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Optimizing Maize Productivity and Soil Fertility: Insights from Tillage, Nitrogen Management, and Hydrochar Applications

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Abstract: Enhancing soil fertility and maize productivity is crucial for sustainable agriculture. This study aimed to evaluate the effects of tillage practices, nitrogen management strategies, and acidified hydrochar on soil fertility and maize productivity. The experiment used a randomized complete block design with split-split plot arrangement and four replications. Main plots received shallow tillage and deep tillage. Subplots were treated with nitrogen (120 kg ha^{-1}) from farmyard manure (FYM) and urea, including control, 33% FYM + 67% urea (M_U), and 80% FYM + 20% urea (M_F). Acidified hydrochar treatments H_0 (no hydrochar) and H_1 (with hydrochar, 2 t ha^{-1}) were applied to sub-sub plots. Deep tillage significantly increased plant height, biological yield, grain yield, ear length, grains ear^{-1}, thousand-grain weight, and nitrogen content compared to shallow tillage. M_U and M_F improved growth parameters and yield over the control. Hydrochar effects varied; H_1 enhanced yield components and soil properties such as soil organic matter and nitrogen availability compared to H_0. Canonical discriminant analysis linked deep tillage and M_U/M_F nitrogen management with improved yield and soil characteristics. In conclusion, deep tillage combined with integrated nitrogen management enhances maize productivity and soil properties. These findings highlight the importance of selecting appropriate tillage and nitrogen strategies for sustainable maize production along with hydrochar addition. These insights guide policymakers, agronomists, and agricultural extension services in adopting evidence-based strategies for sustainable agriculture, enhancing food production, and mitigating environmental impacts. The implication of this study suggests to undertake long-term application of hydrochar for further clarification and validation.

Keywords: agricultural sustainability; organic amendments; soil health; crop yield; soil fertility; canonical discriminant analysis

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1. Introduction

Maize (*Zea mays* L.), a member of the Poaceae family, is a globally significant crop cultivated across various regions, following the ranks of rice and wheat [1]. It serves as a primary source of nutrition for both humans and livestock, as well as a valuable resource for various industrial applications. With its high nutritional value, comprising 10% protein, 4.8% oil, 3% sugar, 5.8% fiber, 72% starch, and 1.7% ash, maize holds a pivotal position in the agricultural landscape [2]. In Pakistan, maize stands as the second most important crop after wheat, contributing significantly to both national and regional agricultural economies, particularly in Khyber Pakhtunkhwa province [3]. Despite its importance, various factors such as geographical conditions, soil quality, climatic variations, pest and disease pressures, seasonal fluctuations, and irrigation practices have posed challenges to maize productivity [4]. Among these factors, soil management practices, particularly tillage, emerge as crucial determinants influencing soil structure and nutrient availability, consequently affecting crop yields.

Tillage operations represent one of the fundamental methods for mitigating soil compaction and enhancing soil tilth and physical properties, thereby facilitating improved nutrient utilization and higher crop yields [5,6]. Techniques such as deep plowing have been advocated to alleviate subsurface compaction, thereby promoting enhanced root growth and nutrient uptake; additionally, tillage practices have been associated with increased carbon sequestration, soil structure enhancement, and overall yield improvement [6,7].

In the realm of sustainable agriculture, organic farming practices play a pivotal role in preserving soil fertility and physical integrity. Organic agriculture prioritizes ecosystem management and natural processes, emphasizing the importance of maintaining soil health for optimal agricultural productivity [2]. Incorporating organic manures alongside inorganic fertilizers has been shown to enhance soil organic matter content, soil structure, water-holding capacity, nutrient cycling, and biological activity, thereby sustaining soil fertility and improving crop performance [8,9]. However, over-reliance on chemical fertilizers has been linked to soil quality degradation over time.

Innovative approaches such as hydrothermal carbonization (HTC), sometimes called hydrochars, offer promising avenues for improving soil fertility and enhancing crop productivity [10,11]. Hydrothermal carbonization, characterized by its low cost and efficient conversion of wet biomass into hydrochars, presents an alternative to traditional biochar production methods [12]. Although hydrochars exhibit similar properties to biochar, their production process and characteristics differ, offering unique opportunities for soil carbon sequestration and the improvement of soil quality [13,14].

Given the challenges and opportunities in maize production, this study aims to investigate the effectiveness of integrating hydrochar and farmyard manure with various tillage practices to enhance soil fertility and maize productivity. Therefore, it was hypothesized that the integration of hydrochar and farmyard manure with different tillage practices would lead to enhanced soil fertility, improved soil structure, and increased maize productivity compared to conventional tillage methods without organic amendments. The objectives include the following: 1. Assessing the impact of different tillage practices on soil physico-chemical properties, and nutrient availability. 2. Evaluating the individual and combined effects of hydrochar and farmyard manure applications on soil fertility indicators and maize growth parameters. 3. Determining the optimal combination of tillage practices and organic amendments for improving soil quality and maize yield.

2. Materials and Methods

2.1. Experimental Site and Soil Characteristics

The experiment was performed at the Agronomy Research Farm, the University of Agriculture Peshawar, Pakistan (34°01′14.2″ N and 71°28′52.6″ E), during Summer 2022. This region lies 340 m above sea level and is classified as a warm-temperate zone. The average annual temperature is ~22 °C, with the highest average in June at ~33 °C and the lowest in January at ~10 °C. The average annual precipitation is 640 mm, with the least amount of rainfall occurring in November [15]. Meteorological data specific to the experimental site are detailed in Figure 1.

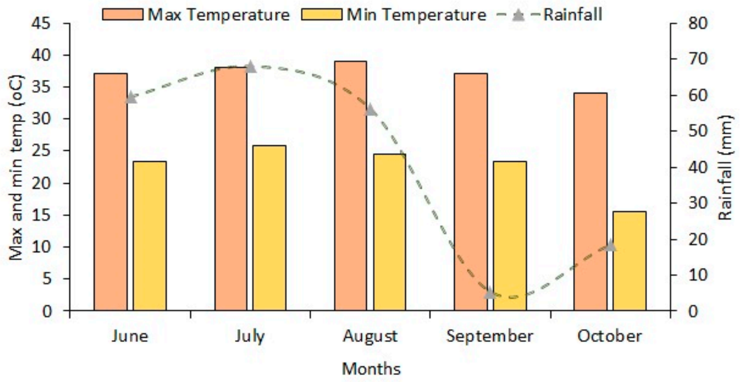

Figure 1. Rainfall (mm), temperature maximum (°C) and minimum (°C) at the experimental site during the growing season of maize.

The soil sample was collected from the Ap horizon with the help of soil auger at 0–30 cm depth before the start of experiment in 2022 with the following results: pH = 8.3 [16], salinity as electrical conductivity (EC) = 0.26 dS m^{-1} [16], SOM = 9.7 g kg^{-1} [17], total nitrogen (N) = 4.8 g kg^{-1}, and plant-available P and potassium (K) were 4.7 and 130 mg kg^{-1}, respectively, as determined through extraction with ammonium bicarbonate-diethylenetriamine pentaacetate (AB-DTPA) [18]. The soil type was Calcaric Luvisols (FL ca), according to the World Reference Base (WRB) system of soil taxonomy; soil had a silt loam texture (sand 19.4%, silt 71.6%, and clay 8.96%). The applied hydrochar has 12 g kg^{-1} N, 6 g kg^{-1} P, and 43 g kg^{-1} organic matter having 5.8 pH. Similarly soil post-harvest total nitrogen and organic matter content were also determined, while soil mineral nitrogen content was determined according to the procedure of Keneey and Nelson [19].

2.2. Treatments and Experimental Setup

The research consisted of three experimental factors: (i) two tillage practices shallow tillage (0–15 cm depth) (S_T) and deep tillage (15–30 cm depth) (D_T), (ii) three levels of nitrogen management, control (M_C), 33% FYM + 67% Urea (M_U), and 80% FYM + 20% Urea (M_F), and (iii) two levels of hydrochar, control (H_0) (no hydrochar) and acidified hydrochar (H_1) at 2 t ha^{-1}. Randomized complete block design (RCBD) with a split-plot layout having four replications was used; different tillage methods were assigned to the main plots, with nitrogen (N) treatments applied to the subplots, and varying levels of acidified hydrochar allocated to the sub-subplots. Tillage operations involved the use of a field cultivator (0–15 cm deep) and chisel plough (0–30 cm deep). To address the issue of plow floor, a subsoiler was often used after two years to break up the hard pan, thereby alleviating soil compaction and promoting better root development and nutrients uptake. The nitrogen concentrations in farmyard manure (FYM) were computed, and the specified rates were determined on a dry basis, with the remaining nitrogen supplied by urea (46%). However, an additional 23 kg N ha^{-1} derived from hydrochar was not taken into account. According to the nitrogen content assessment, the calculated quantity of farmyard manure was applied to the plots 20 days before sowing, along with acidified hydrochar (2 t ha^{-1}). The nitrogen fertilization treatments were applied to the field and were incorporated using rotavator having depth of 10 cm in all plots whether tilled with conventional or deep tillage system for uniform inversion and mixing with soil. The farmyard manure was used as N fertilizer source having a contribution of 11 g kg^{-1} N, 3 g kg^{-1} P, and 4 g kg^{-1}. The manure was incorporated using rotavator having a depth of 10 cm in all plots whether tilled with field cultivator for conventional tillage or chisel plough for deep tillage for uniformly mixing with soil. Half of the nitrogen was applied during seedbed preparation, with the remaining urea applied during the second irrigation. Each plot measured 4.2 m × 5 m, with rows 5 m long and a spacing of 70 cm between rows, accommodating 6 rows per subplot. The maize variety Jalal was planted at a seeding rate of 30 kg ha^{-1}. The experimental plots were irrigated using water sourced from the Kabul River, ensuring a reliable and natural supply of water. Irrigation for maize was conducted once a week as per need basis, with a total of 8 irrigations, with each application delivering approximately 40 mm of water, thus with a total of 320 mm of water. Standard agronomic practices, including hoeing and weeding, were consistently applied across all treatments.

2.3. Procedure for Hydrochar Preparation

Hydrochar was produced from Canola residues in the laboratory using an autoclave. The residues were chopped into 2–3 cm pieces, then milled into smaller particles. The conversion process was carried out at a temperature range of 125 °C for 30 min, with a water ratio of 1:10, using an autoclave reactor under a pressure of 2 MPa. Following the conversion process, the hydrochar was chemically activated using 2.0 N HCl (100 mL per kg of fresh hydrochar) as a catalyst. The procedure described by Costa et al. [20] was followed for the preparation of the hydrochar.

2.4. Field History

The field on which this particular experiment was carried out has a long history of the same conventional and deep tillage. Since 2016, the same experimental layout has been used to till the field with cultivator for conventional and chisel plough with deep tillage having 15 and 30 cm depths, respectively. This includes 120 kg N ha^{-1} sourced from urea (either 20% or 67%) and farmyard manure (33% and 80%), alongside a control. In 2016, the physico-chemical properties of the soil were as follows: soil total nitrogen (4 g kg^{-1}), soil mineral nitrogen (21 mg kg^{-1} soil), soil organic matter (7.9 g kg^{-1}), soil pH (8.1), and soil bulk density (1.23 g cm^{-3}). In this study, a third factor, acidified hydrochar, was introduced as a sub-subplot factor to evaluate its impact on soil fertility and maize productivity.

2.5. Data Collection

Days to emergence, silking, tasseling, and physiological maturity were calculated by counting the days from the date of sowing to the date when emergence, silks, tassel production, and complete loss of glumes green color were observed on 80% of plants in each plot. Emergence per unit area, number of leaves per plant, plant height, and leaf area per plant were determined at the milk stage, BBCH 75 (11 June 2022). Maize yield and related trails were also recorded at final harvest, BBCH 89 (24 July 2022). Ear weight was calculated by weighing the cob without the husk on a weight balance and measuring the ear length, and 10 plants from each subplot were randomly selected and then averaged. To count the number of grains per ear, five cobs were randomly selected from each subplot, the grains were counted separately, and their average was calculated. The number of seedlings in each plot was calculated with a meter rod at three different places and the emergence m^{-2} was calculated using the formula below.

$$\text{Emergence m}^{-2} = \frac{\text{Total number of seedlings emerged}}{\text{R} - \text{R distance (m)} \times \text{Row length (m)} \times \text{No of Row (n)}} \tag{1}$$

Thousand-grain weight (g) was recorded using an electronic balance and counting a thousand grains from each subplot at random. The biological yield was measured by harvesting four central rows in each subplot and calculated as in Equation (2) [21]. The harvested material was sun dried and weighed.

$$\text{Biological yield (t ha}^{-1}) = \frac{\text{Total plant weight in 4 central rows}}{\text{R} - \text{R distance (m)} \times \text{ No. of rows } \times \text{Row length (m)}} \times 10 \tag{2}$$

Grain yield and harvest index were calculated using Equation (3) and Equation (4), respectively, by following the method of [21].

$$\text{Grain yield (t ha}^{-1}) = \frac{\text{Grain yield of four rows}}{\text{R} - \text{R (m)} \times \text{No. of rows } \times \text{row length (m)}} \times 10 \tag{3}$$

$$\text{Harvest index } (\%) = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100 \quad (4)$$

2.5.1. Plant Pigments

Plant pigments in the leaves were measured using a spectrophotometer. Fresh flag leaf material (200 mg) from each sub-subplot was submerged in 5 mL of 80% acetone solution (v/v) and stored at 4 °C in the dark for 48 h to extract chlorophyll (Chl a and Chl b), total chlorophyll, and carotenoids. The extracts were then spectrophotometrically analyzed at absorbance wavelengths of 663.2 nm, 646.8 nm, and 470 nm to determine pigment concentrations (Chl a, Chl b, and carotenoids, respectively). The concentrations were estimated using Lichtenthaler's formula [22] and expressed in mg per mL of fresh leaf weight.

$$\text{Chl a } (\mu\text{g/mL}) = 12.25\text{A}663.2 - 2.79\text{A}646.8 \quad (5)$$

$$\text{Chl b } (\mu\text{g/mL}) = 21.50\text{A}646.8 - 5.10\text{A}663.2 \quad (6)$$

$$\text{TChl } (\mu\text{g/mL}) = 7.15\text{A}663.2 + 18.71\text{A}646.8 \quad (7)$$

$$\text{Total carotenoids } (\mu\text{g/mL}) = 1000\text{A}470 - 1.82\text{Chl a } - 85.02\text{Chl b} \quad (8)$$

where A is the measured absorbance following spectrophotometer of each sample at 663.2, 646.8, 470 wavelengths.

2.5.2. Grains and Stover Nitrogen Content

To quantify the nitrogen content in maize grains and stover, samples from each sub-subplot were dried and ground into a powder (2 mm particle size) using a tissue grinder. For each sample, 3 mL of concentrated H_2SO_4 and 1.23 g of digestion mixture (K_2SO_4:$CuSO_4$:Selenium = 200:20:1.0) were used to digest 0.2 g of powdered sample material. After cooling, the extract was transferred to a 100 mL volumetric flask and filtered before further testing. An aliquot (20 mL) of the extract was distilled using a Kjeldahl ammonium distillation unit, where nitrogen was collected as ammonia. The collected ammonia was titrated against 0.005 N HCl in a receiver containing 4% boric acid solution and a mixed indicator (Bromocresol green and methyl red), following the procedure outlined by Jackson [23].

2.5.3. Nitrogen Use Efficiency and Nitrogen Uptake

Nitrogen use efficiency (NUE) was calculated by dividing grain yield by the N rate applied as outlined by [24], while the nitrogen uptake was determined according to the following formula of Dawar et al. [25]:

$$\text{Nitrogen uptake } (\text{kg ha}^{-1}) = \text{Plant N concentration } \times \text{ Yield } (\text{kg ha}^{-1}) \div 100 \quad (9)$$

2.5.4. Soil Parameters

Soil properties including soil organic matter, soil total, and soil mineral nitrogen were determined at harvesting stage of the maize crop as per recommended procedures. The soil organic matter was measured using modified method of Walkley–Black [26], soil total nitrogen with Kjeldhal method [27], and soil mineral nitrogen by steam distillation method [19].

2.6. Statistical Analysis

The collected data were statistically analyzed with the analysis of variance (ANOVA) as appropriate for split-plot RCBD using statistical package Statistix 8.1 (Statistix 8.1, Tallahassee, FL, USA). If the F values were significant, the means were compared with the LSD test at probability levels of 5%. The Canonical Discriminant Analysis (CDA) was conducted using R software utilizing MASS package both for soil and plant parameters as predictor variables, and the assessments were made as per Wilks' Lambda that indicate a test for the significance of the discriminant functions. Lower values indicate better discrimination between groups.

3. Results

3.1. Phenological and Growth Parameters

Table 1 presents the main effects of tillage practices, nitrogen management, and hydrochar application on the growth stages of maize. For tillage practices, both shallow tillage (S_T) and deep tillage (D_T) resulted in similar days to emergence (DtoE), days to tasseling (DtoT), and days to silking (DtoS) with no significant difference between them. However, shallow tillage (S_T) showed a significantly shorter time to physiological maturity (DtoPM) (93.4 ± 0.40 days) compared to D_T (94.3 ± 0.36 days). The application of nitrogen had significantly affected phenological observation excluding DtoE (Table 1). Maize plants took more days to tasseling (DtoT), silking (DtoS), and physiological maturity (DtoPM) when treated with M_U (53.9 ± 0.35, 64.3 ± 0.35, and 95.0 ± 0.34 days, respectively) and M_F (53.4 ± 0.30, 63.4 ± 0.20, and 94.3 ± 0.40 days, respectively) compared to M_C (control). The use of acidified hydrochar (H_1) resulted in an increase in days to emergence (DtoE) (7.8 ± 0.15 days) while causing a decrease in days to tasseling (DtoT) (53.5 (±0.35) days), silking (DtoS) (63.7 (±0.30) days), and physiological maturity (DtoPM) (94.4 (±0.42) days) compared to the control (H_0).

Table 1. The main effect of tillage practices, nitrogen management, and hydrochar application on the main growth stages of maize.

	DtoE		DtoT		DtoS		DtoPM	
				Days				
				Tillage Practices				
S_T	7.7 (±0.14)	a	52.8 (±0.34)	a	63.2 (±0.31)	a	93.4 (±0.40)	b
D_T	7.4 (±0.17)	a	53.4 (±0.28)	a	63.3 (±0.26)	a	94.3 (±0.36)	a
				Nitrogen Management				
M_C	7.9 (±0.22)	a	51.9 (±0.30)	b	62.0 (±0.18)	b	92.3 (±0.42)	b
M_U	7.4 (±0.18)	a	53.9 (±0.35)	a	64.3 (±0.35)	a	95.0 (±0.34)	a
M_F	7.4 (±0.15)	a	53.4 (±0.30)	a	63.4 (±0.20)	a	94.3 (±0.40)	a
				Hydrochar				
H_0	7.4 (±0.16)	b	52.7 (±0.25)	b	62.8 (±0.25)	b	93.3 (±0.33)	b
H_1	7.8 (±0.15)	a	53.5 (±0.35)	a	63.7 (±0.30)	a	94.4 (±0.42)	a

DtoE = days to emergence; DtoT = days to tasseling; DtoS = days to silking; DtoPM = days to physiological maturity, respectively (mean ± SE; n = 4). S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33%FYM + 67% Urea; M_F = 80%FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.2. Plant Height

Deep tillage (D_T) exhibited taller plants (195.1 ± 3.75 cm) compared to shallow tillage (S_T) (181.7 ± 3.47 cm). Regarding nitrogen management, M_U and M_F resulted in taller plants (193.7 ± 3.56 cm and 196.3 ± 5.00 cm, respectively) in contrast to the control (175.1 ± 3.69 cm). Additionally, H_1 led to taller plants (192.5 ± 3.81 cm) compared to those treated without hydrochar H_0 (184.1 ± 3.76 cm) (Table 2).

Table 2. The main effect of tillage practices, nitrogen management, and hydrochar application on plant height, biological yield, grain yield, and harvest index of maize plant at harvesting, respectively (mean ± SE; n = 4).

	Plant Height (cm)		**Biological Yield (t ha^{-1} of DM)**		**Harvest Index (%)**	
Tillage Practices						
S_T	181.7 (±3.47)	b	8.82 (±0.94)	b	40.0 (±0.78)	a
D_T	195.1 (±3.75)	a	9.59 (±2.16)	a	39.7 (±0.90)	a
Nitrogen Management						
M_C	175.1 (±3.69)	b	8.64 (±1.14)	b	37.1 (±1.10)	b
M_U	193.7 (±3.56)	a	9.26 (±1.74)	a	41.1 (±0.76)	a
M_F	196.3 (±5.00)	a	9.72 (±2.73)	a	41.3 (±0.86)	a
Hydrochar						
H_0	184.1 (±3.76)	b	8.96 (±1.56)	b	39.7 (±0.74)	a
H_1	192.5 (±3.81)	a	9.45 (±1.98)	a	40.0 (±0.93)	a

S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.3. Biological Yield

The biological yield of maize was significantly influenced, with D_T resulting in a higher biological yield (9.59 ± 2.16 t ha^{-1} of DM), while S_T resulted in a lower yield (8.82 ± 0.94 t ha^{-1} of DM). The effect of nitrogen management was also prominent, showing that maize produced a higher biological yield with fertilization of M_U (9.26 ± 1.74 t ha^{-1} of DM) and M_F (9.72 ± 2.73 t ha^{-1} of DM) treatments compared to the control (8.64 ± 1.14 t ha^{-1} of DM). Moreover, applying hydrochar (H_1) led to a higher biological yield (9.45 ± 1.98 t ha^{-1} of DM) when compared to those plots that were treated without hydrochar H_0 (8.96 ± 1.56 t ha^{-1} of DM) (Table 2).

3.4. Harvest Index

Mean data revealed that the harvest index of maize did not differ significantly due to tillage practices and hydrochar application; however, nitrogen management had a prominent effect on the harvest index (Table 2). Notably, a higher harvest index was observed in plots that were fertilized with M_U (41.1 ± 0.76%) and M_F (41.3 ± 0.86%), while control plots had a lower harvest index (37.1 ± 1.10%).

3.5. Grain Yield

Applied treatments led to notable variations in the grain yield of maize (Table 3). D_T practice resulted in the highest grain yield (3.80 ± 1.09 t ha^{-1}), surpassing the yield obtained from S_T (3.53 ± 0.79 t ha^{-1}). Among nitrogen management practices, the utilization of M_U and M_F yielded the highest grain yields (4.00 ± 0.97 and 3.80 ± 0.79 t ha^{-1}, respectively), while the use of M_C exhibited the lowest grain yield (3.20 ± 0.81 t ha^{-1}). In terms of hydrochar application, plots treated with H_1 demonstrated a slightly superior grain yield (3.96 ± 0.94 t ha^{-1}) compared to the control (H_0) (3.76 ± 0.99 t ha^{-1}).

Table 3. The main effect of tillage practices, nitrogen management, and hydrochar application on grain yield and yield components in terms of ear number, ear length, grain number, thousand-grain weight, grain nitrogen content, and stover nitrogen content of maize plants at harvesting, respectively (mean ± SE; n = 4).

	Grain Yield ($t\ ha^{-1}$ of DM)		Ear (n. m^{-2})		Ear Length (cm)		Grains (n. ear^{-1})		TGW (g)		Grain N ($g\ kg^{-1}$)		Stover N ($g\ kg^{-1}$)	
							Tillage Practices							
S_T	3.53 (±0.79)	b	7.3 (±0.13)	a	16.1 (±0.24)	b	307.8 (±5.13)	b	217.0 (±1.57)	b	12.3 (±0.45)	b	3.6 (±0.24)	b
D_T	3.80 (±1.09)	a	7.5 (±0.12)	a	17.0 (±0.33)	a	324.6 (±5.36)	a	221.5 (±1.03)	a	14.1 (±0.42)	a	4.3 (±0.20)	a
							Nitrogen Management							
M_C	3.20 (±0.81)	b	7.1 (±0.12)	b	15.3 (±0.24)	c	284.6 (±2.61)	c	214.6 (±1.08)	b	12.0 (±0.55)	c	3.1 (±0.21)	b
M_U	3.80 (±0.79)	a	7.4 (±0.17)	ab	16.6 (±0.26)	b	321.7 (±3.95)	b	218.4 (±1.73)	ab	13.5 (±0.54)	b	4.3 (±0.23)	a
M_F	4.00 (±0.97)	a	7.6 (±0.13)	a	17.8 (±0.32)	a	342.2 (±2.24)	a	224.8 (±1.19)	a	14.1 (±0.57)	a	4.4 (±0.28)	a
							Hydrochar							
H_0	3.76 (±0.99)	b	7.3 (±0.13)	a	16.0 (±0.30)	b	312.6 (±5.99)	b	217.5 (±1.53)	b	12.6 (±0.46)	b	3.6 (±0.21)	b
H_1	3.96 (±0.94)	a	7.4 (±0.12)	a	17.1 (±0.28)	a	319.7 (±4.93)	a	221.0 (±1.18)	a	13.9 (±0.46)	a	4.2 (±0.24)	a

S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.6. Ear Density

S_T practices exhibited the highest ear density for maize (7.5 ± 0.12 n. m^{-2}), followed closely by deep tillage (D_T) (7.3 ± 0.13 n. m^{-2}). Among nitrogen management, M_F displayed the highest ear density, (7.6 ± 0.13 n. m^{-2}) which was statistically similar to M_U (7.4 ± 0.17 n. m^{-2}), while M_C presented the lowest ear density (7.1 ± 0.12 n. m^{-2}). In terms of hydrochar application, there was no statistical difference between H_0 and H_1 in the recorded results (Table 3).

3.7. Ear Length

Among tillage practices, D_T resulted in longer ears (17.0 ± 0.33 cm) compared to S_T (16.1 ± 0.24 cm). Among the nitrogen management practices, M_F exhibited the longest ears (17.8 ± 0.32 cm) followed by M_U (16.6 ± 0.26 cm) while mineral fertilizer alone (M_C) resulted in shorter ears (15.3 ± 0.24 cm). In terms of hydrochar application, plots where H_1 was applied had longer ears (17.1 ± 0.28 cm) compared to H_0 (16.0 ± 0.30 cm) (Table 3).

3.8. Grains Ear^{-1}

Among the tillage practices, D_T resulted in the highest grains ear^{-1} (324.6 ± 5.36) while S_T yielded fewer grains ear^{-1} (307.8 ± 5.13). Regarding nitrogen management, the highest grain count was observed in plots treated with M_F (342.2 ± 2.24) followed by M_U (321.7 ± 3.95) and M_C (284.6 ± 2.61). For hydrochar application, the highest grain count was found in plots treated with H_1 (319.7 ± 4.93) compared to the control (H_0) (312.6 ± 5.99) (Table 3).

3.9. Thousand-Grain Weight

D_T practices resulted in higher TGW (221.5 ± 1.03 g), while S_T had lower TGW (217.0 ± 1.57 g). Among the nitrogen management practices, plots treated with M_F exhibited the highest TGW (224.8 ± 1.19 g) followed M_U (218.4 ± 1.73 g) and M_C (214.6 ± 1.08 g). In terms of hydrochar application, plots treated with H_1 displayed higher TGW (221.0 ± 1.18 g) compared to the control group without hydrochar (H_0) (217.5 ± 1.53 g) (Table 3).

3.10. Grain N Content

Among the tillage practices, D_T resulted in higher grain N content (14.1 ± 0.42 g kg^{-1}), whereas shallow tillage (S_T) had lower grain N content (12.3 ± 0.45 g kg^{-1}). Regarding nitrogen management, the highest grain N content was observed in plots treated with M_F (14.1 ± 0.57 g kg^{-1}) followed by M_U (13.5 ± 0.54 g kg^{-1}) while M_C had the lowest (12.0 ± 0.55 g kg^{-1}). For hydrochar application, plots treated with H_1 exhibited the highest grain N content (13.9 ± 0.46 g kg^{-1}) compared to H_0 (12.6 ± 0.46 g kg^{-1}) (Table 3).

3.11. Stover N Content

D_T resulted in higher stover N content, with an average (4.3 ± 0.20 g kg^{-1}), while S_T had lower stover N content (3.6 ± 0.24 g kg^{-1}). Among the nitrogen management practices, plots treated with M_F exhibited the highest stover N content (4.4 ± 0.28 g kg^{-1}) that was also comparable to M_U (4.3 ± 0.23 g kg^{-1}) while the lowest results were recorded with M_C (3.1 ± 0.21 g kg^{-1}). In terms of hydrochar application, plots treated with H_1 displayed higher stover N content (4.2 ± 0.24 g kg^{-1}) compared to H_0 (3.6 ± 0.21 g kg^{-1}) (Table 3).

3.12. Nitrogen Uptake

Nitrogen uptake by the maize plant was improved with D_T that resulted in higher nitrogen uptake (45.45 ± 2.40 kg of N ha^{-1}) compared to S_T (36.34 ± 1.79 kg of N ha^{-1}) (Table 4). Among the nitrogen management practices, the highest nitrogen uptake was observed in plots treated with M_F (47.39 ± 2.77 kg of N ha^{-1}) followed by the M_U (42.96 ± 2.29 kg of N ha^{-1}) while M_C recorded the lowest nitrogen uptake (32.32 ± 1.97 kg of N ha^{-1}). The plots that received hydrochar treatment (H_1) exhibited higher nitrogen uptake (44.14 ± 2.38 kg of N ha^{-1}) compared to plots treated without hydrochar H_0 (37.64 ± 2.05 kg of N ha^{-1}) (Table 4).

Table 4. The main effect of tillage practices, nitrogen management, and hydrochar application on Nitrogen uptake and Nitrogen Use Efficiency (NUE) of maize plant at harvesting, respectively (mean ± SE; n = 4).

	Nitrogen Uptake		**NUE**	
	kg of N ha^{-1}			
	Tillage Practices			
S_T	36.34 (±1.79)	b	29.38 (±0.66)	b
D_T	45.45 (±2.40)	a	31.69 (±0.91)	a
	Nitrogen Management			
M_C	32.32 (±1.97)	c	26.64 (±0.67)	b
M_U	42.96 (±2.29)	b	31.64 (±0.66)	a
M_F	47.39 (±2.77)	a	33.31 (±0.81)	a
	Hydrochar			
H_0	37.64 (±2.05)	b	29.61 (±0.78)	b
H_1	44.14 (±2.38)	a	31.46 (±0.83)	a

S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. Means within the same column followed by different letters are significantly different at $p < 0.05$.

3.13. Nitrogen Use Efficiency (NUE)

D_T resulted in higher NUE for maize plants (31.69 ± 0.91 kg of N ha^{-1}) over S_T that recorded the lowest NUE (29.38 ± 0.66 kg of N ha^{-1}) (Table 4). In terms of Nitrogen management, the highest NUE was observed in plots treated with M_F (33.31 ± 0.81 kg of N ha^{-1}) that was comparable to results obtained with M_U treatment (31.64 ± 0.66) over control (26.64 ± 0.67 kg of N ha^{-1}). For hydrochar application, plots treated with hydrochar H_1 exhibited higher NUE (31.46 ± 0.83) compared to plots treated without hydrochar H_0 (29.61 ± 0.78 kg of N ha^{-1}) (Table 4).

3.14. Plant Photo Pigments

Various management practices including tillage, nitrogen management, and hydrochar application had a positive effect on plant photo pigments (Figure 2). Chlorophyll a content was recorded higher with deep tillage (D_T) at approximately 1.00 μg mL^{-1} compared to shallow tillage (S_T) at about 0.80 μg mL^{-1}. Regarding nitrogen management, the treatments M_U (33% FYM + 67% Urea) and M_F (80% FYM + 20% Urea) recorded higher Chl a level, around 0.95 μg mL^{-1}, over the control plots (M_C) which had approximately 0.80 μg mL^{-1}. The application of hydrochar significantly affected Chl a, with acidified hydrochar (H_1) recording improved results at 0.95 μg mL^{-1} compared to without hydrochar (H_0) at 0.80 μg mL^{-1}.

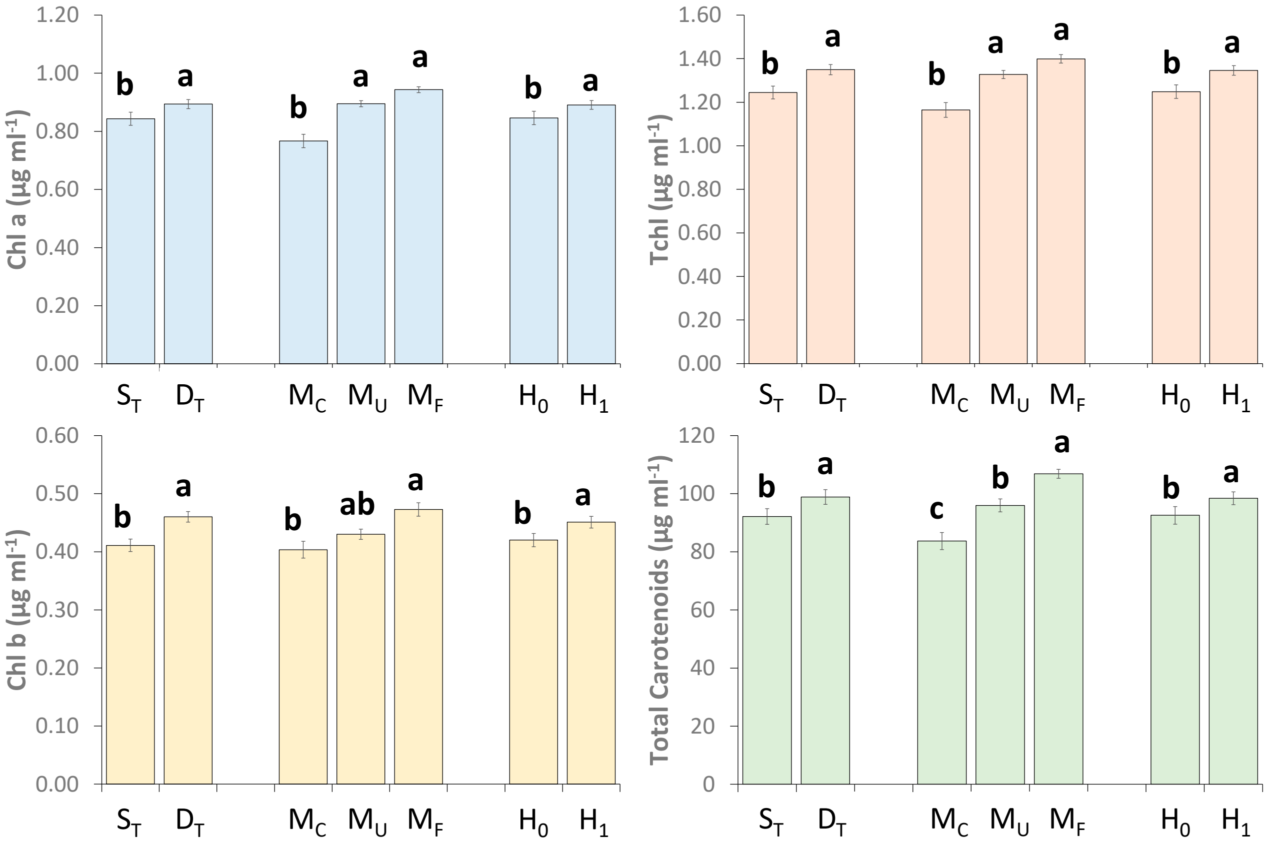

Figure 2. The main effect of tillage practices, nitrogen management, and hydrochar application on Chl a, Chl b, Total Chlorophyll and total carotenoids content in the flag leaves of maize plants at flowering stage, respectively. S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. The data represent means of four replicates. Means with different letters indicate statistically significant differences at $p < 0.05$. Error bars denote standard deviation.

Chlorophyll b content revealed that D_T had higher levels at about 0.50 μg mL^{-1}, whereas S_T had lower levels at approximately 0.40 μg mL^{-1}. Among nitrogen management practices, higher and statistically similar Chl b levels were noted in plots treated with M_U and M_F, around 0.45–0.50 μg mL^{-1}, while M_C had the lowest recorded values at approximately 0.40 μg mL^{-1}. Hydrochar application also caused significant differences in Chl b, with H_1 producing higher Chl b content at 0.50 μg mL^{-1} compared to H_0 at 0.40 μg mL^{-1} (Figure 2).

Total chlorophyll content was higher in D_T-applied plots at about 1.40 μg mL^{-1}, while S_T-applied plots produced lower total chlorophyll at approximately 1.20 μg mL^{-1}. Among nitrogen management practices, higher and statistically similar total chlorophyll content was recorded in plots treated with M_U and M_F, around 1.35 μg mL^{-1}, while M_C had the lowest recorded values at about 1.20 μg mL^{-1}. Hydrochar application caused significant differences in total chlorophyll, with H_1 producing higher total chlorophyll at 1.35 μg mL^{-1} compared to H_0 at 1.20 μg mL^{-1} (Figure 2).

Carotenoids were significantly improved with D_T at about 110 μg mL^{-1} compared to S_T at approximately 95 μg mL^{-1}. Application of M_U and M_F led to higher carotenoid content in maize leaves, around 110 μg mL^{-1}, over the control (M_C) which had approximately 85 μg mL^{-1}. The effect of hydrochar treatment showed that carotenoids were higher with H_1 at about 100 μg mL^{-1}, whereas H_0-treated plots had lower carotenoid content at approximately 90 μg mL^{-1} (Figure 2).

3.15. Soil Properties

Soil organic matter (SOM) was positively influenced by the combined application of tillage practices and nitrogen (N) management (Figure 3). The highest and statistically similar values of SOM were noted in plots where deep tillage (D_T) or shallow tillage (S_T) was carried out and fertilized with M_F (80% FYM + 20% Urea), both recording approximately 0.60%. Moreover, recorded SOM in plots that had received acidified hydrochar (H_1) was higher at about 0.5% compared to the control (H_0) at around 0.45%.

Soil total nitrogen (STN) showed significant disparity. It was noted that D_T-applied plots had higher and statistically similar STN among all treatment combinations regardless of N management, with values around 0.70%. Among S_T practice, the M_F treatment recorded higher results, approximately 0.70%, over the M_U (33% FYM + 67% Urea) and control (M_C) treatments. Moreover, STN in plots that had received H_1 was higher at about 0.70% compared to H_0 at around 0.65% (Figure 3).

The interactive effect of tillage and N management was notable for soil mineral nitrogen (SMN). It was revealed that D_T application in plots, when combined with M_U and M_F, produced similar and higher SMN at around 35 mg kg^{-1} dry soil, which was also similar to S_T application in M_F-treated plots. No notable difference was observed with hydrochar application in SMN, with both H_0 and H_1 treatments recording similar levels around 35 mg kg^{-1} dry soil (Figure 3).

3.16. Relationship of SOM, Total Chl, and SMN with NUE and N Uptake

Scatter plots were drawn to analyze the impact of SOM, total Chl, and SMN on NUE and N uptake by maize plants. It was observed that mentioned parameters had a positive association with NUE and N uptake (Figure 4). Specifically, soil organic matter significantly and linearly increased NUE and uptake of N (R^2 = 0.22* and 0.24*, respectively). Similarly, increase in total Chl was associated with increase in NUE (R^2 = 0.49**) and N uptake (R^2 = 0.35*) and vice versa. Finally, an increase in SOM resulted in improved NUE (R^2 = 0.38*) and N uptake (R^2 = 0.31*) by plants.

3.17. Canonical Discriminant Analysis (CDA) for Yield Characteristics of Maize

CDA was performed to evaluate the sole effect of various management practices (tillage, N management, and hydrochar application) from a multivariable perspective. Among tillage practices, the association of all yield characteristics of maize were more associated with D_T compared to S_T that was not associated with a single variable (Figure 5A). Among N management, more variables were influenced by M_U and M_F whereas no association was shown for M_C (Figure 5B). In terms of hydrochar application, more association was observed for H_1 with the studied variables except for ear numbers of maize that showed association with H_0 (Figure 5C).

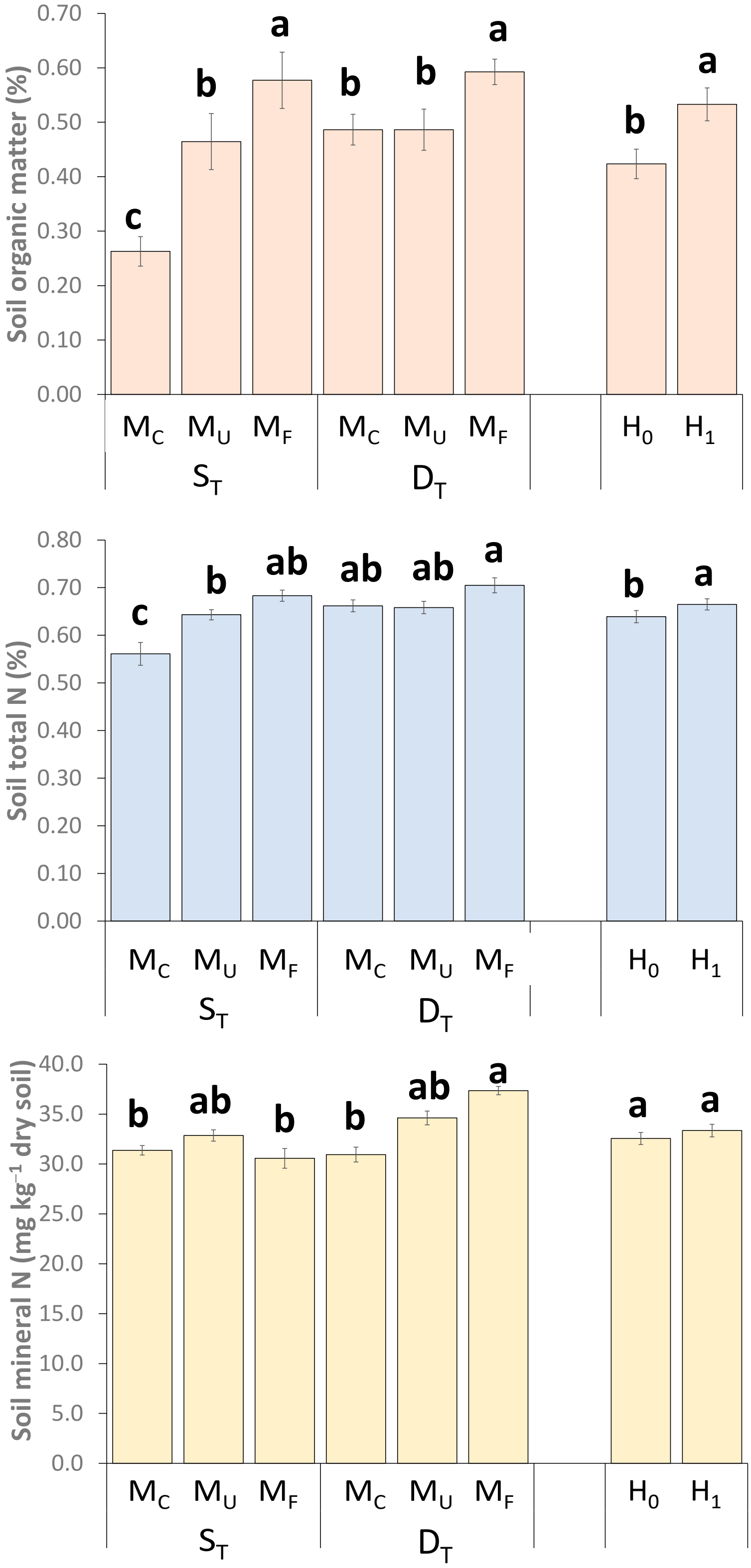

Figure 3. The effect of tillage practice × nitrogen management interaction and hydrochar application on organic matter, total nitrogen, and mineral nitrogen of soil cultivated with maize crop at harvesting. S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar. The data represent means of four replicates. Means with different letters indicate statistically significant differences at $p < 0.05$. Error bars denote standard deviation.

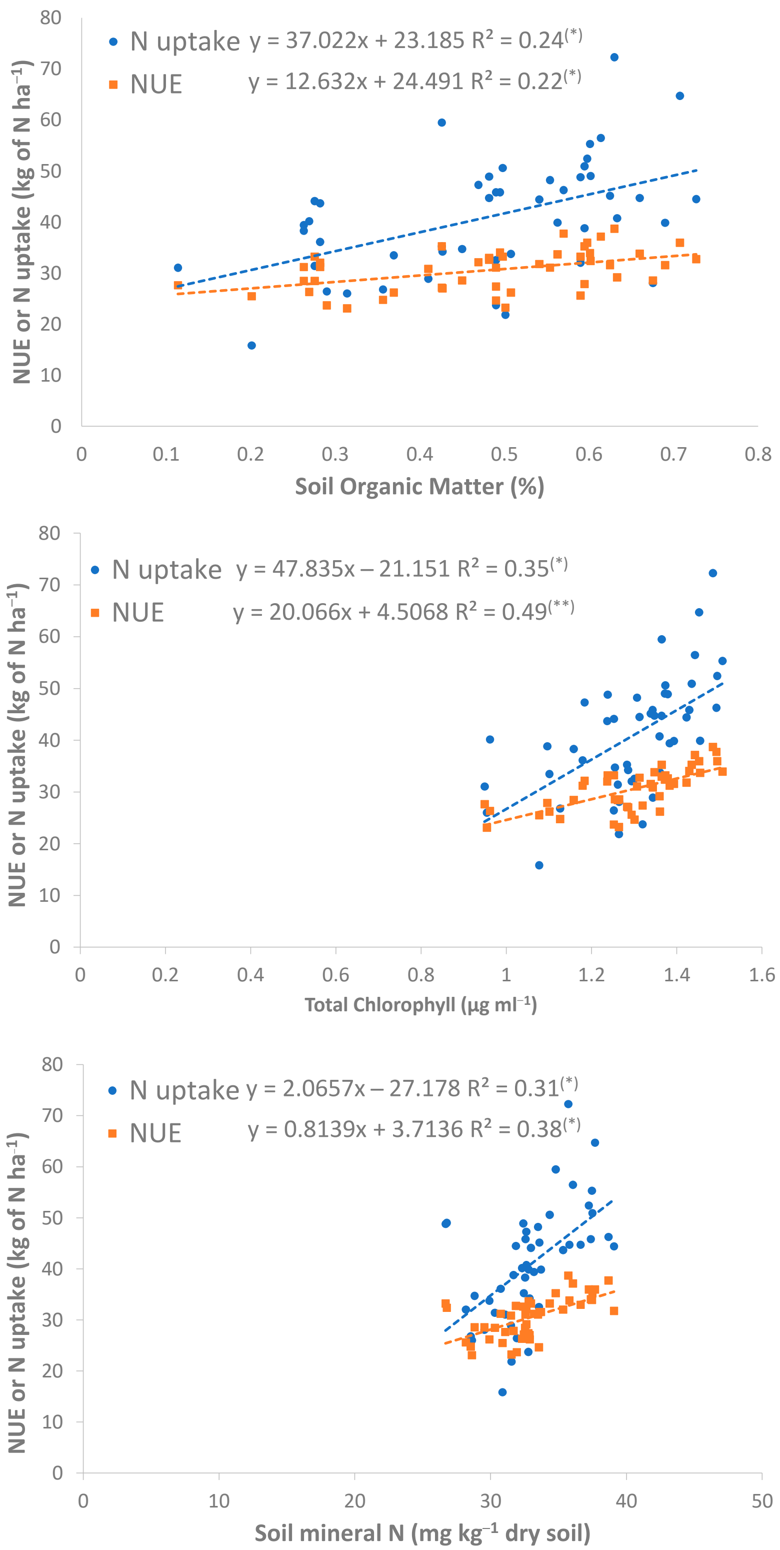

Figure 4. The relationships between Nitrogen Use Efficiency (NUE) and N uptake of maize plants against soil organic matter, total maize leaves' chlorophyll and soil mineral nitrogen (n = 48), respectively. Data correspond to tillage practices, nitrogen management, and hydrochar application and the significance level is * and ** significant at $p \leq 0.05$ and $p \leq 0.01$ level, respectively.

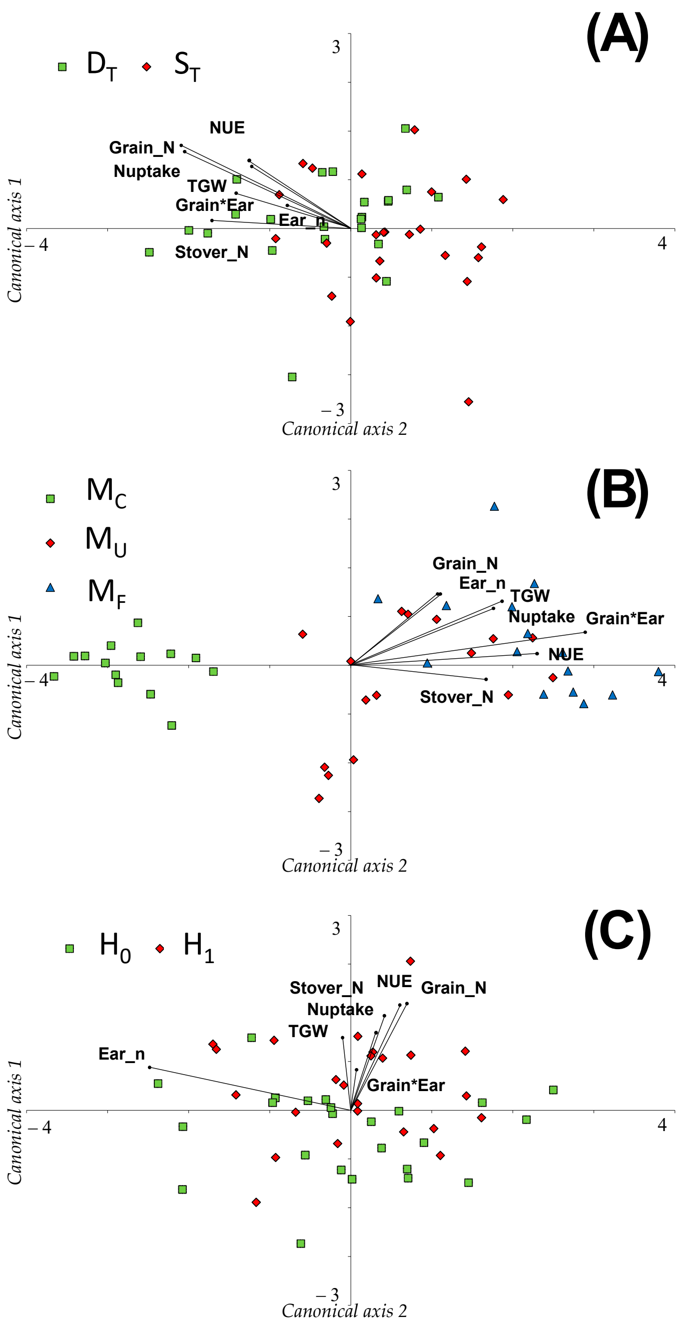

Figure 5. The canonical discriminant analysis (CDA) of the yield characteristics of maize subjected to tillage practices (**A**), nitrogen management (**B**), and hydrochar application (**C**). S_T = shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar.

3.18. Canonical Discriminant Analysis (CDA) for Post-Harvest Soil Characteristics

CDA was performed to estimate the main effect of various management practices (tillage, N management, and hydrochar application) from a multivariable perspective. Significant discrimination was seen in soil characteristics due to applied management practices. Various tillage managements showed that soil mineral nitrogen (SMN), soil organic matter (SOM), and soil total nitrogen (STN) were associated with D_T while soil pH and bulk density (BD) showed more tilt towards S_T (Figure 6A). N management showed that M_F was associated with most of the soil characteristics including STN, SOM, SNM, and soil pH whereas BD had more association with M_U. No significant association of M_C

was recorded on the biplot (Figure 6B). Application of hydrochar to the maize field caused prominent variability in soil characteristics with SMN, SOM, and STN more affected by H_1 compared to H_0 which only showed an effect on soil pH and BD (Figure 6C).

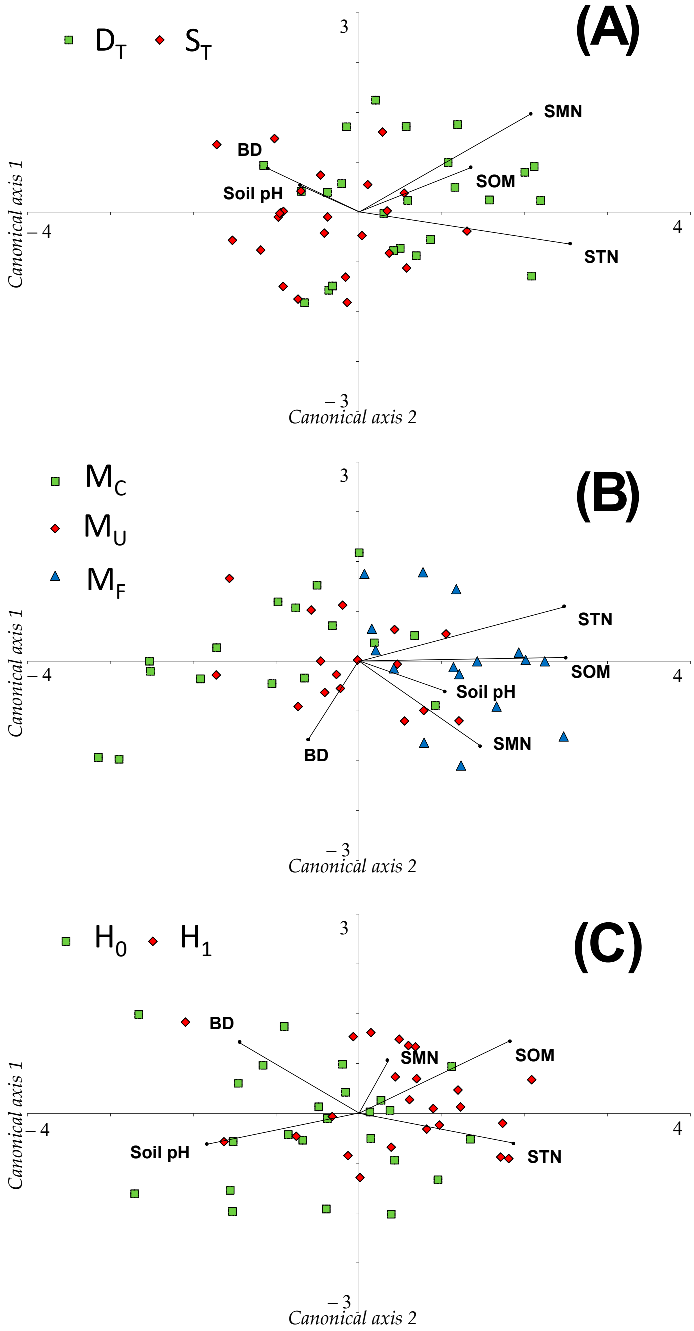

Figure 6. The canonical discriminant analysis (CDA) of soil characteristics of maize subjected to tillage practices (**A**), nitrogen management (**B**), and hydrochar application (**C**). S_T = Shallow tillage; D_T = deep tillage; M_C = control; M_U = 33% FYM + 67% Urea; M_F = 80% FYM + 20% Urea; H_0 = control (no hydrochar); and H_1 = acidified hydrochar.

4. Discussion

The effect of tillage implements, integrated nitrogen management, and acidified hydrochar were found to have no significant impact on the days to maize emergence and emergence m^{-2} of maize. This could be attributed to maize primarily utilizing the stored nutrients within the seed during the germination phase, rather than relying heavily on the nutrients present in the soil during sowing. Furthermore, maize was mostly sown using the dibbler method, which places seeds uniformly with proper plant-to-plant (P-P) and row-to-row (R-R) distances, resulting in no significant difference in days to emergence and emergence m^{-2}. These findings align with those of Ibrahim and Khan [28], who also reported non-significant effects of tillage and nutrient application on emergence metrics. Nitrogen is a crucial nutrient for plant growth and development, affecting various growth-related processes [29,30]. Study by Iqbal et al. [31] revealed that integrated nitrogen management significantly affected the maize phenological observations. Similarly, acidified hydrochar affected maize phenological development by improving soil fertility and plant nutrition [32].

Plant pigments were improved with deep tillage as compared to shallow tillage. Soil disruption typically enhances organic matter and mineralization, thereby increasing nitrogen availability [33]. Nitrogen, being an essential plant nutrient, is a major source for chlorophyll synthesis, photosynthetic activity, and crop growth [34,35], that increases the plant chlorophyll contents [36]. Yang et al. [37] confirmed that nitrogen application enhances leaf expansion and plant pigment activity. Acidified hydrochar significantly increases chlorophyll and carotenoid contents compared to non-acidified hydrochar. Hydrochar is composed mainly of carbon derived from biomass that improves soil properties and results in higher nutrient availability [38]. Simić et al. [39] demonstrated a significant correlation between nitrogen levels and tillage practices as a ready reference for the current study. Wang et al. [40] reported a positive interaction between nitrogen availability and chlorophyll content in plants, that also supports our findings.

Maize plant height and ear length were significantly higher with deep tillage, integrated nitrogen management, and acidified hydrochar addition compared to the shallow tillage, no fertilization, and no hydrochar, respectively. The deep tillage improves seedbed conditions by loosening the soil, thereby promoting better crop growth parameters such as plant height and ear length [30]. The addition of M_F increased the nutrients' availability and thereby increased plant growth [8]. The significant increase in plant height and ear length with acidified hydrochar can be attributed to its enriched content of soil organic carbon. According to Sahin et al. [41], hydrochar treated with sulfuric acid enhances soil properties and nutrient availability, leading to improvements in plant height and ear length.

Maize grains ear^{-1} benefited positively from tillage, integrated nitrogen management, and acidified hydrochar. Tillage practices manipulate soil mechanically, impacting physical properties such as soil moisture content and nutrient availability, thereby promoting enhanced maize growth and yield. Gu et al. [42] reported that deep tillage significantly increases the number of grains ear^{-1}, leading to a 6.3% increase in grain yield. Integrated nitrogen management affects grains ear^{-1} in maize by influencing nitrogen availability during critical growth stages [30]. Acidified hydrochar enhances grains per ear by improving soil fertility and nutrient availability [43]. Soothar et al. [44] showed that hydrochar enhances soil fertility and nutrient availability, improving grains ear^{-1}. Ding et al. [45] found that acidified hydrochar raises soil pH, increases organic matter content, and enhances nutrient availability, thereby resulting in improved crop yields and quality.

Tillage, nitrogen management, and acidified hydrochar each positively affected the thousand-grain weight (TGW) of maize. Higher TGW was recorded in deep tillage compared to shallow tillage, attributed to soil loosening, which enhances root growth and nutrient uptake [30]. The M_F increased the TGW of maize over M_C. Nitrogen application enhances plant growth and chlorophyll contents that increase grain weight [25]. Acidified hydrochar enhances maize TGW by improving nutrient availability and water-holding capacity in the soil. According to Shah et al. [46], acidified hydrochar enhances nitrogen and other macronutrients that contribute to increased TGW.

Biological yield and grain yield were greater with deep tillage compared to shallow tillage. Deep tillage improves soil properties, drainage, aeration, and facilitating movement of NO_3^- and nitrogen uptake [29,47]. Xu et al. [48] reported that tillage affects soil organic carbon and organic matter content, improving crop growth and yield. The integrated nitrogen management significantly increased biological and grain yield more than no fertilization. Zhou et al. [49] found that combining organic and inorganic nitrogen sources increases maize yield. The acidified hydrochar increased biological and grain yield due to its nutrient-rich composition and improved soil properties [8]. Baronti et al. [50] reported that hydrochar enhances soil fertility, and nutrient availability, which increases yield. Similar findings were observed by Islam et al. [43], who reported that acidified hydrochar improves soil quality and nutrient availability, leading to higher crop yields.

The harvest index of maize was significantly influenced by deep tillage, integrated nitrogen management, and the application of acidified hydrochar. Deep tillage improves soil properties and nutrient availability, increasing maize biomass and yield, which increases the harvest index [30]. Integrated nitrogen management enhances nutrient availability and uptake, increasing the harvest index. Acidified hydrochar improves soil properties and nutrient availability, increasing maize growth and yield, and thereby improves the harvest index of maize crop [11,43].

Integrated nitrogen management significantly increased nitrogen content in maize stover and grains, which could possibly be due to improved nitrogen contents in soil that play a critical role in chlorophyll formation. The addition of acidified hydrochar increased the nitrogen content in maize stover and grain compared to non-acidified hydrochar. This increase is attributed to the hydrothermal carbonization of residues, which raises the nitrogen content from 2.52% to 3.81% [51]. The results were also supported by Islam et al. [43], who concluded that hydrochar increases the concentration of nitrogen, phosphorus, and potassium.

Deep tillage significantly improved total nitrogen and soil mineral nitrogen content in the soil. This increase might be due to enhanced decomposition of organic sources in the soil facilitated by deep tillage practices [13]. Chiseling increases the soil penetration through the breaking of compaction, upturns the aeration, and consequently the soil decomposition and nutrient availability [30,52,53]. The M_F had higher soil organic matter and total nitrogen compared to the M_0 treatment. This is likely due to the provision of nitrogen and carbon from the higher application of manure [15]. Being a rich source of C, the addition of hydrochar increased soil organic matter and total nitrogen content [8]. The porosity of hydrochar provides a favorable environment for the development of microorganisms that enhance the soil decomposition [53]. Hydrochar improves soil fertility due to its charged surface and large surface area, which allows it to adsorb nutrients such as nitrogen, phosphate, and carbon, which aid in the retention of nutrients in the soil and act as water retention agents [11].

Both soil properties and plant attributes showed significant discrimination in response to applied management treatments. The soil mineral nitrogen, organic matter, and total nitrogen were associated with D_T while soil pH and bulk density showed more tilt towards S_T. The M_F was associated with most of the soil characteristics whereas soil bulk density was associated with M_U. The hydrochar application caused prominent variability in soil characteristics. The improved soil moisture contents and soil properties in response to added manure could be a possible mechanism for this discrimination [9].

5. Conclusions

This study concludes that deep tillage, coupled with integrated nitrogen management practices, significantly enhances maize productivity and soil properties. Deep tillage consistently outperformed shallow tillage in promoting plant growth and yield, similar to how the combined application of manure and urea was the most effective nitrogen management strategy. The addition of hydrochar improves soil organic matter and mineral nitrogen availability. This study highlights the potential of integrating organic and inorganic fertilizers to achieve sustainable agricultural productivity. The implications of this study suggest the exploration of the long-term impacts of hydrochar addition to soil for further validation of results.

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