

SOIL QUALITY AND NUTRIENT DYNAMICS AS AFFECTED BY RESIDUE MANAGEMENT IN MAIZE–WHEAT CROPPING SYSTEM UNDER REDUCED NITROGEN INPUTS

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Abstract

Excessive nitrogen fertilization and poor residue management in wheat–maize systems have resulted in declining soil fertility in Pakistan. This study assessed the effects of different residue management practices and reduced nitrogen rates on soil properties over two consecutive seasons (2021–2023) at the University of Agriculture Peshawar. Results indicated that application of reduced nitrogen rates (90 kg N ha⁻¹ for wheat and 112.5 kg N ha⁻¹ for maize) significantly improved soil electrical conductivity (0.87–0.88 dS m⁻¹), mineral nitrogen (12.3–14.1 mg kg⁻¹), total nitrogen (804–835.9 mg kg⁻¹), organic matter (1.15–1.20%), potassium (105.0 mg kg⁻¹ in wheat; 99.4 mg kg⁻¹ in maize), and soil moisture (15.3–15.4%). Similarly, 100% residue incorporation into the soil enhanced soil mineral nitrogen (14.0 mg kg⁻¹), total nitrogen (802–810.8 mg kg⁻¹), organic matter (1.26–1.36%), phosphorus (3.8–3.9 mg kg⁻¹), potassium (103.5–104.9 mg kg⁻¹), and soil moisture (15.9–16.2%) compared with control plots. These results demonstrated that integrating full residue incorporation with optimal nitrogen rates greatly improves soil nutrient status and moisture conservation, thereby sustaining soil fertility in the wheat–maize cropping system.

Keywords:

Agronomy; crop management; Pakistan; soil fertility; sustainability.

INTRODUCTION

Sustaining the productivity agriculture systems depends on soil fertility, which is increasingly under pressure from conventional nutrient management practices. Excessive reliance on synthetic nitrogen fertilizers has led to soil degradation, low nitrogen use efficiency, and environmental challenges such as groundwater contamination, greenhouse gas emissions, and loss of biodiversity (Martínez-Dalmau et al., 2021). While nitrogen remains the most important macronutrient for cereal productivity, its inefficient use results in losses through leaching and denitrification, undermining both crop performance and soil health (Rahimizadeh et al., 2010). Hence, improving soil quality and nutrient cycling under reduced nitrogen inputs is essential for long-term sustainability. Crop residue management offers a promising solution by recycling organic matter and nutrients back into the soil. Incorporation or mulching of crop residues improves soil structure, organic matter content, nutrient retention, and water-holding capacity, while reducing erosion, runoff, and nutrient losses (Singh et al., 2022). Retained residues also regulate soil temperature, improve microbial activity, and enhance soil carbon sequestration (Tormena et al., 2016). Such practices not only enhance nutrient availability particularly nitrogen, phosphorus, and potassium but also improve soil organic matter and total carbon content, which are vital indicators of soil health. In contrast, residue burning leads to the loss of valuable organic matter and nutrients, accelerating soil degradation and environmental pollution (Liang et al., 2022).

In maize–wheat cropping systems, where nutrient demand is high and continuous cultivation accelerates nutrient depletion, integrating residue management with reduced nitrogen fertilization emerges as a sustainable strategy to enhance soil fertility and maintain productivity (Chen et al., 2021). Residue incorporation not only improves the immediate availability of mineral nitrogen but also contributes to the gradual buildup of total nitrogen pools through enhanced microbial immobilization and mineralization processes (Lal, 2020). This improves nitrogen use efficiency by synchronizing nutrient release with crop demand. Moreover, the addition of residues enriches soil organic matter, which increases soil carbon stocks, improves cation exchange capacity, and enhances the soil's buffering capacity against pH fluctuations. Residue retention also moderates soil electrical conductivity by balancing the ionic environment and improving nutrient solubility, thereby supporting better root absorption. Enhanced organic matter decomposition fosters microbial activity, which drives nutrient cycling and stabilizes soil structure, leading to improved aeration, porosity, and aggregate stability. These changes positively influence soil moisture dynamics by increasing water infiltration, retention, and availability during critical crop growth stages, ultimately reducing drought stress.

Furthermore, residue incorporation mobilizes phosphorus and potassium by altering the rhizosphere environment and stimulating the activity of phosphate-solubilizing microbes. Such improvements in nutrient bioavailability, coupled with enhanced organic carbon sequestration, directly contribute to both short-term fertility and long-term sustainability of the maize–wheat system under reduced nitrogen inputs (Jiang et al., 2019). Thus, residue management is not merely a soil conservation practice but a holistic approach to sustaining soil health, mitigating climate change through carbon sequestration, and ensuring resilient agro-ecosystems. Therefore, the present study was undertaken to evaluate the impact of different crop residue management techniques under reduced nitrogen inputs on soil quality and nutrient dynamics in a maize–wheat cropping system. The main objectives were to assess changes in soil

physicochemical properties under different residue management practices, to determine how residue incorporation interacts with reduced nitrogen application to influence soil nutrient availability and cycling and promote sustainable residue and nutrient management practices for enhancing soil health and long-term productivity in maize–wheat systems.

Materials and Methods

Design and Location

Field experiments were directed for two consecutive years (2021–2022 and 2022–2023) at the Agronomy Research Farm, The University of Agriculture Peshawar, which has a semi-arid, subtropical climate with annual rainfall of 360 mm and temperatures ranging from 25 °C in winter to 40 °C in summer. The soil is well-drained, calcareous (pH 8.23), silty clay loam with low organic matter (<1%), scarce in nitrogen (23.72 mg kg⁻¹) and phosphorus (3.20 mg kg⁻¹), but sufficient in potassium (85.80 mg kg⁻¹) as stated in Table 1. A randomized complete block split-plot design was used, with crop residue (CR) levels in main plots and nitrogen (N) treatments in subplots with four replications.

Table 1. Soil physiochemical properties at experimental location before plantation during 2021 and 2022.

Property	Value	
	2021	2022
pH	7.8	7.3
Texture class	clay loam	clay loam
Sand (%)	8.6	9.0
Silt (%)	52.4	53.1
Clay (%)	39	37.9
CEC (cmolc kg ⁻¹)	30.2	29.7
EC (dS m ⁻¹)	0.82	0.81
Bulk density (mg ⁻³)	1.4	1.3
Total K (g kg ⁻¹)	14.4	14
Total P (g kg ⁻¹)	0.25	0.2
Total N (mg kg ⁻¹)	562	629
Available N (mg kg ⁻¹)	8.9	10.1
Available P (mg kg ⁻¹)	3.4	3.5
Available K (mg kg ⁻¹)	100.3	96.7

Procedures for Treatment Application

Three nitrogen (N) fertilization regimes were tested in both crops: N1 (no nitrogen), N2 (25% below the recommended rate), and N3 (recommended rate). For maize, the applied levels were 0, 112.5 kg N ha⁻¹ (25% reduced), and 150 kg N ha⁻¹ (recommended), while in wheat, the rates were 0, 90 kg N ha⁻¹ (25%

reduced), and 120 kg N ha⁻¹ (recommended). Nitrogen was applied in split doses according to crop growth stages: in maize, applications were made at sowing, the V6 stage (three weeks post-emergence), and tasseling; in wheat, nitrogen was split equally at sowing, tillering, and booting. A uniform phosphorus dose of 90 kg P₂O₅ ha⁻¹ was applied to both crops during seedbed preparation using diammonium phosphate (DAP) as the source.

Procedures for Soil Analysis

Following soil parameters were evaluated after maize and wheat crop harvest.

Electrical Conductivity (dSm⁻¹) and Soil pH

The electric conductivity (EC) and pH of soil samples were determined using standard procedures. For EC measurement, the meter was first calibrated with a 1413 µS cm⁻¹ standard solution at 25 °C following the manufacturer's instructions. Soil extracts were prepared by mixing soil and water at a 1:5 ratio (1 g soil in 5 mL water), shaking for 30 minutes, and allowing the suspension to settle before immersing the probe. Once stabilized, the EC value along with the corresponding temperature was recorded. For pH determination, soil suspensions were prepared similarly at a 1:5 ratio (10 g soil in 50 mL distilled water), shaken for 30 minutes, and filtered through Whatman No. 42 filter paper. The pH meter was calibrated using standard buffer solutions (pH 7.01 and 10.01), and after rinsing the electrode with deionized water, the stabilized pH value of each sample was recorded.

Mineral Nitrogen (mg kg⁻¹) and Total Nitrogen (%)

Steam distillation procedure was used for the determination of Mineral N (nitrogen) in the form of NH₄-N and NO₃-N it was removed via KCL solution (Keeny and Nelson, 1982). In this procedure, 20 g soil was shaken with the help of mechanical shaker for 1 hour in 100 mL 1 M KCL solutions and filtered by Whatman-42.

$$\text{Mineral N (mg kg}^{-1}\text{)} = \frac{(\text{sample} - \text{blank}) \times 0.005\text{N of HCL} \times 0.014 \text{ meq N}}{\text{Sample taken}} \times 1000$$

Soil nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney, 1982). Briefly, 0.20 g of air-dried soil was digested with 3 mL of concentrated H₂SO₄ and 1.1 g of a catalyst mixture (K₂SO₄, CuSO₄, and Se) on a block digester for 4–5 hours, gradually raising the temperature to 350 °C and maintaining it for 1 hour until the solution turned light green. After cooling, the digest was quantitatively transferred into a 100 mL volumetric flask and diluted to volume with distilled water. A 20 mL aliquot of this digest was made alkaline by adding 5 mL of 40% NaOH and then distilled; the liberated ammonia was trapped in a boric acid receiver and titrated with 0.005 M HCl. Total soil nitrogen was calculated by subtracting the blank titration.

Soil Organic Matter

10 ml of 1 N K₂Cr₂O₇ and 20 ml concentrated H₂SO₄ was added to 1 gram of the soil and was cured. Allow to cool for 15–30 min after oxidation, 200 ml distilled water was added and sieved in conical flask. The solutions and Ortho phenolphthalein as an indicator was titrated by end titrant of 0.5 N FeSO₄ 7

H₂O. Eventually the yellows green was very reddish over sharp. A blank solution was also run along with samples (Nelson and Sommers, 1982). The readings were noted for volume of FeSO₄. The equation for determining the % H₂O and the % organic materials was as follows:

$$\text{Organic Matter \%} = (\text{VK2Cr2O7} - \text{VFeSO4}) \times \text{N FeSO4} \times 0.003 \times 1.3 \times 1.724 \times 100$$

Weight of soil

Soil Phosphorous (P) and Potassium (K) (mg kg⁻¹)

Ten grams of soil were added to 20 mL of AB-DTPA solution and shaken for about 15 minutes. The mixture was then filtered through filter paper. From each sample, 1 mL of the filtrate was taken and mixed with 5 mL of ascorbic acid, then diluted to a final volume of 25 mL. To allow color development, the solution was kept for some time in a shaded area. Finally, potassium (K) and phosphorus (P) were determined using a flame photometer and spectrophotometer, respectively (Soltanpour and Schwab, 1977).

Soil Moisture Content

Soil samples were taken from each plot previous to sowing and crop harvest. Soil obtained from primitive samples was placed in the moisture hand cane and weighed and then dried at 105°C to constant weight and weighed again (Gardner, 1986).

Statistical Analysis

The data recorded for all the above-mentioned parameters during both years were combined over years for statistical analysis using ANOVA techniques appropriate for RCBD split-plot design. Means were compared by least significant differences (LSD) test at $P \leq 0.05$ upon significant F-test (Jan et al., 2009).

Results

Electric Conductivity (ds m⁻¹)

The data showed that nitrogen rates (NR), residue management (RM), and years influenced soil electrical conductivity (EC) after wheat and maize harvest. For wheat, NR significantly affected EC, with higher values recorded at N2 and N3 (0.87 dS m⁻¹) compared to the control N1 (0.86 dS m⁻¹). Similarly, for maize, N2 and N3 resulted in the highest EC (0.88 dS m⁻¹), which was significantly higher than N1 (0.81 dS m⁻¹). Residue management significantly affected EC after wheat harvest, where all residue treatments (0.87 dS m⁻¹) were higher than the control (0.85 dS m⁻¹). However, RM did not significantly influence EC after maize harvest. Year-wise comparison revealed that EC was significantly higher in 2022–23 (0.88 dS m⁻¹) than in 2021–22 (0.85 and 0.82 dS m⁻¹ for wheat and maize, respectively). Interactions between NR × RM were non-significant for both crops.

Soil pH

The results on soil pH after wheat and maize harvest indicated significant effects of NR, RM, and years. For wheat, NR significantly influenced soil pH, with the highest value recorded at N1 (7.5) followed by N2 (7.4) and the lowest at N3 (7.3). For maize, N1 maintained the highest pH (7.5), while N2 (7.3) and

N3 (7.2) recorded lower values. Regarding RM, wheat pH was significantly higher under 50% mulch (7.5) compared to other treatments (7.4), while maize also recorded the highest pH under control and 50% mulch (7.4) compared to lower values in N2 and 100% incorporated (7.3). Year-wise analysis revealed that soil pH was higher in 2021–22 (7.5) compared to 2022–23 (7.2) for both crops. Interactions between NR × RM were non-significant for both crops (Figure 1).

Soil Mineral Nitrogen (mg kg⁻¹)

The results on soil mineral nitrogen (mg kg⁻¹) after wheat and maize harvest showed significant effects of NR, RM, and years. Nitrogen application greatly increased soil mineral N, with the lowest values observed at N1 (5.4 and 6.1 mg kg⁻¹ for wheat and maize, respectively) and the highest at N3 (12.3 and 14.1 mg kg⁻¹). Among residue management practices, 100% incorporation recorded the highest soil mineral N (11.1 and 14.0 mg kg⁻¹ for wheat and maize, respectively), followed by 100% mulch (10.3 and 11.5 mg kg⁻¹) and 50% incorporation (9.7 and 11.1 mg kg⁻¹). Control and 50% mulch plots had comparatively lower values (8.3–10.5 mg kg⁻¹). Year-wise comparison revealed significantly higher mineral N in 2022–23 (9.9 and 12.1 mg kg⁻¹) compared to 2021–22 (9.4 and 10.7 mg kg⁻¹). The interaction NR × RM was significant for both wheat and maize.

Table 2. Impact of nitrogen rates and crop residue management on soil properties after wheat and maize harvest in 2021-22 and 2022-23.

Treatments		Electric conductivity (d Sm ⁻¹)		Soil pH		Soil mineral nitrogen (mg kg ⁻¹)	
Nitrogen (NR)	rates	Wheat	Maize	Wheat	Maize		
N1		0.86 b	0.81 b	7.5 a	7.5 a	5.4 c	6.1 b
N2		0.87 a	0.88 a	7.4 b	7.3 b	11.2 b	14.0 a
N3		0.87 a	0.88 a	7.3 c	7.2 c	12.3 a	14.1 a
LSD		0.01	0.02	0.1	0.1	0.6	0.8
Residue Management (RM)							
Control		0.85 b	0.85	7.4 b	7.4 a	8.3 c	10.0 c
50% incorporated		0.87 a	0.86	7.4 b	7.3 b	9.7 b	11.1 b
50% as mulch		0.87 a	0.86	7.5 a	7.4 a	8.9 c	10.5 c
100%		0.87 a	0.85	7.4 b	7.3 b	11.1 a	14.0 a
100% incorporated							
100% as mulch		0.87 a	0.85	7.4 b	7.4 a	10.3 b	11.5 b
LSD		0.02	NS	0.1	0.1	1.4	1.5
Year (Y)							
2021-22		0.85 b	0.82 b	7.5 a	7.5 a	9.4 b	10.7 b
2022-23		0.88 a	0.88 a	7.2 b	7.2 b	9.9 a	12.1 a
Significance for Y		**	*	*	**	*	*
Interactions							

NR × RM	NS	NS	**	**	NS	NS
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Identical letters with means in the similar category specify non-significant difference among the treatments. NS represents non-significant difference between the applied treatments. ***, ** and *** represents significance at the probability level of 0.001, 0.01 and 0.05 respectively.

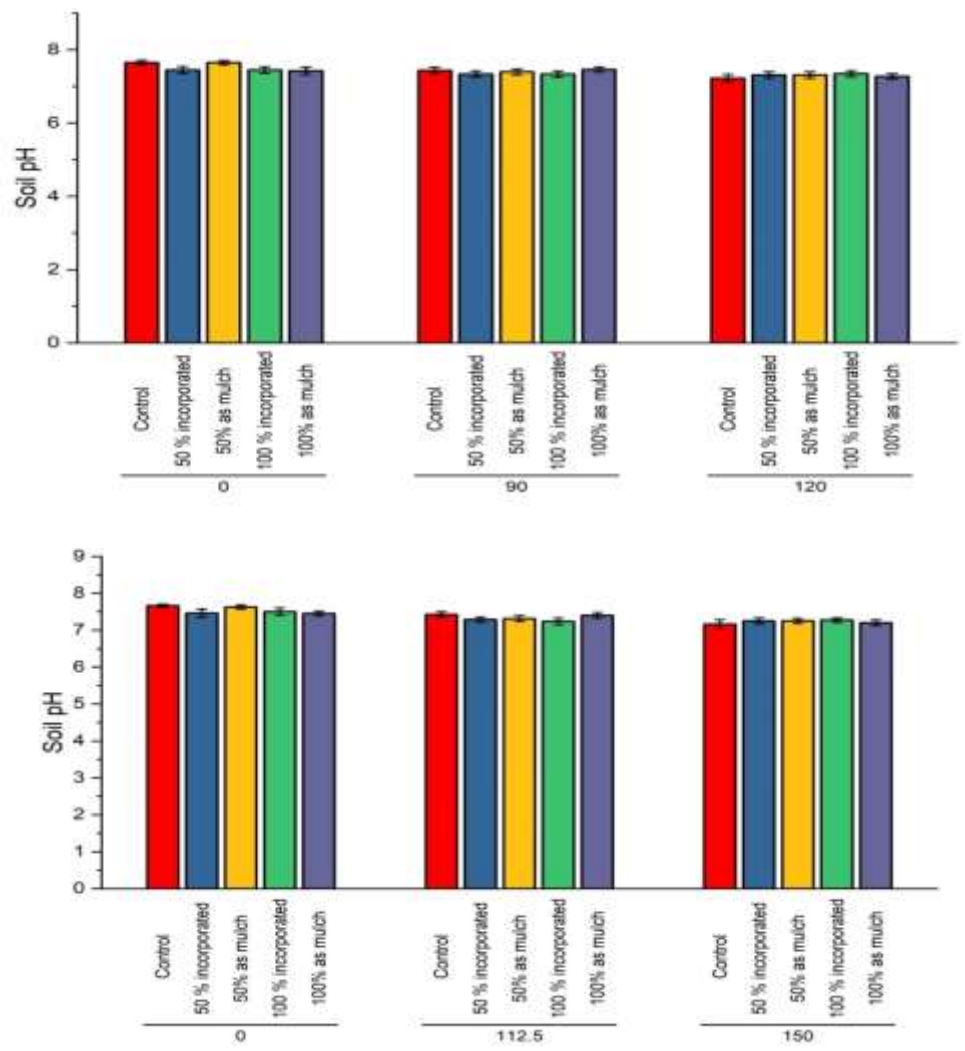


Figure 1. Planned mean comparison for soil pH after wheat and maize harvest. For wheat, N1 = 0 kg N ha⁻¹; N2 = 90 kg N ha⁻¹; N3 = 120 kg N ha⁻¹. For maize, N1 = 0 kg N ha⁻¹; N2 = 112.5 kg N ha⁻¹; N3 = 150 kg N ha⁻¹. Control = no residue applied; 50% residue incorporated = 7.5 tons ha⁻¹ incorporated; 50% as mulch = 7.5 tons ha⁻¹ as mulch; 100% residue incorporated = 15 7.5 tons ha⁻¹ incorporated; 100% residue as mulch = 15 tons ha⁻¹ as mulch.

Soil Total Nitrogen (mg kg⁻¹)

Among nitrogen treatments, N3 recorded the highest total N (831.5 and 835.9 mg kg⁻¹ for wheat and maize, respectively), followed by N2 (798.9 and 793.4 mg kg⁻¹), while the lowest was observed in N1 (661.9 and 668.2 mg kg⁻¹). Residue management also significantly influenced total N, with 100% incorporation resulting in the highest values (802.1 and 810.8 mg kg⁻¹), statistically similar to 50% incorporation (780.2 and 783.4 mg kg⁻¹), whereas control plots recorded the lowest total N (722.3 and

729.2 mg kg⁻¹). Year-wise analysis showed that 2022–23 had higher total N (804.2 and 806.3 mg kg⁻¹) compared to 2021–22 (724.0 and 725.3 mg kg⁻¹). The interaction between NR × RM was non-significant for both crops.

Soil Organic Matter (%)

The results on soil organic matter after wheat and maize harvest showed significant effects of NR, RM, and years. For NR, the highest organic matter was recorded at N3 (1.15 and 1.20% for wheat and maize, respectively), statistically similar to N2 (1.13 and 1.22%), while the lowest was observed in N1 (1.06 and 1.13%). Residue management further enhanced soil organic matter, with 100% incorporation producing the highest values (1.26 and 1.36%) followed by 50% incorporation (1.14 and 1.22%), whereas control plots recorded the lowest (0.95 and 1.02%). Year-wise comparison revealed significantly higher soil organic matter in 2022–23 (1.28 and 1.24%) compared to 2021–22 (0.95 and 1.12%). The interaction between NR × RM was non-significant for both wheat and maize.

Soil Phosphorus Content (mg kg⁻¹)

The results on soil phosphorus (mg kg⁻¹) after wheat and maize harvest showed that NR had no significant effect on soil P. RM, however, significantly influenced soil P, with 100% incorporation recording the highest values (3.9 and 3.8 mg kg⁻¹ for wheat and maize, respectively), followed by 50% incorporation and 100% mulch (3.8–3.5 mg kg⁻¹), while the lowest was observed in control and 50% mulch treatments (3.7–3.4 mg kg⁻¹). Year-wise comparison revealed significantly higher soil P in 2022–23 (3.9 mg kg⁻¹) than 2021–22 (3.6 mg kg⁻¹) for wheat, whereas no significant difference was found for maize. The interaction NR × RM was non-significant for both crops.

Table 3. Impact of nitrogen rates and crop residue management on soil properties after wheat and maize harvest in 2021-22 and 2022-23.

Treatments		Total nitrogen (mg kg ⁻¹)		Soil organic matter (%)		Soil phosphorus (mg kg ⁻¹)	
Nitrogen (NR)	rates	Wheat	Maize	Wheat	Maize		
N1		661.9 c	668.2 c	1.06 b	1.13 b	3.7	3.5
N2		798.9 b	793.4 b	1.13 a	1.22 a	3.8	3.5
N3		831.5 a	835.9 a	1.15 a	1.20 a	3.8	3.5
LSD		19.4	22.3	0.05	0.05	NS	NS
Residue Management (RM)							
Control		722.3 c	729.2 c	0.95 c	1.02 d	3.7 b	3.4 c
50% incorporated		780.2 ab	783.4 a	1.14 b	1.22 c	3.8 ab	3.5 b
50% as mulch		758.7 b	750.5 bc	1.11 b	1.15 b	3.7 b	3.4 c

100% incorporated	802.1 a	810.8 a	1.26 a	1.36 a	3.9 a	3.8 a
100% as mulch	757.1 b	755.2 ab	1.11 b	1.16 b	3.7 b	3.5 b
LSD	58.0	62.5	0.11	0.13	0.2	0.2
Year (Y)						
2021-22	724.0 b	725.3 b	0.95 b	1.12 b	3.6 b	3.5
2022-23	804.2 a	806.3 a	1.28 a	1.24 a	3.9 a	3.5
Significance for Y	**	*	*	**	*	NS
Interactions						
NR × RM	NS	NS	NS	NS	NS	NS

Identical letters with means in the similar category specify non-significant difference among the treatments. NS represents non-significant difference between the applied treatments. ***, ** and * represents significance at the probability level of 0.001, 0.01 and 0.05 respectively.

Soil Potassium (mg kg⁻¹)

The results on soil potassium after wheat and maize harvest indicated significant effects of NR, RM, and year. For wheat, NR significantly increased soil K, with the highest values at N2 (102.6) and N3 (105.0 mg kg⁻¹), both statistically higher than N1 (97.6 mg kg⁻¹). Similarly, for maize, the maximum K was recorded at N3 (99.4 mg kg⁻¹), followed by N2 (98.5 mg kg⁻¹), while N1 showed the lowest (91.6 mg kg⁻¹). Residue management practices also enhanced soil K, with all treatments (50% incorporated, 50% mulch, 100% incorporated, and 100% mulch) recording significantly higher values (102.3–104.9 mg kg⁻¹ for wheat; 96.7–103.5 mg kg⁻¹ for maize) compared to the control (94.1 and 86.3 mg kg⁻¹, respectively). Year-wise comparison showed no significant difference for wheat, whereas maize recorded higher K in 2022–23 (97.9 mg kg⁻¹) compared to 2021–22 (95.1 mg kg⁻¹). The NR × RM interaction was non-significant for both crops.

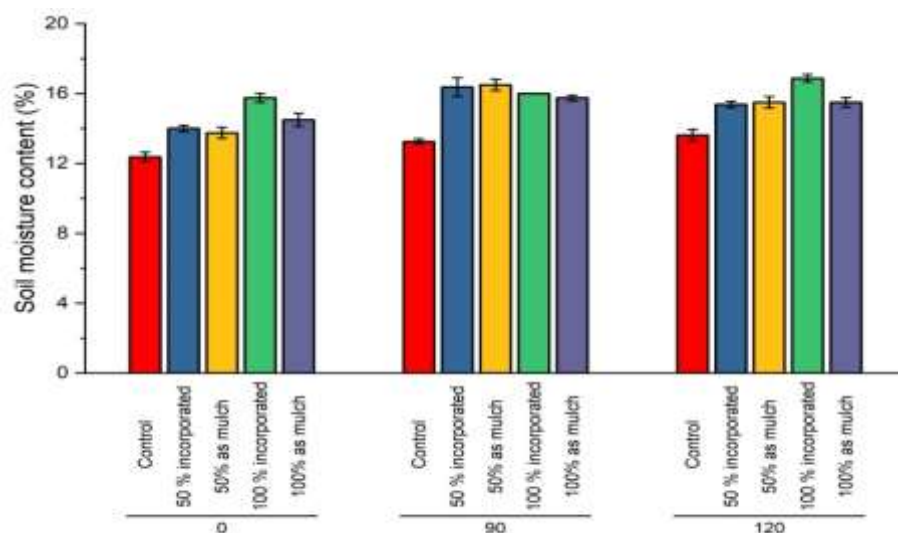
Soil Moisture Content (%)

The results on soil moisture (%) after wheat and maize harvest revealed significant effects of NR, RM, and years. For wheat, the highest soil moisture was recorded at N2 (15.6%) and N3 (15.4%), both significantly higher than N1 (14.1%). A similar trend was observed for maize, where N2 (15.2%) and N3 (15.3%) maintained higher soil moisture compared to N1 (14.0%). Residue management further improved soil moisture, with 100% incorporation recording the maximum values (16.2% for wheat and 15.9% for maize), while the lowest was observed in control plots (13.1% and 14.1%, respectively). Year-wise comparison showed higher soil moisture in 2022–23 (15.2%) than in 2021–22 (14.9%) for wheat, while differences were non-significant for maize. The NR × RM interaction was highly significant for both crops (Figure 2).

Table 4. Impact of nitrogen rates and crop residue management on soil properties after wheat and maize harvest in 2021-22 and 2022-23.

Treatments	Soil potassium (mg kg ⁻¹)		Soil moisture (%)	
Nitrogen rates (NR)	Wheat	Maize	Wheat	Maize
N1	97.6 b	91.6 c	14.1 c	14.0 b
N2	102.6 a	98.5 b	15.6 a	15.2 a
N3	105.0 a	99.4 a	15.4 a	15.3 a
LSD	4.9	4.0	0.4	0.4
Residue Management (RM)				
Control	94.1 b	86.3 b	13.1 c	14.1 cd
50% incorporated	102.6 a	96.7 a	15.3 b	14.8 b
50% as mulch	104.7 a	97.9 a	15.3 b	14.9 b
100% incorporated	104.9 a	103.5 a	16.2 a	15.9 a
100% as mulch	102.3 a	98.3 a	15.3 b	14.5 c
LSD	9.2	12.3	0.7	1.0
Year (Y)				
2021-22	100.9	95.1 b	14.9 b	14.8
2022-23	102.5	97.9 a	15.2 a	14.9
Significance for Y	NS	*	*	NS
Interactions				
NR × RM	NS	NS	**	**

Identical letters with means in the similar category specify non-significant difference among the treatments. NS represents non-significant difference between the applied treatments. ***, ** and * represents significance at the probability level of 0.001, 0.01 and 0.05 respectively.



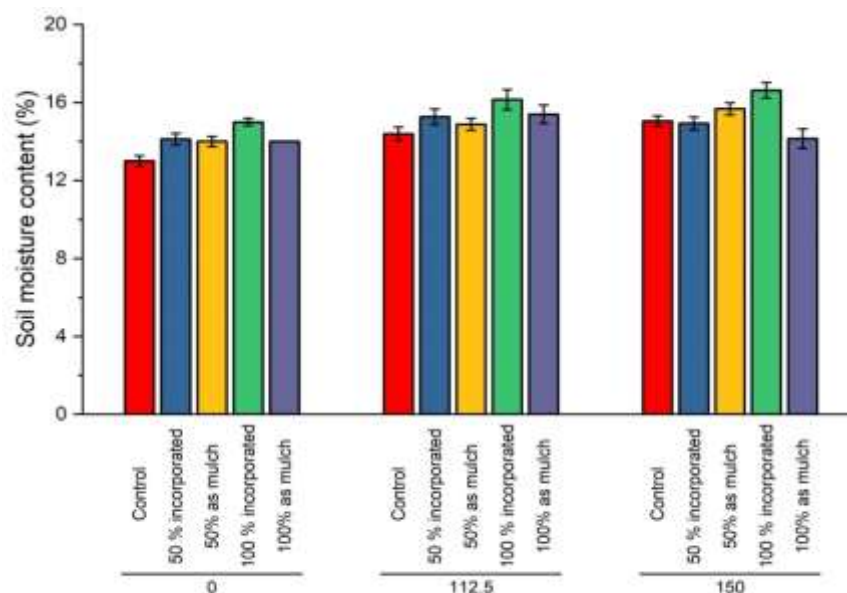


Figure 2. The N × RM interaction for soil moisture content (%) after wheat and maize harvest. For wheat, N1 = 0 kg N ha⁻¹; N2 = 90 kg N ha⁻¹; N3 = 120 kg N ha⁻¹. For maize, N2 = 112.5 kg N ha⁻¹; N3 = 150 kg N ha⁻¹. Control = no residue applied; 50% residue incorporated = 7.5 tons ha⁻¹ incorporated; 50% as mulch = 7.5 tons ha⁻¹ as mulch; 100% residue incorporated = 15 7.5 tons ha⁻¹ incorporated; 100% residue as mulch = 15 tons ha⁻¹ as mulch.

DISCUSSION

Soil EC increased with higher N rates due to the accumulation of fertilizer-derived ions (NH₄⁺, NO₃⁻) from urea hydrolysis and nitrification (Faust et al., 2023). Although statistically significant, the recorded values remained well below the threshold harmful to wheat growth (Hoffman et al., 1983). RM also raised EC compared to control, likely due to ionic release during residue decomposition (K⁺, Ca²⁺, Mg²⁺) and reduced evaporation (Farooqi et al., 2023). Higher EC in the second year reflected cumulative effects of residual nitrate and residue breakdown (Lei et al., 2025). Conversely, soil pH declined with increasing N rates, particularly at 120 kg N ha⁻¹ in wheat and 150 kg N ha⁻¹ in maize, primarily due to nitrification, where ammonium (NH₄⁺) from applied fertilizers is converted into nitrate (NO₃⁻), releasing hydrogen ions (H⁺) and acidifying the soil (Elrys et al., 2024), while plant uptake of ammonium further contributed to acidification through root exudation of H⁺ to maintain charge balance (Tang and Rengel, 2003). Residue management also influenced soil pH, as partial incorporation enhanced microbial activity and mineralization, increasing nitrification and acidification (Chen et al., 2014), while excessive residue retention could cause microbial immobilization and delay these effects (Grzyb et al., 2020). Organic residues acted as pH buffers, with organic acids released during decomposition either mitigating or amplifying acidification depending on residue composition and microbial dynamics (Atasoy et al., 2024).

The observed increase in soil mineral and total nitrogen with higher nitrogen rates is due to greater fertilizer-derived nitrogen availability, which undergoes mineralization and microbial transformation into ammonium (NH₄⁺) and nitrate (NO₃⁻) (Masse, 2016). Higher rates, such as 120 kg N ha⁻¹ in wheat

and 150 kg N ha⁻¹ in maize, enriched the soil nitrogen pool, with residual effects from previous applications and environmental conditions like soil moisture and temperature further enhancing mineralization (Kladivko and Keeney, 1987). Year-to-year variation showed higher mineral N in the second year, reflecting cumulative nitrogen inputs, improved microbial activity, and favorable conditions for organic N conversion (Xue et al., 2006). Residue management also influenced nitrogen dynamics, with 100% incorporation yielding the highest mineral N due to accelerated microbial decomposition and nutrient release (Jilling et al., 2018). In contrast, control and 50% mulch treatments showed lower values, linked to reduced organic inputs and slower mineralization, consistent with limited nitrogen availability (Otto et al., 2013).

The prominent influence of nitrogen rates and residue management on soil organic matter (SOM) underscores their importance in sustaining soil fertility and health after wheat harvest. Higher nitrogen rates (120 kg N ha⁻¹ in wheat and 150 kg N ha⁻¹ in maize) increased SOM by stimulating microbial biomass and activity, which accelerated organic matter decomposition and stabilization in soil (Bhattacharyya et al., 2019). Year-to-year variation showed higher SOM in the second year, likely due to residual nitrogen from prior applications, enhanced microbial dynamics, and favorable environmental conditions that promoted decomposition and SOM buildup (Fageria and Baligar, 2005). Residue management further shaped SOM dynamics, with 100% residue incorporation yielding the highest SOM due to greater organic inputs that supported microbial populations and carbon stabilization (Paul et al., 2016). Partial incorporation or mulching also improved SOM but less effectively, reflecting slower decomposition rates.

Our results confirm that N rates alone do not directly influence soil P availability post-harvest, as P retention and mobilization are primarily governed by soil physicochemical properties (e.g., pH, Fe/Al oxides) and microbial processes (Makowski et al., 2020). In calcareous soils, for instance, P solubility is driven by calcium-phosphate interactions rather than N-induced pH shifts, explaining the non-significant N effects observed (Zhou et al., 2024). Residue incorporation effects may have also strengthened over time as microbial communities adapted to organic inputs, increasing phosphatase activity and P release from organic pools (Chen et al., 2021). Among treatments, 100% incorporation increasing soil P by 0.2–0.3 mg kg⁻¹ compared to partial or mulch applications, supporting conservation agriculture principles that emphasize integrated residue use to enhance nutrient cycling (Sarkar et al., 2020). Similarly, soil potassium (K) increased with higher N rates, consistent with Sharma et al. (2012), as greater N availability enhanced plant growth, nutrient uptake, and subsequent K return through root exudates and residue decomposition (Yahaya et al., 2023). The highest soil K contents at 120 kg N ha⁻¹ in wheat and 150 kg N ha⁻¹ in maize highlight the role of N in stimulating overall nutrient cycling, while maximum values under 100% incorporation and 50% mulch application was noted due to increased soil organic matter and microbial activity enhancing K release during decomposition (Shahbaz et al., 2017). The gradual rise in soil K across years reflects cumulative residue additions, as organic inputs decompose and release K into the soil (Mouhamad et al., 2016), suggesting that while N fertilization indirectly contributes by boosting biomass and residue inputs, residue management remains the primary driver of K enrichment through organic matter turnover (Potrich et al., 2014).

Higher nitrogen application in both crops, coupled with 100% residue incorporation, promotes robust root growth and stimulates soil microbes to produce exopolysaccharides (Paul et al., 2024), which act as natural “biological glues” that stabilize soil macroaggregates, protecting capillary pores from collapse during wet–dry cycles and thus preserving water availability. Nitrogen also increases root exudation of organic acids such as citrate and malate (Nie et al., 2023), which accelerate mineral weathering and release essential cations like magnesium and calcium; these cations enhance clay–organic matter flocculation, forming microporous structures that retain water more effectively. At the same time, complete residue incorporation provides an organic matrix with an optimal carbon-to-nitrogen ratio of 25:1–30:1 (Singh et al., 2020), facilitating efficient decomposition by cellulolytic microbes such as *Streptomyces* and *Trichoderma*. This decomposition produces humic substances that bind with clay minerals to increase surface area and cation exchange capacity, further improving water adsorption, whereas partial incorporation or surface mulching often causes uneven decomposition and hydrophobic patches from lignin accumulation, resulting in only moderate gains in soil moisture retention.

Conclusion

This study demonstrated that integrating reduced nitrogen application with complete residue incorporation is an effective strategy to sustain soil fertility, enhance nutrient availability, and improve crop productivity in the wheat–maize system of Pakistan. Application of 90 kg N ha⁻¹ for wheat and 112.5 kg N ha⁻¹ for maize, when combined with 100% residue incorporation improved soil organic matter, mineral nitrogen, and moisture retention. Our experiment highlighted that reducing nitrogen input by 25% while adopting full residue incorporation can lower environmental risks associated with nitrogen losses, and strengthen long-term soil resilience.

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