil Quality, and Profitability in the Terai Agro-Ecological Zone of West Bengal, India

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Abstract: A field study was conducted from 2021 to 2023 in a rice–wheat cropping system in the Terai agro-ecological zone of West Bengal, India, using different management practices, i.e., tillage (conventional tillage, CT, and zero tillage, ZT), crop residue (R), and plant growth-promoting bacteria (B). This study was a part of long-term research on resource conservation technology (conservation agriculture, CA), undertaken on a research farm in Uttar Banga Krishi Viswavidyalaya, Pundibari (Cooch Behar), West Bengal. The project was established in 2006 in acidic alluvial soil. The aim of this study was to evaluate rice–wheat productivity, nutrient uptake, soil quality, and profitability after the 16th and 17th crop cycles under the above-mentioned management practices. The results revealed that the pooled yield of rice grain and straw was significantly higher under the CT + R + B treatment than under the other treatments (ZT, ZT + B, ZT + R, ZT + R + B, CT, CT + B, and CT + R). However, the wheat grain and straw yields were significantly greater under the ZT + R + B treatment than under other treatments. The system's grain yield and straw yield were significantly higher under the CT + R + B treatment, on par with ZT + R + B, compared to the other treatments. Nutrient uptake (nitrogen, N; phosphorus, P; and potassium, K) was increased by retaining R and inoculating B compared to the sample without R and without B. Soil properties, including organic carbon, available N, available P, and available K, were improved in all the treatments compared to the initial values, but the impact was greater in the treatments with R and B than in those without R and without B. In the 5–10-cm soil layer, the above-mentioned soil properties were also improved over the initial (2006) values by 37, 126, 65 and 60%, respectively, by applying the best treatment (ZT + R + B). In economic terms, the benefit–cost ratio was significantly higher under the CT + R + B treatment for rice crops (2.99) and ZT + R + B for wheat crops (3.37). Therefore, we can conclude that, after 17 years of cultivation, for rice, CT-based treatments performs better than ZT-based treatments; meanwhile, for wheat cultivation, ZT-based treatments produces greater yields than CT-based treatments in the Terai agro-ecological zone of West Bengal, India.

Keywords: tillage; crop residue burning; plant growth-promoting bacteria; acidic alluvial soil; rice–wheat cropping system

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1. Introduction

Rice–wheat systems are a major farming system in South Asian countries; they make intensive use of traditional/conventional tillage (CT) practices [1]. CT is the practice of tilling with a moldboard plow/disc plow to disturb the soil surface and subsurface layers [2]. Continuous traditional practice and the excessive usage of chemical fertilizers in rice–wheat systems have significantly affected productivity, as well as soil quality, in terms of physical, chemical, and biological soil parameters [3]. Researchers in different regions of these countries have reported either stagnation or decline in terms of crop productivity, as well as the degradation of soil fertility [4]. Additionally, climate change has widely affected the farming activities of this cropping system in these regions [5]. Resource conservation technology (conservation agriculture, CA) has been found to be more climate-change-adaptive and to increase the productivity of soil and crops in these regions [6]. Therefore, the adoption of CA maybe best suited to the long-term sustainability of rice–wheat systems for south Asian countries [7].

To promote sustainable food security with higher calorie and protein consumption while increasing the profitability of intensive rice-based rotational systems, partial and full CA-based tillage practices should be used in conjunction with suitable crop diversity [8]. Full adoption entails using all three CA principles: minimum tillage (MT), residue (R) retention, and crop rotation (or intercropping). Partial adoption entails using MT alone or with rotation, intercropping, or R retention [9]. The introduction of legumes into rice–wheat systems can diversify rice–wheat cropping systems and change partial CA to full CA [10]. The use of ZT/MT/reduced tillage under partial or full CA maybe an alternative to CT practices [8–11]. ZT can restore soil and crop productivity and, due to the lower total cost of cultivation, it can lead to higher income per INR invested compared to CT [12]. However, this practice is not possible in several regions in south Asian countries, including the Terai agro-ecological zone, West Bengal (India), due to heavy rainfall (>3000 mm) and the limited window for introducing another crop (i.e., legumes) in rice–wheat systems. Therefore, improving the productivity of cropping systems in the Terai agro-ecological zone is a challenging issue and requires the adoption of suitable management practices in conjunction with proper knowledge among farmers.

Plant growth-promoting bacteria/biofertilizers (B) are the nexus between soil fertility and crop production under climatic and soil stresses. According to Itelima et al. [13], B are microbial inoculants that contain the culture of dormant or living cells of effective N-fixing (*Azospirillum* sp. and *Azotobacter* sp.), P-solubilizing/mobilizing (*pseudomonas* sp.), and K-solubilizing bacteria (*Acidothiobacillus* sp.). Cellular microorganisms are frequently added to seeds, soils, or compost to increase the availability of nutrients so that plants may more easily access them and to speed up the microbial activities of these organisms through their multiplication [14]. The biological activity of microbial inoculants aids in mobilizing the availability of nutrients and recovering nutrients, hence enhancing soil quality in general [15–17]. However, few studies have sought to determine the implications of their use on crop productivity and soil sustainability [18]. Another source of nutrients, plant/crop residue (R), constitutes the parts of the plant that are still in the field after harvest/maturity. Each year, 75% of the R produced worldwide—which ranges from 3.5 to 4×10^9 Megagram (Mg)—comes from cereals [19]. Long-term experimentation in different parts of the world has shown the significant impact of R on crop productivity and soil quality [20–22]. Crop residue and B are alternative sources of nutrients, but limited knowledge of their effects have been reported in different studies [23,24]. Therefore, creating awareness regarding the significance of R and B is possible only through conducting practical experiments in long-term studies. In the Terai agro-ecological zone, R is either used to feed animals (rice straw) or is burned in the field (rice and wheat straws).

A field experiment was established in 2006 to evaluate the impact of tillage, R, and B management practices in a rice–wheat system. We hypothesized in this study that these would improve crop productivity, nutrient uptake, soil quality, and profitability in the Terai agro-ecological zone of West Bengal, India. The broad objective of this study was to evaluate the rice–wheat productivity, nutrient uptake, soil quality, and profitability after the 16th and 17th crop cycles under different management practices, i.e., tillage (ZT and CT), R (with or without) and B (with or without) in acidic alluvial soil.

2. Materials and Method

2.1. Field Location and Treatment Details

To fulfill the objectives of this study, a field experiment was conducted at a research farm in Uttar Banga Krishi Viswavidayalaya, Pundibari, West Bengal, (26°19′ N, 89°23′ E; 43 m above mean sea level) in the lower Indo-Gangetic Plains (IGPs) in eastern India. This study is part of a long-term experiment established in 2006 in the Terai agro-ecological zone. The initial soil of the experimental field was sandy loam textured with acidic pH and low organic carbon, nitrogen (N), phosphorus (P) and potassium (K) contents. The rice–wheat cropping system was applied continuously from 2006 to 2023 (17 years) under two tillage practices (ZT and CT), with or without crop residue addition (R) and with or without plant growth-promoting bacteria (B). All eight treatment combinations (ZT, ZT + B, ZT + R, ZT + R + B, CT, CT + B, CT + R and CT + R + B) were replicated thrice and arranged in a randomized block design (Table 1).

Table 1. Treatment details, plot areas, chemical fertilizers, crop residues, biofertilizers, and cropping systems of the long-term experiment.

Treatment Details	Plot Area (m^2)	Chemical Fertilizer Application (kg ha^{-1})			Crop Residue (t ha^{-1})		Biofertilizers (g Inoculation kg^{-1} Seed)	
		N (R–W)	P (R–W)	K (R–W)	Rice Residue	Wheat Residue	*Azospirillum* and Phosphate Solubilizer	*Azotobacter* and Phosphate Solubilizer
ZT	263	100:120	60:60	80:60	0.0	0.0	0.0	0.0
ZT + B	216	100:120	60:60	80:60	0.0	0.0	5.0	5.0
ZT + R	268	100:120	60:60	80:60	3.0	3.0	0.0	0.0
ZT + B + R	222	100:120	60:60	80:60	3.0	3.0	5.0	5.0
CT	485	100:120	60:60	80:60	0.0	0.0	0.0	0.0
CT + B	189	100:120	60:60	80:60	0.0	0.0	5.0	5.0
CT + R	206	100:120	60:60	80:60	3.0	3.0	0.0	0.0
CT + B + R	214	100:120	60:60	80:60	3.0	3.0	5.0	5.0

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria, N—Nitrogen, P—Phosphorus, K—Potassium, R–W—Rice–wheat cropping system.

2.2. Weather

The region, commonly called the Terai agro-ecological region, is located in a subtropical perhumid climate with moderate summers, cold winters, and monsoonal rainfall. The area has a mean annual rainfall of >3000 mm, of which about 80% is received during the months from June to October. According to estimates based on long-term data, the average annual minimum and maximum temperatures were 19 °C and 30 °C, respectively. Weather data averages for 13 years (2009–2022) in the Terai agro-ecological zone are shown in Table 2. The highest mean temperature, rainfall, and evaporation were in August, July, and March, respectively, while the lowest mean temperature, rainfall, and evaporation were in January, December, and January, respectively.

Table 2. Weather data averages for 13 years (2009–2022) in the Terai agro-ecological situations.

Months	Mean Temperature (°C)	Rainfall (mm)	Evaporation (mm)
January	16.7	7.7	37.9
February	19.3	21.6	71.8
March	23.2	46.3	102.8
April	25.7	159.5	89.2
May	26.9	345.3	96.5
June	28.1	738.8	84.5
July	28.3	773.2	94.2
August	28.8	624.1	74.3
September	27.9	566.8	80.9
October	26.1	175.7	72.0
November	22.4	52.3	62.9
December	18.6	3.2	43.1

2.3. Crop Management

During the 2021–2023 period, rice crop var. MTU 7029 was grown in the Kharif season (June) and wheat crop var. HD 2967 in Rabi season (November). The recommended doses of fertilizer were 100-60-80 and 120-60-60 NPK kg ha^{-1} for rice and wheat crops, respectively. The fertilizer used in the rice crop was 10:26:26 (complex fertilizer) with basal application for NPK at the time of sowing and top dressings with urea at the active tillering and panicle initiation stages. Plots with plant growth-promoting bacteria (B) in rice fields were seed treated using a consortium of microaerophilic N fixer *Azospirillum* sp. (UBAS 1) and fluorescent *pseudomonas* as a phosphate solubilizer (UBPS 9). *Azospirillum* was mass multiplied in the medium using bromothymol blue indicator in N-free broth with malic acid to a population of 10^9, determined using the Most Probable Number (MPN) technique [25]. Phosphate solubilizer was grown in Pikovskaya's Medium using tri-calcium phosphate as an insoluble source of phosphate, and 10^8 populations were established and enumerated using the MPN method. The sources of fertilizer used in wheat crops were urea, single super phosphate, and muriate of potash applied basally for NPK at the time of sowing and top dressings with urea at 21 and 42 days after sowing. Plots with B in wheat fields were seed-treated using fluorescent *pseudomonas* as a phosphate solubilizer (UBPS 9), and *Azotobacter* (UBAZ 1) was mass multiplied to the tune of 10^8 in the Mannitol broth. The broth cultures were then mixed with sterilized talc at 250 mL kg^{-1} talc and used for seed treatment (at 5 g kg^{-1} seed) before the preparation of mat seedlings, which were required for the mechanical transplanting of paddy seedlings, as well as before drilling the seeds in cases of wheat using seed drills. Gum Arabic solution was used as an adhesive to apply bio-inoculants through seed coating. Crop residue (oven-dried) was applied in the treatments at a rate of 3 t ha^{-1}; at harvest, the moisture content of the straw was 10% under both tillage practices in both crops. The residue for ZT was placed on the surface, while for CT; it was incorporated into the plough layer. The tillage system used for CT was puddled transplanted rice (PTR)-CT wheat, and that used for ZT was unpuddled transplanted rice (UPTR)-ZT wheat. In CT-PTR, two to three dry tillage operations were followed by a cross operation of wet-tillage before rice transplanting; for CT wheat, fields were prepared with 2–3 tillage operations, followed by laddering. Seedlings of rice were transplanted at 22-cm row spacing in the UPTR using a mechanical transplanter. The transplanter was also used in the PTR, resulting in 28–30 hill m^{-2}. Wheat was sown with 20-cm row spacing in the ZT (seed drill machine) with continuous seeding (180–200 plant m^{-2}), and line sowing was done manually in the CT. Irrigation was applied in the fields at the critical stages of crop growth for both crops. Weeds were removed both manually and using herbicides (pendimethalin and 2, 4-D) to ensure proper crop growth and favorable conditions.

2.4. Soil and Crop Data Collection and Analysis

Crops were monitored throughout the cropping season and harvested at maturity to record yield and yield attributes. The rice crop was harvested in October to assess the yield of rice grain and straw, and the wheat crop was harvested in April to assess the yield of wheat grain and straw. The crop cuts of both crops were done in an area 5 m × 5 m in size (i.e., 25 m^2), and their moisture content was recorded with a moisture meter. The samples of grain and straw were oven-dried and assessed for actual yields; they presented yields with 14 and 12% moisture content for grains of rice and wheat, respectively, and 10% moisture content for straw. To estimate the nutrient content (N, P, and K) in the plant samples (aboveground mass), the samples were oven-dried, processed, and analyzed using standard protocols as proposed by Horneck and Miller [26], i.e., the modified Kjeldahl method for total N content, the Jackson method [27] for wet digestion, the vanado-molybdate yellow color method for total P content, and the wet digestion method proposed by Blake et al. [28] using a flame photometer to assess the total K content. The nutrient uptake was determined based on the ratio of the product of yield of the plant (grain/straw) to the nutrient content of the plant (grain/straw). Soil samples were also collected from different soil layers (5–10 cm and 20–40 cm) after harvesting each crop (rice/wheat). The soil samples were air-dried, processed, and analyzed for different parameters (pH, soil organic carbon (SOC), and soil available N, P, and K). Soil pH, SOC, N, P, and K were determined using a soil water solution at a ratio of 1:2.5 [27] via the wet digestion method [29], the potassium permanganate method [30], the molybdenum blue method [31], and the ammonium acetate method [32], respectively.

2.5. Economics

$$Benefit - cost\ ratio(B:C) = \frac{\text{Gross returns}\left(\text{USD ha}^{-1}\right)}{\text{Total cost of production}\left(\text{USD ha}^{-1}\right)} \quad (1)$$

where gross return is the difference between gross income based on yield (USD ha^{-1}) and the total cost of production (USD ha^{-1}). The total cost of production includes total fuel cost (USD ha^{-1}), total cost of labor (USD ha^{-1}), total cost of ploughing (USD ha^{-1}), total cost of irrigation (USD ha^{-1}), and total cost of fertilizer and micronutrients (USD ha^{-1}).

2.6. Statistical Analysis

Data were compiled for all parameters (yield, plant, and soil) on an Excel sheet considering treatments, cropping seasons, replications, and years and arranged for analysis using Analysis of Variance (ANOVA) for a simple randomized block design for two years and cropping seasons (separately). Additionally, pooled data analysis was done for both years and cropping seasons. The OPSTAT website (opstat.pythonanywhere.com, accessed on 18 August 2023) [33] was used for treatment analysis, and comparative mean data are presented using Tukey's HSD test for both years and cropping seasons. Tables/graphs are used to show the mean data and significance level at $p < 0.05$.

3. Results

3.1. Effect of Tillage, Crop Residue, and Plant Growth-Promoting Bacteria on Grain Yield in a Rice–Wheat System

Data related to the grain yield in rice–wheat cropping system for two years are shown in Table 3. This table shows that different management practices (tillage, R, and B) influence grain yield in the Terai agro-ecological zone of West Bengal, India. The yield of rice in 2021 was significantly higher under CT + R + B treatment compared to ZT and CT practices and was at par with CT + R and ZT + R treatments. The increases in yield for the above treatments were 26, 27, and 25% over ZT and 17, 18, and 17%, over CT, respectively. The yield of rice in 2022 was significantly highest under CT + R + B compared to ZT and CT. The increase in yield for the above treatment was 59 and 18% greater than those of ZT and CT, respectively. Pooled data revealed that rice yield was significantly highest under CT + R + B treatment compared to ZT and CT. The increase in yield for the best treatment, CT + R + B, was 42 and 20% greater than those of ZT and CT, respectively. Crop residue applied with B along with tillage improved the yield of rice more than the treatments with R and B alone or with tillage practices.

The yield of wheat grain in 2021–2022 was significantly higher under ZT + R + B treatment compared to ZT and CT alone and was at par with ZT + R, ZT + B and CT + R + B treatments. The increase in yield for the above treatments was 13, 4, 8, and 4% greater than ZT and 15, 10, 6, and 5% greater than CT, respectively. The yield of wheat in 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT. The increase in yield for the above treatment was 39 and 18% compared to ZT and CT, respectively. Pooled data revealed that wheat yield was significantly higher under ZT + R + B compared to ZT and CT. The increase in yield for the best treatment, ZT + R + B, was 25 and 16% compared to ZT and CT, respectively.

The yield of our rice–wheat system in 2021–2022 was significantly higher under ZT + R + B compared to ZT and CT and was at par with ZT + R, CT + R and CT + R + B. The increase in yield for the above treatments was 13, 15, 15, and 15% compared to ZT and 10, 12, 12, and 12% compared to CT, respectively. The yield of rice–wheat system in 2022–2023 was significantly higher under CT + R + B compared to ZT and CT. The increase in yield for the above treatment was 37 and 10% compared to ZT and CT. Pooled data revealed that the rice–wheat system's grain yield was significantly higher under CT + R + B compared to ZT and CT and was at par with ZT + R + B. The increase in yield for the best treatment, CT + R + B, was 25 and 11% compared to ZT and CT, respectively, and for ZT + R + B was 22 and 8% compared to ZT and CT, respectively.

Table 3. Effect of tillage, crop residue, and plant growth-promoting bacteria on grain yield in a rice–wheat system in the Terai agro-ecological zone of West Bengal, India.

Treatment	Rice Grain Yield (t ha^{-1})			Wheat Grain Yield (t ha^{-1})			System Grain Yield (t ha^{-1})		
	2021	2022	Mean	2021–2022	2022–2023	Mean	2021–2022	2022–2023	Mean
ZT	3.98 a	3.87 a	3.93 A	3.90 a	3.34 a	3.62 A	7.88 a	7.21 a	7.55 A
ZT + B	3.91 a	4.23 b	4.07 A	4.21 ab	3.36 a	3.79 A	8.12 a	7.59 b	7.86 B
ZT + R	4.99 cd	4.40 b	4.70 B	4.07 ab	3.70 ab	3.89 B	9.06 c	8.10 c	8.58 C
ZT + R + B	4.53 c	4.83 c	4.68 B	4.41 b	4.63 c	4.52 C	8.94 c	9.46 f	9.20 E
CT	4.28 b	5.05 c	4.67 B	3.83 a	3.94 b	3.89 B	8.11 a	8.99 e	8.55 C
CT + B	4.29 b	4.96 c	4.63 B	3.95 a	3.53 a	3.74 A	8.24 b	8.49 d	8.37 C
CT + R	5.06 d	5.27 d	5.17 C	3.99 a	3.87 b	3.93 B	9.05 c	9.14 e	9.10 D
CT + R + B	5.01 d	6.14 e	5.58 D	4.04 ab	3.73 ab	3.89 B	9.05 c	9.87 g	9.46 E

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria; Similar letters are statistically non-significant at $p < 0.005$.

3.2. Effect of Tillage, Crop Residue, and Plant-Growth Promoting Bacteria on Straw Yield in a Rice–Wheat System

Data related to straw yield in a rice–wheat cropping system over two years are shown in Table 4. The table shows that different management practices (tillage, R, and B) influence straw yield in the Terai agro-ecological zone of West Bengal, India.

The straw yield of rice in 2021 was significantly higher under CT + R + B compared to ZT and CT and was at par with CT + R and ZT + R + B. The increase in straw yield for the above treatments was 29, 28, and 28% compared to ZT and 17, 18 and 17%, compared to CT, respectively. The straw yield of rice in 2022 was significantly higher under CT + R + B compared to ZT and CT. The increase in straw yield for the above treatment was 46 and 14% compared to ZT and CT, respectively. Pooled data for rice straw showed a significantly higher yield under CT + R + B compared to ZT and CT. The increase in straw yield for the best treatment CT + R + B was 39 and 16% compared to ZT and CT, respectively. Crop residue applied with B along with tillage further improved the straw yield of rice compared to treatments with R and B alone along with tillage practices.

The straw yield of wheat in 2021–2022 was significantly higher under ZT + R compared to ZT and CT. The increase in straw yield for ZT + R was 5% greater than with ZT and 12% greater than with CT. The straw yield of wheat in 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT was at par with ZT + R. The increase in straw yield for the above treatments was 5 and 6% over ZT and 4 and 5% greater than with CT, respectively. Pooled data of wheat straw showed a significantly higher yield under ZT + R compared to ZT and CT and was at par with ZT + R + B. The increase in yield for the best treatment, ZT + R + B, was 1 and 4% compared to ZT and CT, respectively.

The straw yield of a rice–wheat system in 2021–2022 was significantly higher under ZT + R + B compared to ZT and CT and was at par with ZT + R, CT + R, and CT + R + B. The increase in yield for the above treatments was 12, 10, 12, and 12% compared to ZT and 10, 9, 10, and 10% compared to CT, respectively. The straw yield of the rice–wheat system in 2022–2023 was significantly higher under CT + R + B than with ZT and CT. The increase in yield for the above treatment was 22 and 6% compared to ZT and CT. Pooled data of a rice–wheat system for straw showed a significantly highest yield under CT + R + B treatment compared to ZT and CT and was at par with ZT + R + B. The increase in yield for the best treatment, CT + R + B, was 17 and 8% compared to ZT and CT, respectively, and for ZT + R + B was 16 and 7% compared to ZT and CT, respectively.

Table 4. Effect of tillage, crop residue, and plant growth-promoting bacteria on straw yield in a rice–wheat system under Terai agro-ecological zone of West Bengal, India.

Treatment	Rice Straw Yield (t ha^{-1})			Wheat Straw Yield (t ha^{-1})			System Straw Yield (t ha^{-1})		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	4.98 a	4.73 a	4.86 A	5.15 b	4.82 b	4.99 AB	10.13 a	9.55 a	9.84 A
ZT + B	5.07 a	5.52 b	5.30 B	4.76 a	4.99 b	4.88 A	9.83 a	10.51 b	10.17 B
ZT + R	5.77 c	6.01 c	5.89 C	5.39 c	5.12 c	5.26 B	11.16 b	11.13 c	11.15 CD
ZT + R + B	6.35 d	6.40 d	6.38 D	4.97 b	5.06 bc	5.02 AB	11.32 b	11.46 d	11.39 D
CT	5.45 b	6.07 c	5.76 C	4.83 a	4.87 b	4.85 A	10.28 a	10.94 c	10.61 C
CT + B	5.45 b	6.15 c	5.80 C	4.68 a	4.53 a	4.61 A	10.13 a	10.68 c	10.41 BC
CT + R	6.37 d	6.42 d	6.40 D	4.94 b	4.91 b	4.93 AB	11.31 b	11.33 cd	11.32 D
CT + R + B	6.44 d	6.89 e	6.67 D	4.88 b	4.72 ab	4.80 A	11.32 b	11.61 d	11.47 D

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria; Similar letters are statistically non-significant at $p < 0.05$.

3.3. Effect of Tillage, Crop Residue, and Plant Growth-Promoting Bacteria on Nitrogen Uptake in a Rice–Wheat System

Data related to N uptake by straw and grain in a rice–wheat cropping system for two years is shown in Table 5. The table shows that different management practices (tillage, R, and B) influence N uptake in the Terai agro-ecological zone of West Bengal, India.

Nitrogen uptake by rice straw in 2021 was significantly higher under CT + R + B than under ZT and CT and at par with ZT + R. N uptake by rice straw in 2022 was significantly higher under ZT + R and CT + R compared to ZT and CT. Pooled data of N uptake by rice straw showed significantly higher values under treatments ZT + R, CT + R, and CT + R + B compared to ZT and CT. The increase in N uptake for CT + R + B and ZT + R + B was 25 and 15% compared to ZT and 21 and 11% compared to CT, respectively. Nitrogen uptake by wheat straw in 2021–2022 was significantly higher under ZT + B, ZT + R + B, CT + R and CT + R + B compared to ZT and CT. However, N uptake by wheat straw in 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT and was at par with

ZT + R. Pooled data of N uptake by wheat straw showed significantly higher values under ZT + R + B compared to ZT and CT was at par with ZT + R + B. The increase in N uptake for CT + R + B and ZT + R + B was 18 and 6% compared to ZT and 30 and 17% compared to CT, respectively. N uptake by the straw of our rice–wheat system in 2021–2022 was significantly highest under CT + R + B compared to ZT and CT. Nitrogen uptake by the straw in rice–wheat system in 2022–2023 was significantly highest under ZT + R treatment compared to ZT and CT. Pooled data of N uptake by straw in rice–wheat system showed significantly higher values under CT + R + B treatment compared to ZT and CT and was at par with ZT + R + B, ZT + R, and CT + R. The increase in N uptake by the straw of our rice–wheat system for the CT + R + B treatment was 18 and 20% compared to ZT and CT, respectively, and for the ZT + R + B treatment, it was 16 and 17% compared to ZT and CT, respectively.

Table 5. Effect of tillage, crop residue, and plant growth-promoting bacteria on plant nitrogen uptake in a rice–wheat system in the Terai agro-ecological zone of West Bengal, India.

Treatment	Rice Straw N Uptake (kg ha^{-1})			Wheat Straw N Uptake (kg ha^{-1})			System Straw N Uptake (kg ha^{-1})		
	2021	2022	Mean	2021–2022	2022–2023	Mean	2021–2022	2022–2023	Mean
ZT	48.9 a	47.5 ab	48.2 A	25.7 b	26.9 ab	26.3 B	74.7 a	74.4 a	74.5 A
ZT + B	48.0 a	46.8 a	47.4 A	29.4 c	26.3 ab	27.8 B	77.4 b	73.1 a	75.2 A
ZT + R	61.3 d	63.1 e	62.2 D	21.7 a	33.0 c	27.1 B	83.1 c	96.1 d	89.4 C
ZT + R + B	52.4 b	58.2 cd	55.3 C	30.8 c	31.0 c	30.9 C	83.1 c	89.2 c	86.2 C
CT	50.5 ab	49.0 b	49.7 AB	23.3 a	24.3 a	23.8 A	73.8 a	73.3 a	73.5 A
CT + B	58.0 c	45.1 a	51.5 B	25.2 ab	27.3 b	26.3 B	83.3 c	72.4 a	77.8 B
CT + R	57.3 c	63.1 e	60.2 D	29.3 c	24.0 a	26.6 B	86.6 d	87.0 c	86.8 C
CT + R + B	63.6 de	56.6 c	60.1 D	28.1 c	27.6 b	27.8 B	91.7 e	84.1 b	88.0 C
	Rice grain N uptake (kg ha^{-1})			**Wheat grain N uptake (kg ha^{-1})**			**System grain N uptake (kg ha^{-1})**		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	41.4 a	42.6 b	42.0 B	76.5 b	73.3 a	74.9 B	117.9 a	115.9 a	116.9 A
ZT + B	39.4 a	39.4 a	39.4 A	85.0 c	74.7 a	79.8 C	124.4 b	114.1 a	119.2 A
ZT + R	55.2 d	55.9 d	55.5 D	68.3 a	90.1 d	79.4 C	123.5 b	146.0 c	134.9 B
ZT + R + B	49.4 c	54.5 d	52.0 C	84.2 c	86.0 c	85.1 D	133.6 c	140.5 c	137.1 B
CT	44.9 b	44.3 b	44.6 B	68.7 a	72.6 a	70.6 A	113.6 a	116.9 a	115.2 A
CT + B	50.2 c	41.2 a	45.8 B	76.2 b	76.2 b	76.3 B	126.4 b	117.4 a	122.1 A
CT + R	51.6 c	56.7 d	54.2 CD	79.2 b	73.2 a	76.2 B	130.8 c	129.9 b	130.4 B
CT + R + B	57.0 d	50.8 c	54.0 C	80.2 b	76.4 b	78.3 BC	137.2 c	127.2 b	132.2 B

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria, N—Nitrogen; Similar letters are statistically non-significant at $p < 0.05$.

Nitrogen uptake by rice grain in 2021 was significantly higher under CT + R + B compared to ZT and CT and was at par with ZT + R. Nitrogen uptake by rice grain in 2022 was significantly higher under ZT + R and CT + R compared to ZT and CT. Pooled data of N uptake by the rice grain showed significantly higher values under ZT + R, CT + R, and CT + R + B compared to ZT and CT. The increase in N uptake for CT + R + B and ZT + R + B was 29 and 24% compared to ZT and 21 and 17% compared to CT, respectively. N uptake by wheat grain in 2021–2022 was significantly higher under ZT + B and ZT + R + B compared to ZT and CT. However, N uptake by wheat grain in 2022–2023 was significantly higher under ZT + R compared to ZT and CT. Pooled data of N uptake by wheat grain showed significantly higher values under ZT + R + B compared to ZT and CT. The increase in N uptake for CT + R + B and ZT + R + B was 5 and 13% compared to ZT and 11 and 21% compared to CT, respectively. N uptake by the grain of our rice–wheat system in 2021–2022 was significantly highest under CT + R + B treatment compared to ZT and CT and was at par with CT + R and ZT + R + B. N uptake by the grain of rice–wheat system in 2022–2023 was significantly highest under ZT + R + B compared to ZT and CT and was at par with ZT + R. Pooled data of N uptake by grain in rice–wheat system showed significantly higher values under CT + R + B compared to ZT and CT and was at par with ZT + R + B, ZT + R, and CT + R. The N uptake increase by the grain of our rice–wheat system under the CT + R + B treatment was 13 and 15% compared to ZT and CT, respectively, and for ZT + R + B, was 17 and 19% compared to ZT and CT, respectively.

3.4. Effect of Tillage, Crop Residue, and Plant Growth-Promoting Bacteria on Phosphorus Uptake in Rice–Wheat System

Data related to P uptake by the straw and grain of our rice–wheat cropping system for two years is shown in Table 6. The table shows that different management practices (tillage, R, and B) influence P uptake in the Terai agro-ecological zone of West Bengal, India.

Phosphorus uptake by rice straw in 2021 was significantly higher under ZT + B compared to ZT and CT and was at par with ZT + R treatment. Phosphorus uptake by the rice straw in 2022 was significantly higher under ZT + R and ZT + R + B compared to ZT and CT. Pooled data regarding P uptake by rice straw showed significantly higher values under ZT + R and ZT + R + B compared to ZT and CT. Phosphorus uptake by wheat straw in 2021–2022 was significantly higher under ZT and ZT + R + B compared to CT. Phosphorus uptake by wheat straw in 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT and was at par with ZT + R. Pooled data regarding P uptake by wheat straw revealed significantly higher values under ZT + R + B treatment compared to CT was at par with ZT. The increase in P uptake for the ZT + R + B treatment was 7 and 61% compared to ZT and CT, respectively. P uptake by the straw of rice–wheat system in 2021–2022 was significantly highest under ZT + R + B treatment compared to CT. Phosphorus uptake by the straw of our rice–wheat system in 2022–2023 was significantly higher under ZT + R + B treatment compared to ZT and CT and was at par with ZT + R. Pooled data regarding P uptake by the straw of our rice–wheat system showed significantly higher values under ZT + R + B compared to ZT and CT and was at par with ZT + R treatment. The P uptake increase by the straw in rice–wheat system under ZT + R + B treatment was 24 and 25% compared to ZT and CT, respectively.

The phosphorus uptake by rice grain in 2021 was significantly higher under CT + R + B compared to ZT and CT and was at par with ZT + R + B. P uptake by rice grain in 2022 was significantly higher under CT + R treatment compared to ZT and CT. Pooled data of P uptake by the rice grain showed significantly higher values under treatments CT + R and CT + R + B compared to ZT and CT. The increase in P uptake under the CT + R + B treatment was 48 and 20% compared to ZT and CT, respectively. P uptake by the wheat grain in 2021–2022 was significantly higher under ZT + R treatment compared to ZT and CT. However, P uptake by wheat grain in 2022–2023 was significantly higher under ZT + R treatment compared to ZT and CT and was at par with ZT + R + B and CT + R + B. Pooled data of P uptake by wheat grain showed significantly higher values under ZT + R treatment compared to ZT and CT. P uptake by grain in rice–wheat system in 2021–2022 was significantly highest under CT + R + B treatment compared to ZT and CT and was at par with ZT + R. Phosphorus uptake by the grain in rice–wheat system in 2022–2023 was significantly highest under ZT + R + B treatment compared to ZT and CT and was at par with ZT + R. Pooled data of P uptake by grain in rice–wheat system revealed significantly higher values under CT + R + B treatment compared to ZT and CT and was at par with ZT + R + B and ZT + R. The increase in P uptake by the grain in rice–wheat system for the CT + R + B treatment was 22 and 15% compared to ZT and CT, respectively, and for the ZT + R + B treatment was 20 and 15% compared to ZT and CT, respectively.

Table 6. Effect of tillage, crop residue, and plant growth-promoting bacteria on plant phosphorus uptake in a rice–wheat system in the Terai agro-ecological zone of West Bengal, India.

Treatments	Rice Straw P Uptake ($kg\ ha^{-1}$)			Wheat Straw P Uptake ($kg\ ha^{-1}$)			System Straw P Uptake ($kg\ ha^{-1}$)		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	10.0 b	10.2 a	10.1 A	6.2 d	5.1 bc	5.7 B	16.2 b	15.3 ab	15.8 B
ZT + B	12.4 d	9.2 a	10.8 B	4.4 b	4.4 b	4.4 AB	16.8 b	13.6 a	15.2 B
ZT + R	12.7 d	18.0 d	15.4 D	3.1 a	4.5 b	3.8 A	15.8 b	22.5 c	19.1 C
ZT + R + B	11.2 cd	16.0 c	13.5 D	5.7 c	6.5 c	6.1 B	16.9 b	22.5 c	19.6 C
CT	10.9 bc	12.9 b	11.9 C	3.7 a	3.8 ab	3.8 A	14.7 a	16.7 b	15.7 B
CT + B	8.9 a	9.8 a	9.5 A	3.2 a	2.8 a	3.0 A	12.0 a	12.7 a	12.5 A
CT + R	9.0 a	12.3 b	10.6 B	3.4 a	3.4 a	3.5 A	12.4 a	15.8 ab	14.1 A
CT + R + B	9.1 ab	9.4 a	9.3 A	3.5 a	3.9 ab	3.7 A	12.6 a	13.3 a	13.0 A
	Rice grain P uptake ($kg\ ha^{-1}$)			**Wheat grain P uptake ($kg\ ha^{-1}$)**			**System grain P uptake ($kg\ ha^{-1}$)**		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	9.6 a	9.2 a	9.4 A	19.2 b	16.8 a	18.0 B	28.8 a	26.0 a	27.4 A
ZT + B	11.6 b	10.6 a	11.1 B	18.6 b	17.9 a	18.2 B	30.2 b	28.5 b	29.3 AB
ZT + R	12.6 b	14.1 bc	13.4 BC	20.8 c	21.2 bc	21.0 C	33.3 cd	35.4 d	34.4 D
ZT + R + B	14.5 bc	13.0 bc	13.7 BC	15.6 a	22.6 c	19.1 BC	30.1 b	35.6 d	32.8 C
CT	11.7 b	11.4 ab	11.6 B	16.1 a	17.9 a	17.0 A	27.9 a	29.3 b	28.5 A
CT + B	13.4 b	10.5 a	12.0 B	18.1 b	18.7 ab	18.4	31.5 bc	29.3 b	30.4 B
CT + R	13.4 b	14.8 c	14.1 C	16.9 a	15.8 a	16.3 A	30.2 b	30.6 bc	30.4 B
CT + R + B	15.4 c	12.4 b	13.9 BC	19.7 bc	19.2 b	19.4 BC	35.1 d	31.6 c	33.3 CD

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria, P—Phosphorus; Similar letters are statistically non-significant at $p < 0.05$.

3.5. Effect of Tillage, Crop Residue, and Plant Growth-Promoting Bacteria on Potassium Uptake in Rice–Wheat System

Data related to K uptake by the straw and grain in our rice–wheat cropping system for two years is shown in Table 7. That table shows that different management practices (tillage, R, and B) influence K uptake in the Terai agro-ecological zone of West Bengal, India.

Potassium uptake by rice straw in 2021 was significantly higher under CT + R + B treatment compared to ZT and CT and was at par with ZT + R, CT + R, and CT + B. K uptake by rice straw in 2022 was significantly higher under ZT + R + B and CT + R + B compared to ZT and CT. Pooled data for K uptake by rice straw revealed significantly higher values under ZT + R + B, CT + R and CT + R + B compared to ZT and CT. The increase in K uptake for CT + R + B and ZT + R + B was 34 and 32% compared to ZT and 21 and 20% over CT, respectively. K uptake by wheat straw in 2021–2022 was significantly highest under ZT + R + B treatment compared to ZT and CT. Potassium uptake by wheat straw in 2022–2023 was significantly higher under ZT + R + B treatment compared to ZT and CT and was at par with ZT + R. Pooled data for K uptake by wheat straw showed a significantly higher values under ZT + R + B compared to ZT and CT. The increase in K uptake for ZT + R + B was 23 and 65% compared to ZT and CT, respectively. K uptake by the straw in rice–wheat system in 2021–2022 was significantly highest under ZT + R + B treatment compared to ZT and CT. K uptake by the straw in rice–wheat system in 2022–2023 was significantly highest under ZT + R compared to ZT and CT. Pooled data for K uptake by straw in rice–wheat system showed significantly a higher values under CT + R + B treatment compared to ZT and CT and was at par with ZT + R + B, ZT + R and CT + R. The increase in K uptake by the straw in rice–wheat system for CT + R + B was 26 and 31% compared to ZT and CT, respectively, and for the ZT + R + B treatment was 21 and 27% compared to ZT and CT, respectively.

Table 7. Effect of tillage, crop residue, and plant growth-promoting bacteria on plant potassium uptake in rice–wheat system in the Terai agro-ecological zone of West Bengal, India.

Treatments	Rice Straw K Uptake ($kg\ ha^{-1}$)			Wheat Straw K Uptake ($kg\ ha^{-1}$)			System Straw K Uptake ($kg\ ha^{-1}$)		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	122.8 a	133.0 b	127.9 A	30.0 cd	29.7 c	29.9 BC	152.9 a	162.7 b	157.8 A
ZT + B	125.0 a	120.6 a	122.8 A	30.8 d	26.9 b	28.8 B	155.7 a	147.5 a	151.6 A
ZT + R	176.7 c	148.6 c	162.7 C	25.1 b	37.3 d	31.0 C	201.8 c	185.9 c	193.7 C
ZT + R + B	138.5 b	173.5 e	154.9 BC	35.9 e	37.5 d	36.7 D	164.4 a	221.0 d	191.6 C
CT	135.6 b	122.6 a	129.1 A	20.5 a	24.2 a	22.3 A	156.1 a	146.9 a	151.5 A
CT + B	175.7 c	120.9 a	147.1 B	21.8 a	23.0 a	22.4 A	197.6 bc	143.9 a	169.6 B
CT + R	166.5 c	169.4 d	168.4 CD	23.2 ab	23.5 a	23.4 A	189.7 b	192.9 c	191.8 C
CT + R + B	176.3 c	164.2 d	170.7 D	28.3 c	26.4 b	27.3 B	204.6 c	190.7 c	198.1 C
	Rice grain K uptake ($kg\ ha^{-1}$)			**Wheat grain K uptake ($kg\ ha^{-1}$)**			**System grain K uptake ($kg\ ha^{-1}$)**		
	2021	**2022**	**Mean**	**2021–2022**	**2022–2023**	**Mean**	**2021–2022**	**2022–2023**	**Mean**
ZT	10.5 ab	16.4 c	13.5 AB	17.0 ab	16.2 a	16.6 A	27.6 a	32.6 bc	30.1 A
ZT + B	9.1 a	14.0 b	11.6 A	19.6 bc	16.7 a	18.2 B	28.7 a	30.7 b	29.7 A
ZT + R	18.5 de	16.1 c	17.3 C	16.0 a	19.8 b	18.0 B	34.4 c	35.9 d	35.3 B
ZT + R + B	15.3 c	15.9 bc	15.6 B	20.8 c	18.8 b	19.8 B	36.1 cd	34.6 cd	35.4 B
CT	13.6 bc	14.7 b	14.1 AB	15.7 a	16.9 a	16.3 A	29.3 ab	31.6 b	30.4 A
CT + B	17.0 d	8.7 a	12.5 A	16.6 a	17.1 ab	16.9 A	33.6 bc	25.8 a	29.4 A
CT + R	12.3 b	19.1 d	15.6 B	18.8 bc	16.6 a	17.7 A	31.1 b	35.7 d	33.2 B
CT + R + B	19.6 e	15.2 bc	17.3 C	17.9 b	18.5 b	18.2 B	37.4 d	33.7 c	35.5 B

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria, K—Potassium; Similar letters are statistically non-significant at $p < 0.05$.

Potassium uptake by rice grain in 2021 was significantly higher under CT + R + B treatment compared to ZT and CT and was at par with ZT + R treatment. Potassium uptake by rice grain in 2022 was significantly higher under CT + R compared to ZT and CT. Pooled data for K uptake by rice grain showed significantly higher values under ZT + R and CT + R + B compared to ZT and CT. The increase in K uptake for the treatments CT + R + B and ZT + R + B was 28 and 16% compared to ZT and 23 and 11% compared to CT, respectively. Potassium uptake by wheat grain in 2021–2022 was significantly higher under ZT + R + B treatment compared to ZT and CT. Potassium uptake by wheat grain in 2022–2023 was significantly higher under ZT + R + B and CT + R + B compared to ZT and CT. Pooled data for K uptake by wheat grain revealed significantly higher values under ZT + R + B and CT + R + B compared to ZT and CT. The increase in K uptake for the treatments CT + R + B and ZT + R + B was 10 and 19% compared to ZT and 12 and 22% compared to CT, respectively. Potassium uptake by the grain in rice–wheat system in 2021–2022 was significantly highest under CT + R + B treatment compared to ZT and CT and was at par with ZT + R + B. K uptake by grain in rice–wheat system in 2022–2023 was significantly highest under ZT + R + B treatment compared to ZT and CT and was at par with ZT + R and CT + R. Pooled data for K uptake by the grain in rice–wheat system showed significantly higher values under CT + R + B compared to ZT and CT and was at par with ZT + R + B, ZT + R and CT + R. The increase in K uptake by the grain in rice–wheat system for the CT + R + B treatment was 18 and 17% compared to ZT and CT, respectively, and for the ZT + R + B treatment was 18 and 16% compared to ZT and CT, respectively.

3.6. Effect of Tillage, Crop Residue, and Plant Growth-Promoting Bacteriaon Soil Properties in Rice–Wheat System

Data related to the soil properties in the rice–wheat cropping system after the 16th crop cycle for two soil layers (5–10 cm and 20–40 cm) are shown in Table 8. The table shows that different management practices (tillage, R, and B) influence soil properties in the Terai agro-ecological zone of West Bengal, India. Initial soil (2006) data in the 5–10-cm soil layer was as follows: pH—5.5;soil organic carbon—8.7 g kg^{-1};soil available N—77 kg ha^{-1}; soil available P—10 kg ha^{-1}; and soil available K—81 kg ha^{-1}. The changes due to management practices on soil properties showed that overall, tillage, R, and B improved the soil parameters, irrespective of the crop. Crop residue had a greater impact on soil parameters in comparison to B. ZT-based treatments had higher soil test values than the CT-based treatments. In the 5–10-cm soil layer, the above-mentioned soil properties were improved under the best treatment (ZT + R + B) compared to the initial (2006) values by 37, 126, 65, and 60%, respectively. Similarly, for the CT + R + B treatment, the soil properties (soil organic carbon, available N, and available K) increased compared to initial values by 34, 130, and 48%; however, soil available P decreased by 17%. The availability of soil nutrients declined from the surface layer (5–10 cm) to the subsurface layer (20–40 cm), irrespective of the crop or nutrients.

Table 8. Effect of tillage, crop residue, and plant growth-promoting bacteria on soil properties under acid alluvial soil after the 16th crop cycle.

	Soil pH (Soil:Water:1:2.5)		**SOC (g kg^{-1})**		**Available N (kg ha^{-1})**		**Available P (kg ha^{-1})**		**Available K (kg ha^{-1})**	
Treatment / **Soil Depth (cm)**	**5–10**	**20–40**	**5–10**	**20–40**	**5–10**	**20–40**	**5–10**	**20–40**	**5–10**	**20–40**
					Post rice soil					
ZT	5.5 ab	6.5 bc	11.4 a	2.8 b	142 a	44 ab	13 c	4 ab	128 ab	77 b
ZT + B	5.8 c	6.6 c	11.4 a	2.9 b	158 b	47 b	10 b	5 b	128 ab	93 c
ZT + R	6.1 d	6.7 c	11.9 ab	3.9 c	176 c	47 b	17 d	7 c	129 b	113 d
ZT + R + B	6.4 e	6.9 d	11.9 ab	3.9 c	174 c	44 ab	17 d	7 c	130 b	114 d
CT	5.6 b	6.2 a	11.4 a	1.6 a	158 b	41 a	5 a	3 a	123 a	59 a
CT + B	5.7 bc	6.5 bc	11.5 a	2.9 b	154 b	41 a	9 ab	4 ab	127 ab	60 a
CT + R	5.4 a	6.4 b	12.1 b	2.7 b	154 b	47 b	8 ab	5 b	127 ab	90 c
CT + R + B	5.7 bc	6.6 c	12.1 b	2.9 b	161 b	41a	10 b	5 b	129 b	88 c
					Post wheat soil					
ZT	5.5 a	6.4 ab	11.5 bc	2.7 b	151 b	76 d	10 c	3 a	61 a	85 c
ZT + B	6.0 c	6.7 c	11.6 c	3.0 b	151 b	44 b	8 bc	4 b	58 a	90 cd
ZT + R	6.0 c	6.4 a	11.9 c	3.7 c	172 cd	47 b	15 d	4 b	148 f	105 e
ZT + R + B	6.1 c	6.7 c	12.1 c	3.9 c	174 d	57 c	15 d	4 b	149 f	108 e
CT	5.4 a	6.3 a	10.9 b	1.6 a	158 bc	38 b	4 a	3 a	106 d	68 b
CT + B	5.4 a	6.4 ab	11.1 b	3.5 c	167 c	63 c	6 ab	3 a	91 c	62 a
CT + R	5.7 b	6.7 c	11.7 c	2.5 b	176 d	44 b	6 ab	3 a	118 e	96 d
CT + R + B	5.4 a	6.5 b	11.7 c	2.5 b	177 d	22 a	8 bc	4 b	120 e	117 f
Initial	**5.5 a**	-	**8.7 a**	-	**77 a**	-	**10 c**	-	**81 b**	-

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria, SOC—Soil organic carbon, N—Nitrogen, P—Phosphorus, K—Potassium; Similar letters are statistically non-significant at $p < 0.05$.

3.7. Effect of Tillage, Crop Residue, and Plant Growth-promoting Bacteria on the Economics of Rice–Wheat System

Data related to the gross return, net return, and benefit–cost ratio of a rice–wheat cropping system for two years is shown in Table 9. The table shows that different management practices (tillage, R, and B) influence these factors in the Terai agro-ecological zone of West Bengal, India.

The gross return of rice in 2021 was significantly higher under CT + R + B compared to ZT and CT and was at par with ZT + R, CT + R and ZT + R + B. The gross return of rice in 2022 was significantly higher under CT + R + B compared to ZT and CT. Pooled data of the gross return of rice showed significantly higher values under CT + R + B compared to ZT and CT. The gross return of wheat in 2021–2022 and 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT. Pooled data of the gross return of wheat revealed significantly higher values under ZT + R + B compared to ZT and CT.

Table 9. Effect of tillage, crop residue, and plant growth-promoting bacteria on economics in rice–wheat system under Terai agro-ecological zone of West Bengal, India.

Treatment	Gross Return (USD ha^{-1})					
	Rice (2021)	**Rice (2022)**	**Mean**	**Wheat (2021–22)**	**Wheat (2022–23)**	**Mean**
ZT	965 a	987 a	976 a	982 a	841 a	912 a
ZT + B	948 a	1079 b	1013 a	1060 b	846 a	955 a
ZT + R	1210 c	1122 c	1166 b	1025 ab	932 c	980 b
ZT + R + B	1099 c	1232 d	1165 b	1111 c	1166 e	1138 c
CT	1038 b	1288 d	1163 b	965 a	992 d	980 b
CT + B	1040 b	1265 d	1153 b	995 a	889 b	942 a
CT + R	1227 c	1344 e	1285 c	1005 ab	975 cd	990 b
CT + R + B	1215 c	1566 f	1390 d	1018 ab	939 c	980 b
	Net return (USD ha^{-1})					
ZT	553 a	568 a	560 a	645 ab	504 a	574 a
ZT + B	536 a	660 b	598 b	723 c	509 a	617 b
ZT + R	798 e	703 c	750 d	688 b	594 c	642 bc
ZT + R + B	686 c	813 d	749 d	773 d	829 d	801 d
CT	575 b	819 d	697 c	577 a	605 c	592 ab
CT + B	578 b	796 d	687 c	607 a	502 a	555 a
CT + R	765 de	875 e	820 e	617 a	587 bc	602 ab
CT + R + B	752 d	1097 f	925 f	630 ab	552 b	592 ab
	Benefit–cost ratio					
ZT	2.34 a	2.36 a	2.35 a	2.91 b	2.49 b	2.70 b
ZT + B	2.30 a	2.58 ab	2.44 a	3.14 bc	2.51 b	2.83 b
ZT + R	2.93 c	2.68 b	2.81 b	3.04 b	2.76 c	2.90 b
ZT + R + B	2.66 b	2.94 c	2.80 b	3.29 c	3.46 d	3.37 c
CT	2.24 a	2.75 b	2.50 a	2.49 a	2.56 b	2.53 a
CT + B	2.25 a	2.70 b	2.48 a	2.57 a	2.29 a	2.43 a
CT + R	2.65 b	2.87 bc	2.76 b	2.59 a	2.52 b	2.55 a
CT + R + B	2.63 b	3.34 d	2.99 b	2.63 a	2.42 ab	2.53 a

ZT—Zero tillage, CT—Conventional tillage, R—Crop residue, B—Plant growth-promoting bacteria. Similar letters are statistically non-significant at $p < 0.05$.

The net return of rice in 2021 was significantly higher under ZT + R compared to ZT and CT and was at par with CT + R treatment. The net return of rice in 2022 was significantly higher under CT + R + B compared to ZT and CT. Pooled data of the gross return of rice showed significantly higher values under CT + R + B compared to ZT and CT. The net return of wheat in 2021–2022 and 2022–2023 was significantly higher under ZT + R + B compared to ZT and CT. Pooled data of the net return of wheat showed significantly higher values under ZT + R + B compared to ZT and CT.

The benefit–cost ratio of rice in 2021 was significantly higher under ZT + R treatment compared to ZT and CT. The B: C ratio of the rice in 2022 was significantly higher under CT + R + B compared to ZT and CT. Pooled data of the B: C ratio of rice revealed significantly higher values under CT + R + B compared to ZT and CT and was at par with ZT + R + B, CT + R, and ZT + R. The B: C ratio of wheat in 2021–2022 and 2022–2023 was significantly highest under ZT + R + B compared to ZT and CT. Pooled data of the B:C ratio of wheat showed significantly higher values under ZT + R + B compared to ZT and CT.

4. Discussion

Rice–wheat cropping systems are the main farming systems in South Asian countries. Intensive cultivation and excessive synthetic fertilizer use have affected soil productivity, which has ultimately led to a decline/stagnation in the productivity and profitability of this cropping system. The Terai agro-ecological region in eastern India has similarly been affected by such farming activities. This region is also impaired due to heavy rainfall (>3000 mm) during the pre-sowing and harvesting phases of wheat crops and the coarse light textured soil below the soil layer of 20 cm, resulting in nutrient and organic matter loss. Due to the constrained window for introducing legumes in a rice–wheat system, the diversification of crops/cropping systems is either absent or limited in the region. Therefore, full CA (with all three ideas for cultivation) is not possible, and hence, partial CA, i.e., two principles (minimal soil disturbance and soil cover throughout the year) is used. Considering the above limitations, a long-term CA experiment was planned in Uttar Banga Krishi Viswavidyalaya, Pundibari (Cooch Behar), West Bengal, in 2006, with different management practices (tillage, R, and B) used alone and in combination.

In this study, tillage (CT or ZT), R (retention), and B management were used as treatment combinations. The study clearly showed that CT-based treatments performed better for rice cultivation than ZT-based treatments, while ZT-based treatments yielded greater harvests with wheat cultivation than CT-based treatments. In rice, the ranges of yield increment under CT-based treatments and ZT-based treatments compared to ZT were 18–42% and 4–20%, respectively, whereas in wheat, ranges of yield increment under CT-based treatments and ZT-based treatments compared to ZT were 3–9% and 5–25%, respectively. In the cropping system, ranges of yield increment under CT-based treatments and ZT-based treatments compared to ZT were 11–25% and 4–21%, respectively. In rice, ranges of yield increment/decrement with CT-based treatments and ZT-based treatments compared to CT were (−) 1–20% and (−) 16–1%, respectively, whereas in wheat, ranges of yield increment/decrement with CT-based treatments and ZT-based treatments compared to CT were (−) 4–1% and (−) 7–16%, respectively. In the cropping system, ranges of yield increment/decrement under CT-based treatments and ZT-based treatments compared to CT were (−) 2–11% and (−) 12–0.4%, respectively. Retention of R along with B management also supported the yield, and the highest yield for rice was recorded with CT + R + B, where CT was done with R retention and B management, whereas the highest yield for wheat was recorded with ZT + R + B, where ZT was done with R retention and B management.

The most recent worldwide meta-analysis [34,35] showed a yield decline of 5.7% in CA over CT. The yield was also lower in CA than in CT, according to a meta-analysis of studies on maize crops that used global tillage techniques [36]. Reduced aggregate stability, increased soil penetration resistance, surface soil slaking, and increased water runoff have been blamed for the decline in yield under ZT/reduced tillage over CT. According to a worldwide meta-analysis study by Pittelkow et al. [37], except for oilseeds and cotton, all crop categories have experienced a decline in yield under no-tilling techniques. However, by using ZT or reduced tillage, Kassam et al. [38] observed improved crop growth and higher grain yield under CA in comparison to CT. This was accomplished by causing the least amount of soil disturbance, which ensures: (a) the presence of a favorable amount of respiration gases close to the root system; (b) moderate organic matter oxidation; (c) better porosity for water movement; and (d) limited exposure toweed seeds and their germination. Similar crop yields under CA and CT were reported by Alamet al. [39], even though the cropping system used various types of fertilizer.

Crop residue retention provides a favorable environment for crop growth and development. In our study, R with tillage and B improved the grain and straw yield of rice and wheat. Similar results were observed by Singh et al. [40] and Zamir et al. [41] in wheat crops using a Happy-seeder. They reported that R retention in ZT plots improved the grain yield by 5–9% over CT practice. This was due to improved soil organic matter, increased nutrient availability, and better soil pulverization caused by R integration. Meenakshi [42] and Kaushal et al. [43] observed the highest wheat productivity with a ZT planter compared to a Happy-seeder, rotavator, or CT wheat. Tripathi et al. [44] observed that rice yields declined by 35–45% under ZT, whereas TiMalsina et al. [45] reported that wheat yields improved by 18% with the ZT compared to CT. These results were consistent with our findings in the case of rice and wheat crops.

All stakeholders involved in agricultural production are increasingly accepting the use of B. Diverse B species strains have been shown to have a wide range of actions, while also having varying their effects on certain crops. Different B strains were shown to improve yield by 10–16% [46]. Our study examined the performance of B applied along with R under different tillage practices in the Terai agro-ecological region. We observed a yield advantage in treatments with tillage, R, and B compared tillage alone. A similar result was recorded by Roy et al. [47] in the same region, i.e., that R addition and B seed inoculation at sowing each resulted in an increase in grain yield to the tune of 11%. They also reported that the treatment combinations of tillage and R, tillage and B, and R and B did not show any yield differences.

In our study, the straw yield of the crops showed a similar trend to the grain yield and was greater in rice under CT-based treatments compared to ZT-based treatments, while in wheat; straw yield was higher under ZT-based treatments compared to CT-based treatments. Biological yield is the sum of grain yield and straw yield. We found that grain yield and straw yield were highest in CT-based treatments in rice and ZT-based treatments in wheat, and biological yield was highest in CT-based treatments and ZT-based treatments in rice and wheat, respectively.

The amount of each nutrient needed for the crop to finish its life cycle at a specific yield level is known as nutrient uptake. The concentration of each nutrient in the harvested material is multiplied by the harvest yield to determine the amount of nutrients removed. In grain crops like maize, nutrient uptake levels are typically higher than nutrient removal levels. However, removal levels can be roughly similar to absorption in crops like alfalfa or silage when the bulk of the above-ground biomass is removed from a field. To calculate the rates of nutrient application for both current and future crops, these data are crucial. In this study, nutrient uptake (N, P and K) was assessed. Tillage systems influence nutrient uptake (N, P and K) under various agro-ecological conditions [48,49]. The nutrient uptake of different plant nutrients also depends on the soil type and other management operations [50]. The nutrient uptake by rice and wheat crops is largely dependent on their root system. The mineralization of incorporated R is enhanced by different tillage methods [51]. Here, nutrient uptake for N, P, and K was increased by retaining R and B compared to when R was not retained and in the absence of B. N, P, and K uptake for both crops was found to be directly linked to the yield of the both crops. The effects of tillage and other management practices on nutrient uptake are critical to improve long-term productivity [48].

Soil properties (physical, chemical, and biological) are also impacted due to variations in management practices worldwide. This study showed that management practices such as tillage and R and B management positively influence the soil properties in acidic alluvial soil. The soil pH of the experimental plots is approaching normal after initially being acidic due to the increase in the organic matter content. Organic matter acts as a buffering agent for soil pH. Crop residue (R) retention and decomposition with time enriched the soil with organic matter [52]. Decomposition processes are influenced by biological activity as well as environmental factors like temperature, soil management, rainfall, irrigation, and the quantities of soil organic matter that are already present. Soil organic carbon also improved under all treatments, irrespective of crop and tillage practice. ZT-based treatments showed greater SOC concentration than CT-based treatments. CT enhances the loss of SOC by increasing the oxygen concentration in the soil layers, destroying soil aggregates and facilitating the mineralization of organic matter [53]. ZT minimizes soil disturbance, can augment soil aggregation, and may conserve and/or sequester SOC [54,55], which is vital to meet worldwide targets for soil carbon sequestration [56]. Following the meta-analysis methodology, Tadiello et al. [57] revealed that in humid subtropical and Mediterranean climates, CA accumulated 13% more SOC than CT. Through a meta-analysis, Robert Crystal-Ornelas et al. [58] also noted that the use of CA enhanced SOC content over CT by 14%. The implementation of CA methods in the eastern IGPs in India, Bangladesh, and Nepal led to a comparable increase in SOC concentration [59]. The rapid increase in soil nutrient content is of major significance for agricultural sustainable development, since soil nutrients are essential for plant growth [60]. In this study, soil nutrient status (N, P, and K) improved over initial values, irrespective of the treatment applied. The study also supported the notion that R management enhances soil nutrient status under both tillage practices. Finally, in some of cases, B also improved the nutrient availability.

According to Buragohain et al. [61], B is source of nutrients that may increase agricultural productivity, shield plants from various diseases and pests, and provide plant growth hormones. Additionally, it improves the soil's carbon status, microbial growth, and biological system health [62]. To ensure sustainable crop production, B is also an adjunct to soil and crop management practices like tillage, recycling crop residue, and restoring soil fertility. Biofertilizers were used in this study either alone or in conjunction with R and tillage techniques. The findings showed that, regardless of years or crops, B increased agricultural productivity when applied with R.

In this study, the cost of cultivation was high under traditional CT practice. The rising cost of cultivation and declining profitability are the main reasons that farmers are seeking alternative options such as ZT/reduced tillage/minimum tillage, which require less capital and resources than the traditional CT practices. The use of ZT in a rice–wheat system decreased the cost of cultivation due to a huge curtailment in land preparation costs and labor, and as an outcome, improved the net return. Such findings were also reported by several researchers [63]. In economic terms, the B: C ratio was significantly highest under CT + R + B treatment for rice (2.99) and ZT + R + B treatment for wheat (3.37). After 17 years of cultivation, for rice, CT-based treatments are performing better than ZT-based treatments, while for wheat cultivation; ZT-based treatments are performing better than CT-based treatments in the Terai agro-ecological zone of West Bengal, India.

5. Conclusions

Based on this study, we conclude that rice and wheat cultivation is most effective under conventional tillage and zero tillage, respectively, in terms of productivity in a Terai agro-ecological context. The rice–wheat cropping system's yield was enhanced through the use of crop residue, biofertilizers, and tillage techniques. In terms of soil organic carbon and nutrient availability, the application of zero-tillage, crop residue addition, and biofertilizers inoculation significantly enhanced the soil quality. In terms of economics, zero tillage proved to be more profitable for wheat and conventional tillage for rice crops. The inclusion of crop residue and inoculation with biofertilizers increased the profitability of our rice–wheat system. In general, using biofertilizers, crop residue, and zero tillage in the

Terai agro-ecological zone could be sustainable if done appropriately, i.e., by addressing location-specific problems.

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