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Assessing the Effects of Conservation Tillage and In-Situ Crop Residue Management on Crop Yield and Soil Properties in Rice–Wheat Cropping System

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Abstract: Rice–wheat cropping system (RWCS) is a dominant agricultural practice in the Indo-Gangetic plains, particularly in the North–Western states of India. The prevalent practice of open burning of rice residue, driven by the need for timely land preparation, poses severe environmental and health consequences, including nutrient loss, greenhouse gas emissions, high concentrations of particulate matter (PM), and disruption of the ecological cycle. This study focuses on implementing effective management practices in the RWCS through tillage-based crop establishment, residue retention, and incorporation methods. The objective is to improve crop yield and its attributes by enhancing soil health properties. A split-plot experimental design was practiced with four different treatments, zero-tillage with manual harvesting (ZT), Happy Seeder with combine harvester (HS), Happy Seeder with Mulcher and combine harvesting, and conventional tillage (CT). By evaluating soil nutrient content, including organic carbon (OC), N, P, and K, at a 0–10 cm depth, the study demonstrates the superiority of the mulcher with Happy Seeder (MHS), which significantly increased soil nutrient levels by 105, 59, 102, and 97%, respectively, compared to conventional tilled broadcasted wheat (CT). Furthermore, the MHS treatment exhibited the highest yield of 56.8 q ha^{-1}, outperforming the yield of 43.6 q ha^{-1} recorded under conventional tilled broadcasted wheat. These findings underscore the critical role of surface residue retention with MHS in ensuring crop productivity and overall production sustainability of the RWCS in Haryana, India. Moreover, effective rice residue management holds long-term implications for agricultural resilience, farm economics, environmental conservation, and human health. It emphasizes the importance of adopting sustainable practices, prioritizing research efforts, and advocating for policies that ensure the prolonged sustainability and productivity of the RWCS while safeguarding environmental well-being.

Keywords: crop productivity; rice residue burning; environment; soil fertility; sustainable agriculture; tillage practices

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1. Introduction

Wheat (*Triticum aestivum*), a prominent cereal crop belonging to the family Poaceae, holds great significance in India's rice–wheat cropping system (RWCS). This system plays a crucial role in providing sustenance to millions of people. It is a primary ingredient for various food products, including flour for chapatti, cookies, pasta, noodles, and livestock feed. With a cultivation area of 31.36 million hectares, wheat production in India stands at 107.86 million tonnes with an average productivity of 34.40 q ha^{-1} [1]. The RWCS is extensively practiced in states like Haryana, Punjab, Uttar Pradesh, Bihar, and Madhya Pradesh in an approximate area of 9.2 M ha, making a substantial contribution to national food security and self-sufficiency on a global scale [2].

However, conventional crop management practices pose challenges in effectively managing RWCS. Conventional tillage practices necessitate substantial capital investment, excessive water usage, and high labor requirements, leading to resource depletion, soil organic carbon loss, groundwater depletion, and ecological imbalance [3]. A significant concern in this system is the burning of rice residue, which is prevalent due to the limited time available between rice harvest and wheat sowing. Farmers resort to the environmentally hazardous practice of open residue burning to meet the deadline [4,5].

Burning of rice residues in the field cause the emission of greenhouse gases (GHGs) such as CO_2, CH_4, SO_2, NH_3, CO, NO, and volatile organic compounds, besides posing profound health implications for human exposure to high concentrations of particulate matter (PM) [6]. Studies have reported significant quantities of CO_2, CO, SO, NO_x, NH_3, NMHC, NMVOC, and PM released from the residue burning [7]. Furthermore, climate change consequences, including shifting monsoons, have resulted in a decline in the productivity potential of crops. With the limited window available for harvesting rice and sowing wheat, delayed wheat planting occurs, leading to lower yields due to unfavorable weather conditions during crop maturity [8–10]. Additionally, conventional tillage and puddling practices in RWCS contribute to soil compaction, reduced input-use efficiency, and poor soil aeration [11]. Crop residue burning seriously pollutes the surrounding ecosystem, depletes soil organic matter, micronutrients, and microbial activity, elevates soil temperature, and renders the land more susceptible to erosion [5,12]. Furthermore, the economic impact of agricultural residue burning-related air pollution has been estimated at USD 30 billion annually in three northern Indian states [13].

To enhance the resilience of the farming/cropping system to changing climatic conditions, technological interventions such as conservation agriculture (CA) practices have been introduced. These practices involve direct sowing of crops with minimal soil disturbance (zero tillage), crop diversification with legumes, crop rotation with non-cereal crops, and surface residue retention while sowing wheat using the Happy Seeder (HS) technology [14–21]. The HS, in combination with zero tillage, offers cost-effective and resource-saving alternatives to conventional practices. HS enables the sowing of wheat seeds by removing residue with a front-mounted blade, followed by seed placement using an attached zero-till drill in fields where rice is harvested using a combine harvester [22–25]. HS-based wheat fields result in mulching paddy residue, which provides benefits such as nitrogen immobilization, weed management, enhanced organic carbon content, and improved soil moisture conservation [26–28].

Similarly, zero tillage facilitates direct wheat planting on moist soil immediately after manual rice harvesting, using a nine-tine machine at a depth of 7.5–10 cm [29–31]. Compared to conventional practices, zero tillage has been proven superior in crop production, saving on inputs such as irrigation water, fuel, and nutrients, preventing lodging during the grain filling stage, and reducing pest and disease infestation [32,33]. Field trials have shown that zero tillage improves specific energy, operational field capacity, and energy usage efficiency by 81%, 17%, and 13%, respectively, compared to conventional tillage [34]. These practices reduce cultivation costs and result in reduced weed infestation, enhanced soil moisture conservation, and thermal stability, which directly contribute to higher yields in subsequent wheat crops.

Despite the increasing adoption of zero tillage and Happy Seeder-based practices for wheat sowing, there is a need to evaluate their impact on wheat yield attributes and the soil microclimate to identify effective rice residue management strategies and enhance wheat productivity. Therefore, this study compares the performance of different wheat sowing practices with residue management, including Happy Seeder, zero tillage, and conventional methods.

2. Materials and Methods

2.1. Experimental Site

The field experiments were conducted at the agricultural research site of Krishi Vigyan Kendra, affiliated with the Indian Council of Agricultural Research–National Dairy Research Institute, located in Karnal, Haryana. Additionally, four representative villages within the Karnal district were selected for the study: Kamalpur Rodan (latitude 29.80° N; longitude 77.04° E), Sirsi (latitude 29.68° N; longitude 77.88° E), Nabipur (latitude 29.72° N; longitude 77.11° E), and Kunjpura (latitude 29.71° N; longitude 77.07° E). The experiments were meticulously conducted during the *Rabi* seasons of 2020–21 and 2021–22, with the primary objective of elucidating the intricate relationships between various agricultural practices, crop yield, and soil health parameters. These chosen research locations provide valuable insights into the diverse agro-ecological conditions prevailing in the region and ensure the generalizability and robustness of the findings.

The study area experiences a typical tropical and subtropical climate, characterized by semi-arid conditions with cold winters and warm, dry summers. Throughout the experimental periods of 2020–21 and 2021–22, the region received a total precipitation of 75.94 mm and 106.69 mm, respectively. Among these totals, 39 mm (51.35%) and 36.40 mm (34.11%) were identified as effective rainfall during 2020–21 and 2021–22, respectively (Figure 1). Detailed weather data, including temperature, rainfall, and other relevant factors, were systematically recorded at the District Agricultural Meteorological Unit (DAMU) of the Krishi Vigyan Kendra, Indian Council of Agricultural Research (ICAR)–National Dairy Research Institute, located in Karnal, India.

2.2. Soil Properties

The soils present in the Karnal district were predominantly classified as loam and sandy loam, exhibiting sufficient depth and good drainage characteristics. The pH levels of these soils ranged from neutral to slightly alkaline. Soil analysis revealed relatively low levels of available nitrogen (115–193 kg ha^{-1}) and phosphorus (9–46 kg ha^{-1}), while the available potassium content was found to be moderate (126–456 kg ha^{-1}). Before initiating the experiment, representative soil samples were collected at a 0–10 cm depth using soil sampling post-hole Auger, and their chemical properties were assessed (Table 1). In addition, various physical properties of the soil were recorded for the experiment (Table 2).

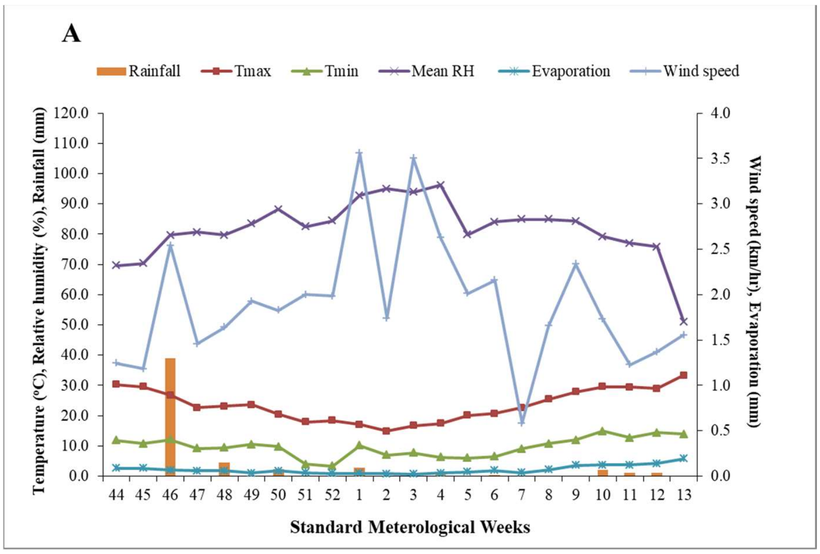


Figure 1. *Cont.*

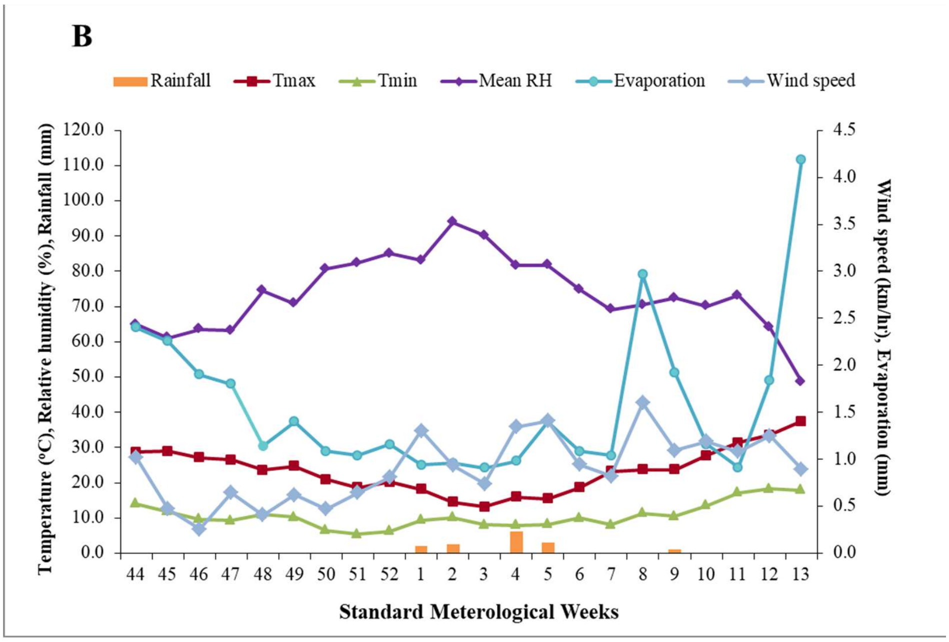


Figure 1. Weekly average maximum temperature (Tmax), minimum temperature (Tmin), rainfall (RF), Relative humidity (RH), and class A pan evaporation (EVP) observed during the investigation (November to April) in (**A**) 2020–21; and (**B**) 2021–22.

Table 1. Physico-chemical soil characteristics (0–15 cm depth) before beginning the experiment.

Parameter	Status/Value
Organic Carbon (Percentage)	0.79
Nitrogen (kg ha^{-1})	172.52
Phosphorus (kg ha^{-1})	22
Potassium (kg ha^{-1})	206.81
EC (dSm^{-1} at 25 °C)	0.27
pH	7.84

Table 2. Initial soil physical properties at the research site.

Soil Depth (cm)	Field Capacity (FC)	PWP	Saturation	Bulk Density (dS m^{-1})
0–15	0.32	0.10	0.40	1.71
15–30	0.30	0.09	0.38	1.72
30–45	0.28	0.07	0.39	1.75
45–60	0.24	0.05	0.37	1.80

2.3. Design of the Experimental Field and Its Management

In this study, a split-plot experimental design was employed to investigate the various treatment practices. The experiment was replicated five times, and it involved four different treatment practices: zero-tillage (ZT) with manual harvesting, Happy Seeder (HS) with combine harvester, Happy Seeder with Mulcher (MHS) and combine harvesting, and conventional tillage (CT). For each treatment, an area of 0.40 ha was used. The tillage practices were conducted in rice crops (PR114) after harvesting. The spacing of transplanted seedlings of rice was 20 × 15 cm. In both years, the rice was transplanted within the second fortnight of June. Detailed information on the tillage practices and residue management for each treatment can be found in Table 3.

Table 3. Details of experimental treatment.

Treatment Categories	Crop Sowing Methodology	Tillage Methods	Crop Residue Management
T1: Random puddled transplanted rice (RPTR)–Conventional till broadcast wheat (CT)	Rice: random transplanting Wheat: broadcasting	Rice: puddling (2 dry harrowing + 1 wet tillage) Wheat: CT (2 harrowing + rotavator)	Rice: Burnt in the field Wheat: one-third of residue retained on the soil surface, other threshed
T2: Random puddled transplanted rice (RPTR)–Zero tillage sown wheat (ZT)	Rice: random transplanting Wheat: Zero tillage	Rice: puddling (2 dry harrowing + 1 wet tillage) Wheat: zero tillage	Rice: manual take out of the field after harvesting Wheat: one-third of residue retained on the soil surface, other threshed
T3: Random puddled transplanted rice (RPTR)–Happy Seeder (HS)	Rice: random transplanting Wheat: Happy Seeder	Rice: puddling (2 dry harrowing + 1 wet tillage) Wheat: Happy Seeder	Rice: Fully retained on the field after combined harvesting. Wheat: one-third of residue retained on the soil surface, other threshed
T4: Random puddled transplanted rice (RPTR)–Happy Seeder with mulcher (MHS)	Rice: random transplanting Wheat: Happy Seeder	Rice: puddling (2 dry harrowing + 1 wet tillage) Wheat: Happy Seeder	Rice: harvesting with combine and mulched with mulcher. Wheat: one-third of residue retained on the soil surface, other threshed

The wheat variety DBW 187 was sown in the first week of November in both 2020 and 2021, with a row spacing of 45 cm and a seed rate of 100 kg ha^{-1}. The crop was shown under the irrigated situation. Fertilizers, including nitrogen (N), phosphorus (P), and potassium (K), were applied using urea (46% N), single superphosphate (16% P_2O_5), and muriate of potash (60% K_2O), respectively. Two-thirds of the N and the recommended amounts of P and K were applied as a basal dose during sowing. Depending on the soil moisture conditions, the remaining N was broadcasted between 25 and 40 days after sowing. The wheat crop was harvested in the first fortnight of April 2021 and 2022.

2.4. Yield and Yield Attributes

Measurements of wheat yield parameters, including spike length, grain weight per spike, and the number of grains per spike, were conducted on ten randomly selected plants from each 1.0 m^2 treatment plot. To determine the number of effective tillers, 1.0 m^2 plots were selected, and plants were randomly chosen from these plots. The count of effective tillers was recorded for each treatment. The crop was harvested after the boundary rows were taken out, and the total plot-wise grain and straw yields were measured at a moisture content of 12%.

2.5. Chemical Analysis of Soil Samples

Upon completion of the experimental season, soil samples were collected from a depth of 0–10 cm. A soil sampling tool-auger was used to collect soil samples from five randomly selected plots and then combine these samples into a composite sample.

In the laboratory, the samples were air-dried and sieved through a 2 mm filter to prepare them for chemical analysis. The organic carbon (OC) content of the samples was determined through dichromate oxidation and titration with ferrous ammonium sulfate [35]. The accessible nitrogen (N) concentration was determined using the Kjeldahl technique, followed by titration with diluted sulfuric acid [36]. Available phosphorus (P) content was determined using the ascorbic acid method with $NaHCO_3$, while available potassium (K) content was measured using the ammonium acetate method and a flame photometer [37,38]. For pH and electrical conductivity (EC) measurements, a suspension of 30.0 g of air-dried soil sample in 60 mL of double-distilled water was prepared in a covered

100 mL beaker and agitated for 1 h on a magnetic stirrer [39,40]. The EC was measured using a calibrated EC meter after allowing the suspension to settle for 10 min. The pH of the solution was measured by adding 10 mL of double-distilled water to the suspension and using a calibrated pH meter.

2.6. Statistical Analysis

The F-test was used to analyze the entire sample data received from the investigation, as described in [41]. The significance of the difference between treatment means was determined using least significant difference (LSD) values at $p = 0.05$. Tukey's HSD test was also performed. At a 5% level of significance, correlation analyses and treatment means were compared.

3. Results

3.1. Yield Attributes

A two-year experiment revealed substantial impacts of various tillage practices (Table 4). The yield and its attributes, such as the number of tillers per meter square area, grains per spike, spike weight, spike length, spike weight, and wheat grain test weight, all improved considerably in ZT, HS, and MHS compared to CT.

3.2. Yield Performance

The impact of different tillage practices on wheat grain yield and straw yield was found to be statistically significant ($p < 0.05$), as shown in Table 4. The MHS system exhibited the highest grain yield (56.8 q ha^{-1}) and straw yield (62.2 q ha^{-1}). Conservation practices led to a grain yield increase of 30.27% in MHS, 21.33% in ZT, and 18.11% in HS compared to the CT treatment. Similarly, straw yield increases in conservation practices relative to CT were observed in the MHS (27.98%), ZT (21.19%), and HS (15.84%) systems. CT practices resulted in the lowest grain and straw yields. The significant increase in production under the MHS system can be attributed to the improved moisture retention by crop residues, which minimized moisture stress in the plants.

3.3. Soil Chemical Properties

The implementation of different tillage practices combined with in situ rice residue management significantly ($p < 0.05$) influenced the chemical properties of the soil in the upper 0–10 cm soil layer, as presented in Table 5. Retaining crop residues on the soil surface resulted in a higher soil organic carbon (SOC) content than removing residues and burning them in the field. Our study observed that combining HS with rice crop residue retention increased SOC by 0.80 to 1.13 times compared to the CT treatment with rice crop residue burning. The adoption of conservation practices led to a substantial increase in SOC, with a rise of 105.45% in MHS, 74.54% in HS, and 56.36% in ZT relative to the CT treatment.

The soil pH and electrical conductivity (EC) did not differ significantly among the treatments after two years of study (Table 5). However, a slightly higher EC was observed in the conservation tillage treatments compared to the CT treatment (0.36 dS m^{-1}). The pH value for all treatments decreased slightly compared to the CT treatment.

Table 4. Effect of tillage and crop residue practices on yield attributes of wheat.

Treatment	Effective Tillers (Numbers)	Spike Length (cm)	Grain per Spike (Numbers)	Grain Weight per Spike (g)	Test Weight (g)	Grain Yield (q ha^{-1})	Straw Yield (q ha^{-1})	Production Efficiency (q ha^{-1} day^{-1})
CT	299.1 ± 3.51 ^{c}	8.5 ± 1.39 ^{b}	35.8 ± 3.45 ^{c}	1.31 ± 0.06 ^{b}	33.2 ± 1.68 ^{c}	43.6 ± 2.31 ^{c}	48.6 ± 2.61 ^{c}	0.28 ± 0.014 ^{d}
ZT	335.2 ± 3.45 ^{b}	10.4 ± 0.93 ^{a}	42.8 ± 1.87 ^{b}	1.57 ± 0.04 ^{a}	37.2 ± 0.75 ^{b}	52.9 ± 0.83 ^{b}	58.9 ± 2.00 ^{b}	0.33 ± 0.006 ^{b}
HS	332.3 ± 2.62 ^{b}	9.9 ± 0.67 ^{ab}	42.9 ± 3.14 ^{b}	1.53 ± 0.06 ^{a}	37.0 ± 1.06 ^{b}	51.5 ± 1.81 ^{b}	56.3 ± 0.65 ^{b}	0.31 ± 0.015 ^{c}
Happy MHS	347.5 ± 4.76 ^{a}	10.9 ± 1.42 ^{a}	47.0 ± 1.15 ^{a}	1.56 ± 0.06 ^{a}	40.9 ± 2.98 ^{a}	56.8 ± 2.59 ^{a}	62.2 ± 3.18 ^{a}	0.35 ± 0.019 ^{a}
Year								
2020–21	327.8 ± 17.2 ^{a}	9.75 ± 1.08 ^{a}	41.65 ± 3.4 ^{a}	1.47 ± 0.09 ^{a}	36.6 ± 2.30 ^{a}	50.8 ± 4.60 ^{a}	57.1 ± 5.16 ^{a}	0.320 ± 0.02 ^{a}
2021–22	329.2 ± 20.0 ^{a}	10.15 ± 1.71 ^{a}	42.60 ± 5.8 ^{a}	1.51 ± 0.14 ^{a}	37.5 ± 4.03 ^{a}	51.6 ± 5.92 ^{a}	55.9 ± 5.96 ^{a}	0.324 ± 0.03 ^{a}
ANOVA								
Treatment	NS	***	NS	NS	NS	NS	NS	NS
Year	NS	NS	NS	NS	NS	NS	NS	NS
Treatment× Year	NS	NS	NS	NS	NS	NS	NS	NS

NS—Non-significant; *** shows significance at *p*-value 0.001; letters a, b, c, and d denote the significance among treatments.

Table 5. Effect of tillage and crop residue practices on soil chemical properties.

Treatment	Soil Organic Carbon (%)	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})	pH	EC (dS m^{-1})
CT	0.55 ± 0.05 ^{d}	134.47 ± 4.33 ^{d}	19.15 ± 1.47 ^{c}	153.31 ± 36.03 ^{c}	8.17 ± 0.12 ^{a}	0.36 ± 0.10 ^{b}
ZT	0.86 ± 0.02 ^{c}	193.95 ± 6.62 ^{c}	33.69 ± 2.66 ^{b}	272.30 14.50 ^{b}	7.77 ± 0.12 ^{c}	0.54 ± 0.05 ^{a}
HS	0.96 ± 0.04 ^{b}	205.61 ± 6.03 ^{b}	36.53 ± 1.70 ^{ab}	284.50 ± 15.16 ^{ab}	7.76 ± 0.15 ^{b}	0.52 ± 0.07 ^{a}
MHS	1.13 ± 0.07 ^{a}	214.42 ± 7.23 ^{a}	38.73 ± 3.88^{a}	302.76 ± 20.23 ^{a}	7.49 ± 0.25 ^{b}	0.54 ± 0.06 ^{a}
Year						
2020–21	0.86 ± 0.17 ^{a}	184.39 ± 30.2 ^{a}	30.53 ± 6.34 ^{a}	253.0 ± 42.14 ^{a}	7.80 ± 0.28 ^{a}	0.50 ± 0.09 ^{a}
2021–22	0.89 ± 0.26 ^{a}	189.83 ± 34.6 ^{a}	33.51 ± 9.54 ^{a}	253.43 ± 80.57 ^{a}	7.80 ± 0.31 ^{a}	0.48 ± 0.12 ^{a}

NS—Non-significant; letters a, b, c, and d denote the significance among treatments.

3.4. Correlation Matrix and Principal Components Analysis of Different Soil Chemical Attributes

The correlation matrix revealed the interrelationships between grain yield and various soil chemical attributes during the years 2020–21 and 2021–22 and the combined data (Figure 2). Grain yield demonstrated a strong positive correlation with soil chemical properties. It exhibited a strong positive correlation with OC (r = 0.907, 0.886, 0.920), N (r = 0.875, 0.853, 0.892), P (r = 0.865, 0.794, 0.911), K (r = 0.878, 0.874, 0.904), and EC (r = 0.599, 0.643, 0.583) for the combined data, 2020–21, and 2021–22, respectively. Furthermore, OC displayed a strong positive correlation with other soil chemical properties. It exhibited a strong positive correlation with N (r = 0.945, 0.960, 0.948), P (r = 0.950, 0.928, 0.965), K (r = 0.926, 0.957, 0.927), and EC (r = 0.646, 0.684, 0.644) for the combined data, 2020–21, and 2021–22, respectively. P, K, and EC attributes also demonstrated a strong positive correlation with N. Conversely, all attributes including grain yield (r = −0.781, −0.657, −0.879), OC (r = −0.818, −0.762, −0.865), N (r = −0.776, −0.688, −0.853), P (r = −0.789, −0.685, −0.893), K (r = −0.791, −0.747, −0.853), and EC (r = −0.655, −0.704, −0.623) exhibited a negative correlation with pH for the combined data, 2020–21, and 2021–22 years, respectively. Principal component analysis (PCA) was conducted with all six variables, which accounted for 92.7% of the total dataset inertia. This indicates that the PCA plane explains 92.7% of the variability within the dataset.

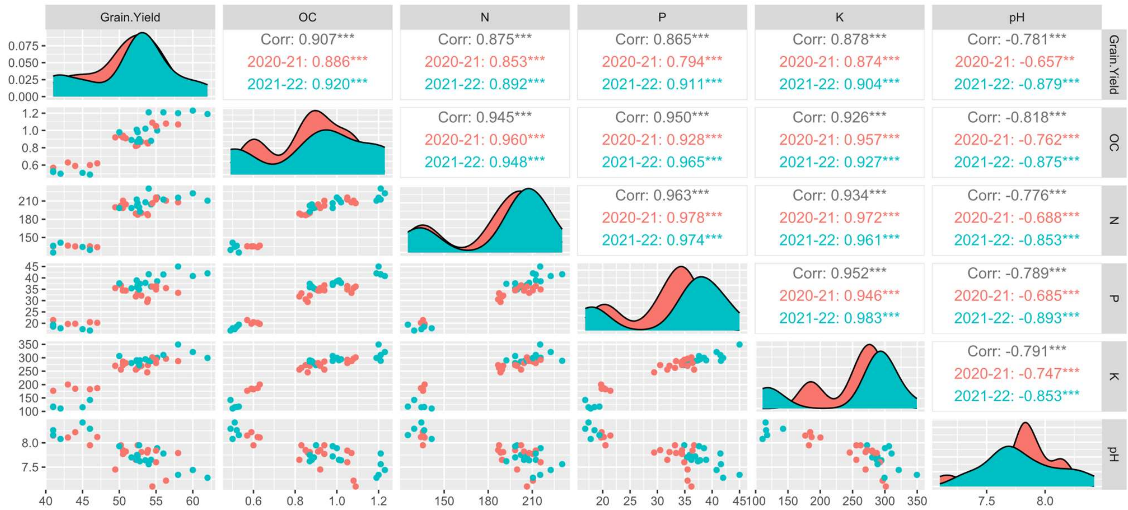
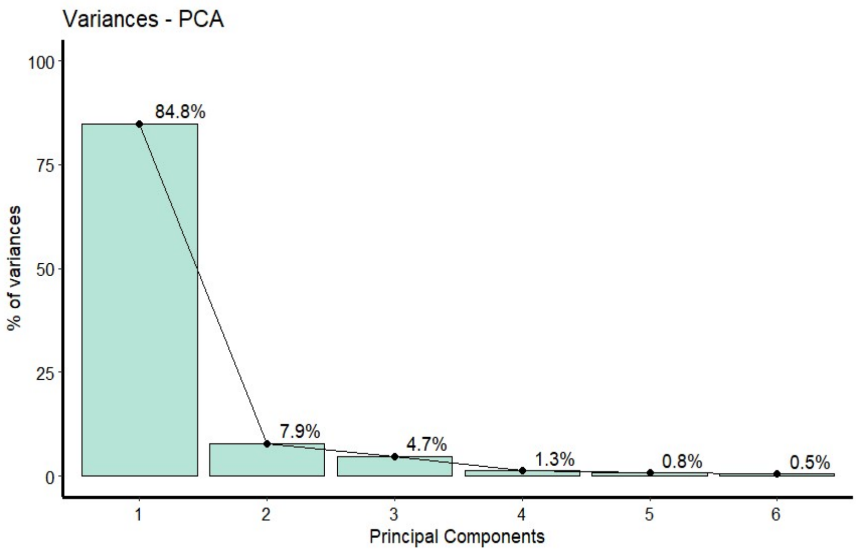


Figure 2. Pearson correlation matrix of different soil chemical attributes. ** and *** shows significance at *p*-value 0.01 and 0.001, respectively.

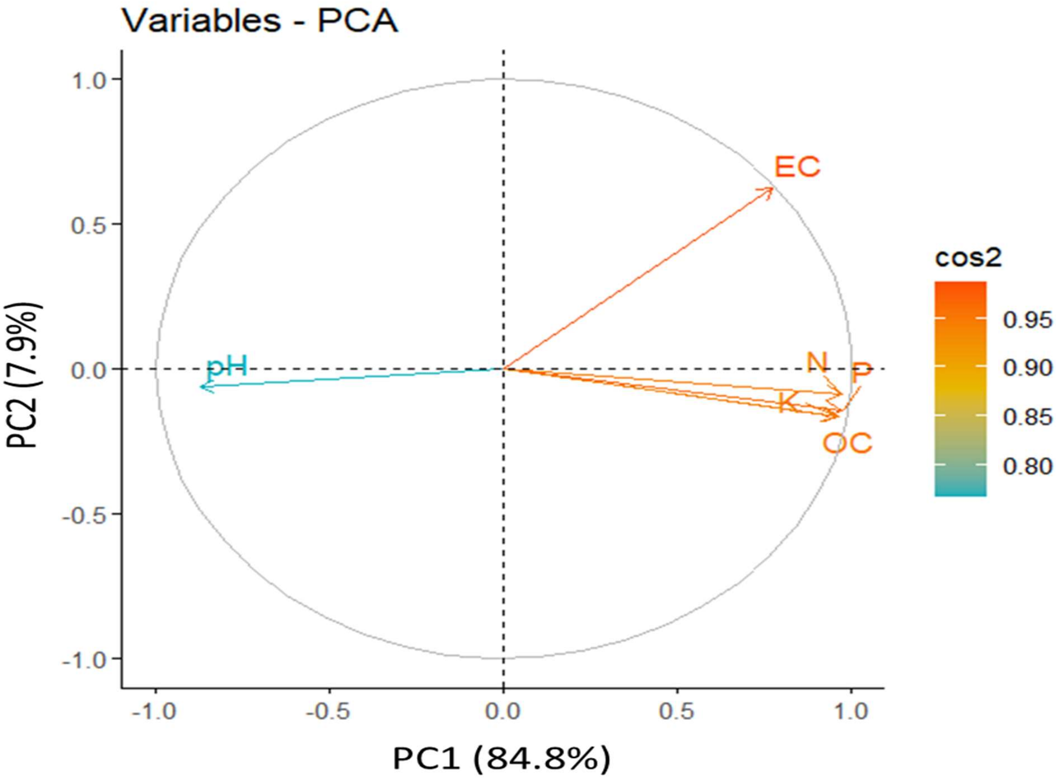
The first principal component describes 84.8% of the total variability, the second explains 7.9%, and the third represents 4.7% (Figure 3a,b). The quality of the representation of variables on the factor map is identified with cos2 values. A high cos2 value indicates a good indication of the variables on the principal component. All the positively correlated variables (OC, N, P, K, and EC) flock together and positively correlate with Dim1. In contrast, the pH negatively correlates with Dim1 while contributing more to Dim2.

3.5. Correlation Matrix Analysis of Wheat Grain Yield with Different Yield Attributes

The correlation matrix showed the interrelationship between grain yield and its attributes during 2020–21, 2021–22, and combined (Figure 4). The grain yield strongly correlates with 'different yield attributes'. The grain yield (GY) records a strong positive correlation with effective tiller (ET) (r = 0.931), spike length (SL) (r = 0.596), grain per spike (G/S) (r = 0.863), grain weight per spike (GW/S) (r = 0.823), test weight (TW) (r = 0.838), straw yield (SY) (r = 0.947), and days to maturity (DTM) (r = 0.501) on a combined basis. Moreover, effective tiller strongly correlates with other 'yield attributes'. The effective tiller records a strong positive correlation with spike length (SL) (r = 0.634), grain per spike (r = 0.865), grain weight per spike (GW/S) (r = 0.848), and test weight (r = 0.841) on a combined basis, respectively. Grain per spike and grain weight per spike, test weight, and maturity days attribute are also strongly correlated with spike length.



(**a**)



(**b**)

Figure 3. (**a**) Decomposition of the total inertia shown in the scree plot. The first factor is the major one responsible for 84.8% of the data variability, while the second factor contributes 7.9% of the variability; cumulatively, these two factors contribute 92.7% of the total variability. (**b**) The score bi-plot of the first principal component (PC1) vs. the second principal component (PC2) depicts the means grouped by combined two years. Abbreviations for eigenvectors: OC (organic carbon %), N (nitrogen kg ha^{-1}), P (phosphorus kg ha^{-1}), K (potassium kg ha^{-1}), pH, and EC (electrical conductivity dS m^{-1}).

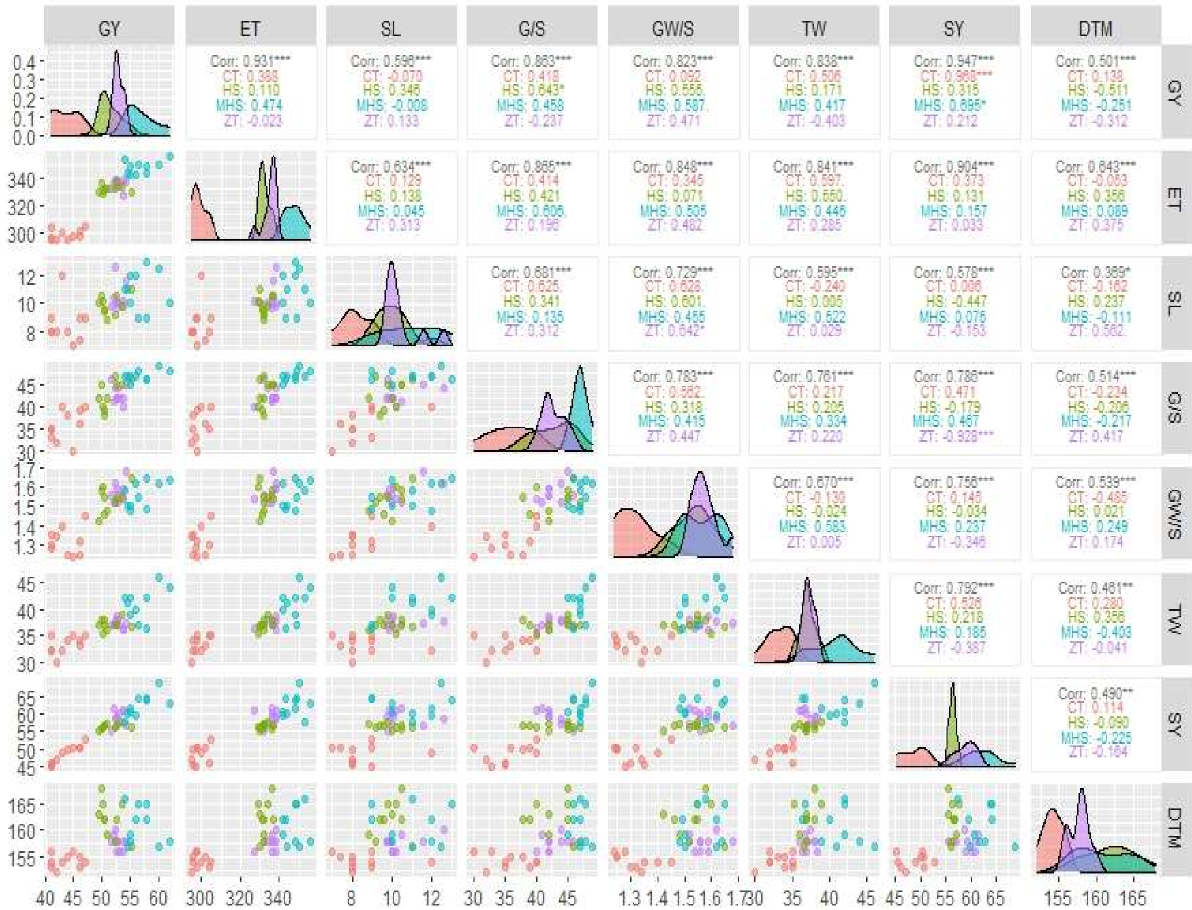


Figure 4. Pearson correlation matrix of yield and different yield attributes. *, ** and *** shows significance at p-value 0.05, 0.01 and 0.001, respectively.

3.6. Economic Analysis

The average cost of cultivation was found at a minimum in ZT, where it was INR 30,976 per hectare, followed by MHS, where it was INR 31,242 per hectare during 2020–21. The net return was found to be maximum in MHS, where it was INR 102,666 ha^{-1} during 2021–22, followed by INR 96,127 ha^{-1} in MHS in 2020–21. The maximum net gain was observed in MHS consecutively during 2020–21 and 2021–22 with a B:C ratio of 1:4.07 and 1:4.14, respectively.

4. Discussion

4.1. Yield Performance

The MHS treatment in the experiment exhibited a significant increase in grain yield (56.8 q ha^{-1}) and straw yield (62.2 q ha^{-1}) compared to the CT treatment. Using a mulcher for rice residue, mulching played a crucial role in achieving higher yields. The superiority of the MHS treatment can be attributed to its ability to maintain optimal moisture levels continuously, provide essential nutrients, better root development and improved nutrient uptake and preserve the soil's chemical properties. The Happy Seeder also reduces the cost of field preparation compared with conventional methods and produces similar or improved mean wheat yields. The Happy Seeder mainly increases wheat yields due to the residue mulching effect [42]. Moreover, the test weight of grains in the MHS treatment surpassed that of the CT treatment, contributing to the maximum grain and straw yield. Additionally, the MHS treatment exhibited more tillers per plant (347 vs. 299) and a greater number of grains per spike (47 vs. 35.8), directly contributing to the overall grain yield and establishing its superiority over the CT treatment. Furthermore, the improved performance of the MHS and HS treatments can be attributed to enhanced nutrient availability from preceding crops and adequate soil moisture under retained residues [42]. Maximum plant height, effective tillers, ear length, grains per ear, and test weight observed with Happy Seeder were observed by Singh et al. [43]. Also, these findings align with similar studies conducted by various researchers, further confirming the favorable response of wheat grain yield to the MHS practice [44–46].

4.2. Soil Chemical Properties

Sustainable tillage practices hold the key to unlocking the full potential and properties of soil microflora. Analysis of soil chemical properties (Table 5) revealed that the MHS treatment exhibited the highest organic carbon (OC) content compared to other tillage practices. Additionally, nutrient parameters such as N, P, and K were also higher in the MHS treatment. This improved nutrient status in MHS can be directly attributed to the increased number of effective tillers, contributing to higher grain yields. Thus, the experimental trials demonstrated that retaining one-third of rice residue on the soil surface and implementing a happy seeder and mulcher facilitated OC sequestration. Under an intensive rice–wheat cropping system, the use of ZT in conjunction with crop residue retention in the soil increased rice–wheat system productivity with favorable nutrient balance and improved soil quality in terms of decreased bulk density, soil pH, enhanced available phosphorus, exchangeable potassium, and soil organic matter. Similar to how adding crop residues to the soil improved aggregate stability, doing so also improved soil quality in terms of increased soil organic carbon, hydraulic conductivity, infiltration rate, water holding and cation exchange capacity, and enzymatic activities [47]. Consistent with their findings, previous studies [48,49] concluded that combining direct-seeded rice (DSR) and zero-till wheat with crop residue retention is an effective management practice for enhancing sequestration, resulting in a 33.6% increase in total soil organic carbon (SOC) compared to conventional tillage. Zero tillage (ZT), with or without crop residues, enhances SOC accumulation by minimizing soil disturbance, promoting soil aggregation, and reducing the disruptive effects of tillage on SOC loss through increased soil microbial respiration [50,51]. The availability of nutrients varied significantly ($p < 0.05$) among different treatments (Table 5). The highest nitrogen availability in the 0–10 cm soil depth was observed in the mulcher and Happy Seeder practice (T4) with a value of 214.42 kg ha^{-1}, closely followed by ZT (T2) with 193.95 kg ha^{-1} and Happy Seeder (T3) with 205.61 kg ha^{-1}. Total P content was higher in the MHS treatment compared to the CT treatment (an increase of 102.24%). Similarly, K content was higher in both MHS and HS treatments compared to CT. The slow decomposition of crop residues under conservation practices, which limits exposure to soil microbiota, likely contributed to higher SOC and total soil nitrogen in the uppermost layer [52–57].

Furthermore, under MHS tillage and residue management practices, there was a slight increase in EC, although MHS was statistically similar to HS and ZT. Regarding soil pH, all the rice residue management practices showed a decrease compared to CT. Supporting this finding, Cao et al. [58] reported a significant reduction in soil pH from 7.7 to 7.4 and 7.2 with straw coverage in no-till and rotary tillage, respectively. Similar results have been reported by various researchers [59–61].

4.3. Economic Analysis

Minimum tillage practices have a highly positive impact on the economic aspects of production, playing a crucial role in reducing cultivation costs and minimizing input requirements. The economic data presented in Table 6 demonstrated that zero tillage (ZT) exhibited the lowest average cultivation cost (INR 30,976), closely followed by the mulching Happy Seeder (MHS) practice (INR 31,242) during the 2020–21 season. Moreover, the maximum benefit-cost ratio was observed in MHS tillage practices (4.14) in the 2021–22 season, with a slightly lower ratio of 4.07 in the 2020–21 seasons. This might be due to the increased costs of field preparation operations under conventional methods associated with higher fuel consumption, more labor usage, and repeated use of herbicides application for weed management. These results strongly support adopting in situ paddy crop residue management through different tillage practices, as they offer reduced cultivation costs and minimal input requirements. At the same time, Happy Seeder saves time and fuel, particularly when wheat sowing is put off until after rice harvest, particularly of the basmati variety [62]. Our findings are consistent with previous studies by Singh et al. [63] and Bons and Singh [64], where they reported that among four prevalent strategies—complete burning (CB), partial burning (PB), complete incorporation (CI), and complete removal (CR). The CI practice proved to be the most cost-effective, yielding the highest returns [65].

Table 6. Economics for the treatment plan.

	CT		ZT		HS		MHS	
	2020–21	**2021–22**	**2020–21**	**2021–22**	**2020–21**	**2021–22**	**2020–21**	**2021–22**
The average cost of cultivation (INR ha^{-1})	32,602	35,093	30,976	33,055	31,575	33,795	31,242	32,690
The sale price of grain (INR ha^{-1})	1950	2000	1950	2000	1950	2000	1950	2000
The sale price of straw (INR ha^{-1})	300	310	300	310	300	310	300	310
Gross return (INR ha^{-1})	101,079	100,781	121,669	123,322	114,996	122,873	127,369	135,356
Net return (INR ha^{-1})	68,477	65,688	90,693	90,267	83,421	89,078	96,127	102,666
BC ratio	1:3.10	1:2.87	1:3.92	1:3.73	1:3.64	1:3.63	1:4.07	1:4.14
Economic efficiency (INR ha^{-1} day^{-1})	445.2	424.9	576.2	571.3	514.3	549.9	600.1	635.3

5. Conclusions

This study provides compelling evidence for the significant impact of different tillage practices on soil properties and crop yield attributes. Among the various technological interventions, the adoption of conservation tillage practices, specifically utilizing a Happy Seeder after mulching with in situ paddy crop residue retention, emerged as the superior crop establishment practice across all four treatments in terms of wheat productivity and nutrient enrichment when compared with conventional tillage (CT) practices. The order of wheat grain and straw yield, from highest to lowest, was observed as MHS (mulcher with Happy Seeder) > ZT (zero tillage) > HS (Happy Seeder) > CT. Traditionally, CT practices exhibited lower soil organic carbon content (0.55) and higher pH levels (8.17). In contrast, conservation tillage practices (MHS and HS) demonstrated higher soil organic carbon (1.13 and 0.96), nitrogen (214.42 and 205.61), phosphorus (38.73 and 36.53), and potassium (302.76 and 284.50), along with lower pH levels (7.49 and 7.76). Notably, in sustainable irrigation cropping systems, ZTR (zero tillage with residue retention) mitigated the impact of moisture stress on wheat crops. Minimum tillage practices significantly influenced crop yields and the associated residue inputs, ultimately contributing to improved soil quality and fertility. The strong correlation observed between selected soil parameters and crop production highlights the positive relationship between residue application, reduced tillage, and enhanced system yields. Consequently, this study strongly suggests that adopting minimum tillage practices combined with in situ crop residue management can improve soil structure and fertility status within the conventional rice–wheat cropping system.

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