EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(8), 28–42
https://doi.org/10.12912/27197050/205698
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.05.09
Accepted: 2025.07.17
Published: 2025.08.01

Nitrogen mineralization efficiency across wheat growth stages under no-tillage and conventional tillage systems (Marchouch, Morocco)

Kenza Kadiri Hassani[1,2,3*], Rachid Moussadek[1,2,3], Bouamar Baghdad[4], Abdelmjid Zouahri[3], Houria Dakak[3], Ahmed Douaik[3], Yousra Cheikhaoui[1], Hassnae Maher[2,3,5], Abdelhak Bouabdli[1]

[1] Laboratory of Geosciences, Department of Geology, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco
[2] International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat P.O. Box 1014,Morocco
[3] Research Unit on Environment and Conservation of Natural Resources, Regional Center of Rabat, National Institute of Agricultural Research, Rabat P.O. Box 6356, Morocco
[4] Casablanca School of Architecture and Landscape – Honoris United Universities, Rabat B.P. 20100, Morocco
[5] Laboratory of Materials, Nanotechnology and Environment, Department of Chemistry, Faculty of Sciences, Mohammed V University, Rabat B.P. 703, Morocco
* Corresponding author's e-mail: kenza.kadiri-hassani@uit.ac.ma

ABSTRACT

The present study aimed to determine the optimal nitrogen dose that preserves soil mineralization properties. The evaluation managed for ammonium (NH_4^+), nitrate (NO_3^-) and mineral nitrogen (N min) concentrations under no-tillage (NT) and conventional tillage (CT) systems. The experiment was monitored in the greenhouse of the National Institute of Agricultural Research (INRA) in Rabat, Morocco, using a vertisol soil type from Marchouch INRA station. The analysis of variance (ANOVA) revealed a highly significant effect of sampling stage (stages 1,2,3 and 4; $p < 0.001$), and significant effects of nitrogen dose (0, 50, 100, and 150 kg/ha; $p < 0.05$) and tillage system (CT vs NT; $p < 0.05$). Several significant interactions between these factors were considered. The NH_4^+ concentrations were influenced by stage × tillage system × depth, stage × tillage system, and stage × dose interactions ($p < 0.05$). For NO_3^-, a significant stage × dose interaction was detected ($p < 0.05$), while for N min, a significant tillage system × dose interaction was found ($p < 0.05$). The recommended optimal dose is 50 kg/ha, which demonstrated a nitrogen mineralization efficiency of 63% at the 0–10 cm depth and 40% at the 10–20 cm depth under NT. Nitrogen doses exceeding 100 kg/ha resulted in substantial N min losses under both tillage systems. These results provide new patterns into the nitrogen dose-tillage systems interaction in vertisol soils, offering the first experimental quantification of N mineralization efficiency across wheat growth stages in Marchouch, Morocco.

Keywords: mineral nitrogen, ammonium nitrate, ANOVA, conventional tillage, no-tillage, Morocco.

INTRODUCTION

Nitrogen (N) is a nutrient element influencing crop productivity and sustainability of the agricultural systems, particularly cereals, which require balanced nitrogen inputs to maximize yield and minimize losses (Moussadek, 2012; Neufeld, 2020). However, excessive or inefficient nitrogen use can degrade natural resources, reduce biodiversity, and cause socio-economic repercussions (Maher et al., 2023; INRA, 2024). Nitrogen management in agricultural soils represents a major challenge for cereal crops. It is an essential nutrient for their growth and yield (Moussadek et al., 2023). Nitrogen is a principal component of proteins and enzymes that plays an important role for plant metabolism. However, the inefficient nitrogen management can lead to some significant economic and environmental losses, due to volatilization, leaching, or denitrification. These consequences affect the farm profitability, and contribute to the environmental pollution, particularly on groundwater resources (Neufeld, 2020). Optimizing the nitrogen use is therefore essential to ensure the agricultural efficiency production while preserving the environment.

In North Africa, CT remains deeply embedded in agricultural practices. Rainfed and irrigated crops, notably wheat, are typically established through mechanical soil preparation, accompanied by the consideration of various factors. Due to the growing scarcity of resources, the adverse impacts of climate change and increasing demographic pressure, the productivity of the conventional tillage (CT) system has become constrained, posing an intense challenge that necessitates production enhancements (Mrabet et al., 2022). Agricultural research and development initiatives, shifted the interest on conservation agriculture practices alternatives such as the NT system. The NT practices incorporate, soil non-disturbance, residue cover maintenance, and diverse crop rotations (Robinson et al., 2024). The no-tillage (NT) adoption is being explored and expanded across diverse climatic conditions, including semi-arid regions (Kadiri Hassani et al., 2024). Over time, NT has demonstrated the potential to mitigate drought effects and improve soil water retention.

The expansion of NT system in Moroccan semi-arid regions has gained prominence as a sustainable agricultural practice, addressing the limitations of CT system, as reported by Moussadek (2012). The impacts of NT are measurable in terms of, improved crop productivity, enhanced environmental stability, and reduced economic costs over long term. The recent years accentuate the challenges imposed by climate change have intensified the focus of agricultural research on preserving soil and water resources.

Many years of research have documented the benefits of NT for, enhancing soil health, improving the crop establishment, and achieving stable yields in adequacy with the environment (Mrabet et al., 2012; Moussadek et al., 2023). These advantages are relevant for durum wheat production under NT, as cereal represent an indefectible role in the agricultural economies of many countries (Kadiri Hassani et al., 2024; Mrabet, 2011). Conforming to the Mediterranean regional studies, wheat yields under NT can surpass those of CT systems by 8% to 20% (Neufeld, 2020).

However, realizing these benefits under NT also depends on the effective fertilization management (Maher et al., 2023). Particular attention is being directed towards the evaluation of nutrient elements, such as nitrogen (N), and identification of mechanisms that optimize their utilization. Nitrogen is a nutrient element influencing crop productivity and sustainability of the agricultural systems, particularly cereals, which require balanced nitrogen inputs to maximize yield and minimize losses (Moussadek, 2012; Neufeld, 2020). However, excessive or inefficient nitrogen use can degrade natural resources, reduce biodiversity, and cause socio-economic repercussions. Despite increasing attention to conservation agriculture, a significant knowledge gap remains. Thus, regarding how nitrogen mineralization dynamics vary across wheat growth stages, under different tillage systems and nitrogen doses. Particularly in vertisol soils, typical of Morocco's semi-arid zones (Maher et al., 2023; INRA, 2024). Few studies have quantified how ammonium (NH_4^+), nitrate (NO_3^-), and mineral nitrogen (N min) concentrations respond to tillage system × nitrogen dose × depths interactions, especially in controlled environments that isolate these variables (Jat et al., 2017; Mrabet et al., 2022; Olfs et al., 2006).

This study aimed to determine the optimal nitrogen dose that enhances soil nitrogen mineralization efficiency under no-tillage and conservation tillage systems across wheat growth stages, in a greenhouse controlled vertisol setting.

It sought to quantify how nitrogen mineralization evolutions vary with soil depth and tillage systems, and to identify the interaction effects between, sampling stage, nitrogen dose, tillage system, and depth. The research specially addresses the lack of empirical data on nitrogen efficiency patterns under NT and CT in Moroccan vertisols, offering alternatives into how nitrogen management can be tailored for conservation agriculture.

The authors hypothesize that:

- Moderate nitrogen doses (50 kg/ha) will achieve higher mineralization efficiency compared to excessive doses.
- No-tillage system will show enhanced nitrogen retention and mineralization at surface soil layers.

- Sampling stage × tillage system ×nitrogen dose interactions will significantly affect nitrogen dynamics.

The findings aimed to bridge a critical gap in sustainable nutrient management strategies for semi-arid agroecosystems. Thus, with implications for improving wheat productivity while minimizing environmental impacts.

MATERIALS AND METHODS

This section outlines the experimental procedures to evaluate N mineralization dynamics under NT and CT systems, as the methodologies used to monitor mineral nitrogen (N min), ammonium (NH_4^+), and nitrate (NO_3^-) concentrations in a controlled greenhouse.

Field sampling and soil characteristics

The experiment was conducted during the 2022–2023 crop season. A total of 24 soil samples were collected using cylinders (16 cm diameter × 26 cm height) from, the National Institute of Agricultural Research (INRA) Marchouch experimental station (Figure 1). The sampling consisted of 12 cylinders taken from a CT managed plot and 12 cylinders from a NT managed plot, where NT practices have been applied for over 18 years. The INRA Marchouch station is located approximately 60 km Southeast of Rabat, Morocco, at latitude 33°37′ N and longitude 6°43′ W (Figure 1). The region is characterized by a warm, temperate Mediterranean climate, with an average temperature of 19.9 °C and an annual precipitation of 289 mm in 2022 (NASA Power, 2024).

Before the greenhouse experiment, a composite soil analysis was performed on the samples collected from two depth intervals (0–20 and 20–40 cm). The samples were directly transported to, the Soil and Water Chemistry Laboratory of the Research Unit on Environment and Conservation of Natural Resources (URECRN), INRA Rabat, to obtain the initial information about the soil physicochemical properties.

The soil characterization is essential to understand its inherent properties. The analysis conducted for this study identified the soil as a vertisol, characterized by a clay content of 40% (Tables 1 and 2). The granulometric and the physicochemical analyses provide a comprehensive overview of the soil texture and chemical composition. These baseline data form the foundation for subsequent evaluations of soil responses to nitrogen treatments and tillage systems (NT and CT) throughout the experimental protocol.

This step provided essential preliminary information on the soil composition, allowing to frame the experimental protocol choice.

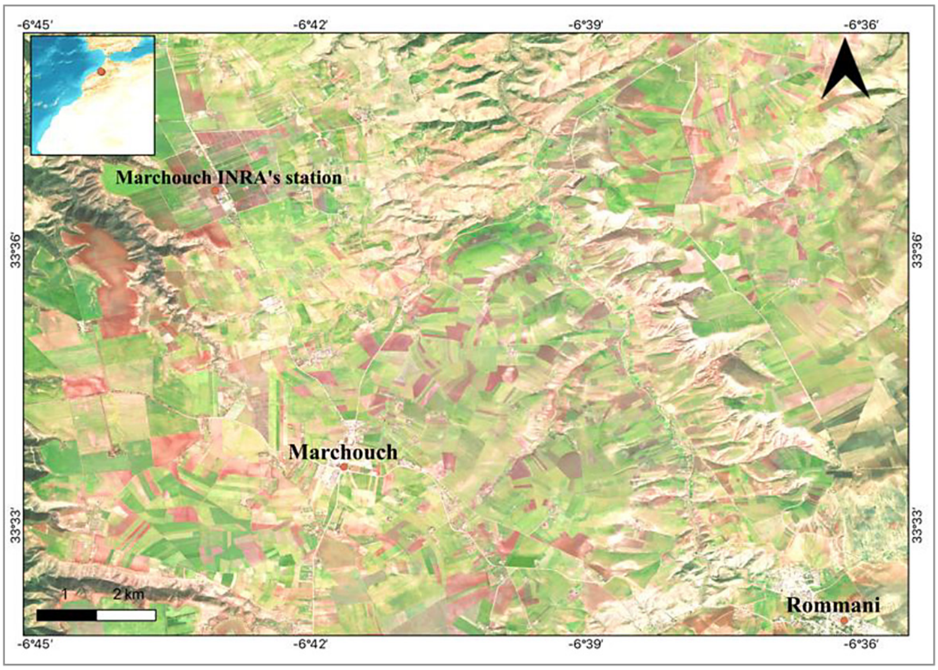

Figure 1. Location of Marchouch INRA's experimental station

Table 1. Soil granulometry analysis

Type	Depth	Clay (%)	Silt (%)	Sand (%)
NT	0–20	40.0	49.7	10.3
	20–40	40.0	49.7	10.3
CT	0–20	40.0	45.8	14.2
	20–40	40.0	44.8	15.2

Table 2. Initial chemical analysis of soil properties

Type	Depth (cm)	pH water	pH Kcl	MO %	CE µs/cm	Na^+ mg/kg	K^+ mg/kg	N total (%)	NH_4^+ mg/kg	NO_3^- mg/kg	P mg/kg	Ca^{++} mg/kg	Mg^{++} mg/kg
CT	0–20	6.3	5.2	1.71	461	0.32	301.3	0.014	28.6	114.3	90.5	140	90
	20–40	6.1	4.9	1.07	369	0.33	111.5	0.007	35.7	35.7	76.4	160	40
NT	0–20	6.9	6.1	1.74	1057	0.37	195.8	0.007	50.0	121.4	68.6	190	80
	20–40	7.3	6.3	1.77	537	0.42	289.2	0.007	35.7	42.9	47.3	200	20

Experimental protocol

This part describes the experimental protocol established to monitor and assess the dynamics of mineral nitrogen (N min), NH_4^+, and NO_3^-. The agronomic trial was conducted under controlled conditions, in the greenhouse of the Research Unit on Environment and Conservation of Natural Resources (URECRN), INRA Rabat. The experimental design, illustrated in Figure 2, involved the application of four N doses (0, 50, 100 and 150 N kg/ha), evaluated at two soil depths (0–10 cm and 10–20 cm), four sampling stages, and under two tillage systems (NT and CT). A randomized complete block was implemented. Durum wheat (*Triticum turgidum* L. var. *durum*) of the Faraj variety, developed in Morocco and supplied by INRA (2024), was used and sown at a rate of 30 seeds per cylinder. This variety was selected for its regional adaptation and relevance to the Moroccan cereal production systems.

Referencing to nitrogen efficiency, fertilization was applied in two split doses. One-third of the total nitrogen was supplied at the beginning, using ammonium sulfate (21%), while the remaining two-thirds were applied at the stem elongation stage in the ammonium nitrate (33.5%) form (Table 3). The application doses were adjusted based on the measured bulk density, which was 1.2 g/cm^3 for CT and 1.3 g/cm^3 for NT.

To assess soil nitrogen dynamics throughout the wheat growth cycle, soil samples were collected at three-week intervals. The sampling protocol is in adequacy with the standard nitrogen analysis procedures as described by Maher et al. (2023), Sellami et al. (2023), and Maynard (2007). These periodic samplings aimed to pursue the evolution of mineral nitrogen (N min), NH_4^+, and NO_3^- concentrations over time. The first sampling was realized before sowing, and the final sampling occurred immediately after the harvest period. This sequential monitoring enabled a comprehensive evaluation of nitrogen availability and evolution.

Statistical analysis

Statistical analyses were performed using SPSS (Version 25 (IBM Corp., Armonk, NY, USA)). The dataset reported in Excel form (Index (Supplementary Online Material)), included a total of 192 samples, based on 4 nitrogen doses (0, 50, 100 and 150 kg N/ha) × 2 tillage systems (NT and CT) × 2 soil depths (0–10 and 10–20 cm) × 4 sampling stages, with 3 replicates per treatment combination.

Before applying parametric tests, the assumptions of normality and homogeneity of variances were verified. Normality of residuals was assessed using the Shapiro-Wilk test, and homogeneity of variances was tested with Levene's test. Both tests were conducted at a 95% confidence level ($\alpha = 0.05$).

The variables meeting these assumptions were analyzed using three-way Analysis of Variance (ANOVA) to determine the effects of tillage system, nitrogen dose, sampling stage, soil depth as well as their interactions, on the concentrations of NH_4^+, NO_3^- and N min.

When statistically significant main or interaction effects where observed ($p < 0.05$), Tukey's honest significant difference (HSD) was applied to identify specific differences between treatment

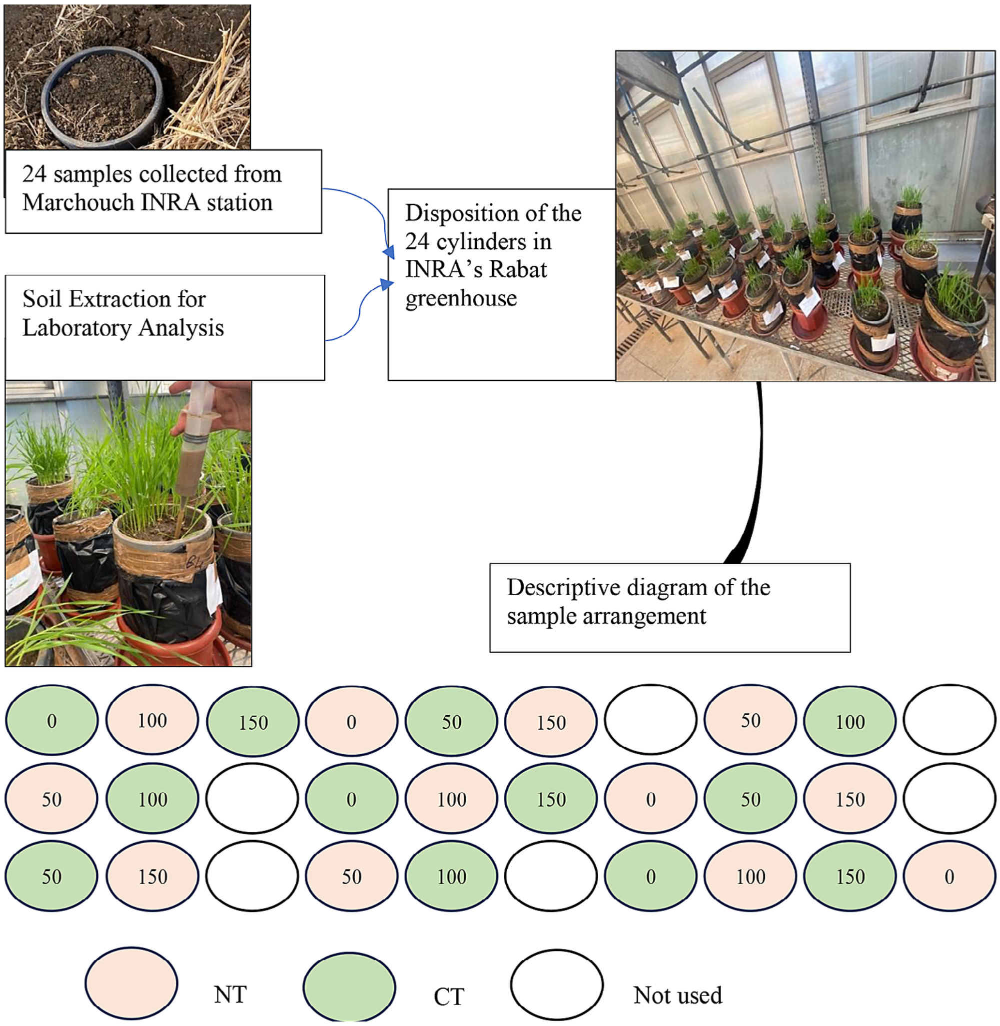

Figure 2. Descriptive diagram of the process implemented for the evaluation of N min, NH_4^+ and NO_3^- at INRA Rabat

means. Significance was established at $p < 0.05$, and all reported *p*-values were two-tailed. The results of these analysis were presented and discussed in the following section.

RESULTS AND DISCUSSION

The results are presented in three predefined sections, each part addressing the findings from a distinct perspective. The focus lies on elucidating the dynamics of NH_4^+, NO_3^-, and N min throughout the study period.

Concentrations of N min,NH_4^+ and NO_3^- before sowing and after harvest obtained on NT and CT

The nitrogen management is primordial for durum wheat productivity while minimizing environmental impacts. The concentrations of NH_4^+, NO_3^-, and N min in soils repartition are influenced by tillage systems and their quality. At the initial stage, soil analysis at the 0–10 cm depth revealed comparable N min concentrations under the NT and CT systems (Figure 3). The N min under NT was, 81.0 mg/kg including, 42.3 mg/kg of NH_4^+ and 38.7 mg/kg of NO_3^-. Under CT, the N min obtained was 80.4 mg/kg with, 44.1 mg/kg of NH_4^+ and 36.3 mg/kg of NO_3^-. The difference in N min between the two systems was minimal. Notably, the NO_3^- concentrations were slightly higher under NT, whereas the NH_4^+ concentrations were marginally elevated under CT. For the 10–20 cm depth, N min under mean concentrations was 75.6 mg/kg, with 37.5 mg/kg of NH_4^+ and 38.1 mg/kg of NO_3^-. Under CT, N min mean concentrations was 85.7 mg/kg, with 50.6 mg/kg of NH_4^+ and 35.1 mg/kg of NO_3^- (Figure 3).

Table 3. The contribution of nitrogen doses used under NT and CT in the greenhouse experimentation for each cylinder

Type of tillage	Nitrogen doses (kg /ha)	Dose of nitrogen with ammonium sulfate 21% (g)	Dose of nitrogen with ammonium nitrate 33.5% (g)
NT	0	0.00	0.00
	50	0.04	0.07
	100	0.07	0.14
	150	0.11	0.22
CT	0	0.00	0.00
	50	0.04	0.08
	100	0.08	0.15
	150	0.11	0.23

Although, the differences were subtle. It indicates a potential positive effect of NT on nitrogen retention, particularly in enhancing NO_3^- accumulation at depth. Conversely, NH_4^+ concentrations were slightly more pronounced under CT, which may reflect differences in soil aeration and microbial activity associated with tillage disturbance.

The results in Figure 3 illustrate nitrogen variation and its distribution patterns as influenced by the two tillage systems (NT and CT). The NT system appears to promote greater retention of NO_3^- and overall N min, particularly at the 10–20 cm depth, whereas the CT system tends to favor higher NH_4^+ retention across both soil depths.

The final sampling stage related in Figure 4, the NO_3^- mean concentrations at the 0–10 cm depth under NT increased, notably with higher nitrogen doses. The concentrations related 14.3mg/kg at the 100 kg/ha dose and 16.7 mg/kg for the dose of 150 kg/ha. Under CT, NO_3^- concentrations were moderately lower, with 16.7 mg/kg at the 100 kg/ha dose and declining to 9.5 mg/kg at the 150 kg/ha dose. In contrast, the NH_4^+ concentrations consistently remained elevated under CT for all the nitrogen doses tested. Under CT, the mean NH_4^+ concentrations for the doses, 0, 50, 100, and 150 kg/ha, were 33.3, 35.7, 28.6, and 33.3 mg/kg, respectively. Under NT, the corresponding NH_4^+ concentrations were lower: 11.9, 9.5, 14.3, and 23.8 mg/kg. For the 10–20 cm depth, a continuous increase in NO_3^- concentrations under NT were observed, beginning at the dose of 100 kg/ha (14.3mg/kg) and confirmed at the dose of 15 kg/ha (19.1 mg/kg). Under CT, NO_3^- concentrations at these doses were lower, recording to 11.9 mg/kg at 100 kg/ha and 14.3 mg/kg at 150 kg/ha (Figure 4).

Additionally, NH_4^+ concentrations at the 10–20 cm depth under NT showed a modest increase, particularly at the highest nitrogen dose, reaching 19.1 mg/kg. These findings underscore the importance of selecting an appropriate tillage system to optimize nitrogen distribution and availability. This is consistent with previous research related to the agronomic relevance of tillage practices on

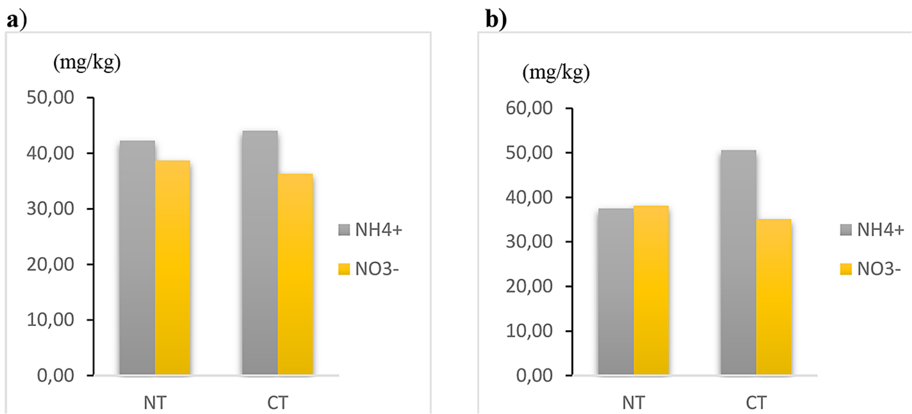

Figure 3. Initial sampling stage analysis results for NH_4^+ and NO_3^- mean concentrations (mg/kg) at the depths 0–10 cm (a), and 10–20 cm (b), under both tillage systems (CT and NT)

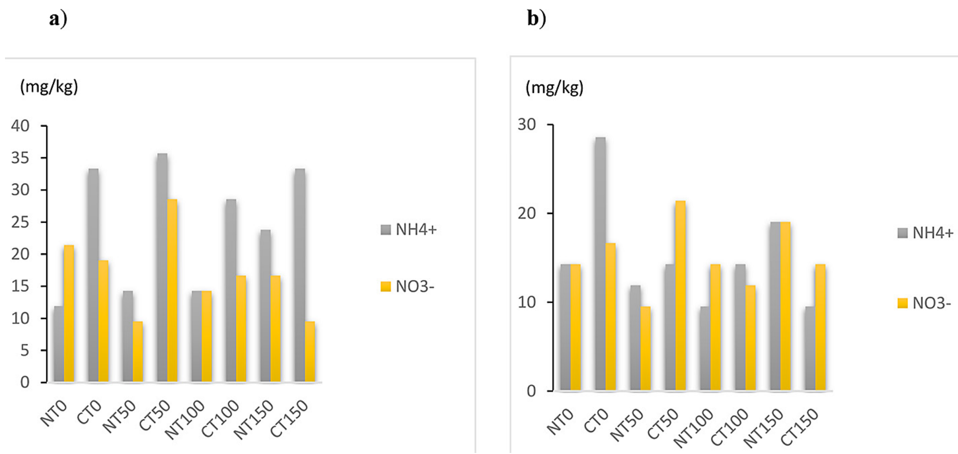

Figure 4. Final sampling stage analysis results for NH_4^+ and NO_3^- concentrations (mg/kg) at the depths 0–10 cm (a), and 10–20 cm (b), for each dose (0, 50, 100 and 150 kg/ha) respectively compared under NT (NT0, NT50, NT100 and NT150) and CT (CT0, CT50, CT100 and CT150)

wheat performance and nutrient dynamics (Devita et al., 2007; Farooq et al., 2011; Yang et al., 2015; Hirzel et al., 2019; Han et al., 2020; Bartaula et al., 2020).

The both soil depths presented in Figure 4 define the interest to work on the efficiency of nitrogen fertilization, which appears to be greater at the interval of nitrogen doses from 50 to 100 kg/ha. At the 0–10 cm depth, mean NH_4^+ concentrations, under NT for, the 50, 100, and 150 kg/ha doses were 14.3, 14.3, and 23.8 mg/kg, respectively. These values correspond to a reduction of 66%, 66%, and 44%, relatively to the initial concentrations. Comparably, under CT, NH_4^+ mean concentrations at the same doses were 35.7, 28.6, and 33.3 mg/kg, reflecting a reduction of 19%, 35%, and 24%, respectively. This indicates a stable retention of NH_4^+ concentrations under CT at this depth across the doses tested. For NO_3^- concentrations at this same depth, NT treatments recorded 9.5, 16.7, and 23.8 mg/kg for the 50, 100, and 150 kg/ha doses. These reflect decreases of 75%, 57%, and 38% relative to initial concentrations. Under CT, corresponding values were 28.6,16.7, and 9.5 mg/kg, with reductions of 21%, 54%, and 74%, respectively. These results suggest that NT favored a gradual increase and retention of NO_3^- with higher nitrogen doses, while CT displayed a more variable pattern.

Corresponding to the 10–20 cm depth, the NH_4^+ mean concentrations under NT were for the doses 11.9, 9.5, and 19.1 mg/kg for the 50, 100, and 150 kg/ha, indicating comparatively to the initial stage (Figure 3) decreases of 68%, 79%, and 49%. Under CT, the NH_4^+ mean concentrations were 14.3, 14.3, and 9.5 mg/kg, corresponding to the reduction of 72%,72%, and 81%, respectively. These indicates more consistency for the NH_4^+ under CT in concordance with the doses, and a greater variability under NT. For the mean concentration values of NO_3^-, under NT were 9.5, 14.3, and 19.1 mg/kg, presenting a reduction of 75%,62%, and 50% relative to baseline levels. The mean concentrations of CT were equal to 21.4, 11.9, and 14.3 mg/kg, with a respective reduction of 39%, 66%, and 59%.

Overall, these results demonstrate that nitrogen mineralization efficiency is influenced by the interaction of tillage system, nitrogen dose, and soil depth, factors corroborated by the ANOVA analysis. The NT system shows promise for enhancing NO_3^- retention, particularly at higher nitrogen doses and deeper soil layers, while CT tends to maintain more stable NH_4^+ levels.

Effects and interactions of tillage system, soil depth, nitrogen dose, and growth stage on N min, NH_4^+ and NO_3^-

A descriptive statistical analysis was conducted to verify the normality and distribution characteristics of the data for NH_4^+, NO_3^-, and N min concentrations. This preliminary step ensured the robustness of subsequent inferential analyses. The analysis was performed using SPSS software version 25 (IBM Corp., Armonk, NY, USA), and results were summarized across the different combinations of tillage system, soil depth, nitrogen dose, and wheat growth stages. The CT system ranged mean concentrations values for, N min from 23.8 to 119.1 mg/kg, the NH_4^+, and the NO_3^- varied between 9.5 and 64.3 mg/kg. Concerning the NT system, mean concentrations values interval for, N min was between 21.4 to 133.3 mg/kg, the NH_4^+, between 9.5 and 61.9 mg/kg and the NO_3^-, ranging from 9.5 to 78.6 mg/kg (Table 4).

These preliminary descriptive statistics indicate that under NT, both total mineral nitrogen (N min) and NO_3^- concentrations reached higher maximum values compared to CT, suggesting a potential enhancement of nitrogen retention and availability under conservation practices. Conversely, NH_4^+ concentrations were relatively similar between the two systems.

The ANOVA analysis (Table 5) performs to evaluate the individual and interactive effects of the factors experimented; tillage system, soil depth, nitrogen dose, and growth stage on nitrogen variables (N min, NH_4^+, and NO_3^-). The findings revealed that the stage impact with a highly significant effect on all the nitrogen variables ($p < 0.001$), underlining the importance of crop phenology in the appropriation of the nitrogen dynamics throughout the wheat cycle. Additionally, the tillage system and nitrogen dose revealed a significant main effect on NH_4^+ concentrations ($p < 0.05$), indicating the notably influence on the NH_4^+ availability (Table 5).

Several significant interaction effects were also identified:

- For NH_4^+, interactions were significant for stage × tillage system × depth, stage × dose × depth, stage × tillage system, and stage × dose ($p < 0.05$).
- For NO_3^-, a significant interaction was observed between stage × depth ($p < 0.05$).
- For N min, the interaction tillage system × dose was significant ($p < 0.05$), highlighting that nitrogen availability is influenced by the combined effects of soil management and fertilization practices (Table 5).

Table. 4. The mean concentrations rang for, N min, NH_4^+ and NO_3^- (mg/kg)

Tillage system	Variable	Minimum	Maximum	Mean	*p*-value
CT	NH_4^+	9.5	64.3	38.8	13.8
	NO_3^-	9.5	64.3	34.8	14.5
	N min	23.8	119.0	73.6	25.0
NT	NH_4^+	9.5	61.9	35.9	14.8
	NO_3^-	9.5	78.6	35.5	16.9
	N min	21.4	133.3	71.4	29.9

Table 5. ANOVA results for NH_4^+, NO_3^-, and N min variables

Source	Degrees of freedom	N min (mg/kg)		NO_3^- (mg/kg)		NH_4^+(mg/kg)	
		F value	p-value	F value	p-value	F value	p-value
Stage (S)	3	147 669	0.000	84 576	0.000	103 349	0.000
Tillage system (T)	1	0.950	0.355	0.159	0.699	5 413	0.045
Dose (Do)	3	1 582	0.261	0.705	0.573	5 043	0.025
Depth (De)	1	0.068	0.801	0.159	0.699	1 028	0.337
Do * De	3	1 993	0.186	4 176	0.041	.801	0.524
S * De	3	2 937	0.092	0.574	0.647	7 130	0.009
T * De	1	.511	0.493	0.096	0.763	.801	0.394
S * Do	9	3 552	0.036	2 500	0.094	4 622	0.016
T * Do	3	5 117	0.024	2 320	0.144	5 356	0.022
S * T	3	2 924	0.092	0.416	0.746	7 187	0.009
S * Do * De	9	0.921	0.548	0.612	0.762	3 575	0.036
T * Do * De	3	0.916	0.471	1 166	0.375	0.991	0.440
S * T * De	3	1 961	0.190	1 140	0.384	5 100	0.025
S * T * Do	9	1 730	0.213	2 206	0.127	2 310	0.114

It is important to emphasize that these findings were observed within the same soil type (Tables 1 and 2), a vertisol with 40% clay content. The long-term application of NT maintained for over 18 years – has likely contributed to enhanced soil structural stability, improving nutrient conservation, particularly for N min. This positive effect of NT on nitrogen retention and availability aligns with earlier studies, which demonstrated long-term benefits of conservation agriculture on nutrient cycling and soil quality (Oorts, 2006; Olfs et al., 2005; Franchini et al., 2006; Hungria et al., 2009).

Supporting evidence can be found in Alburquerque et al. (2015), who reported substantial nitrogen accumulation after 21 years of NT and Zihlmann et al. (2006), who observed more sustained nitrogen mineralization under NT after 11 years, reinforcing these findings. Together, these results highlight the importance of considering interactive effects, when assessing nitrogen management strategies under varying tillage systems.

The interaction tests highlighted the effects of the stage and the nitrogen dose applied (Tables 5 and 6). Eventually, a significant effect appeared at the second sampling stage, with concentration values of NH_4^+ (49.0 mg/kg), NO_3^- (53.7 mg/kg), and N min (102.7 mg/kg). The phenomenon observed at this stage is more pronounced, as the wheat is expected to accumulate a reserve of N min to support its growth phases.

The application of the four nitrogen doses (0, 50, 100, and 150 kg/ha) revealed distinct devices in nitrogen dynamics, generating an optimal dose for each nitrogen form. As expected in Table 6, the dose of 50 kg/ha resulted in the highest mean concentrations of the NH_4^+ (41.4 mg/kg) and N min (76.5 mg/kg), while 100 kg/ha emerged as interesting for the NO_3^- (36.8 mg/kg). These elements reinforce the importance of dose effectiveness choice to support wheat growth, consistent with the conclusions drawn by Sadiq et al. (2021).

Further in-depth, analyses were conducted by examining NH_4^+, NO_3^-, and N min concentrations at the four stages, nitrogen dose, and soil depth (0–10 and 10–20 cm) under both systems (CT and NT). The ANOVA results (Table 5) indicated no significant differences on the soil depth factor ($p = 0.337$), suggesting to continue the ANOVA process without considering this factor.

Consequently, Table 7 illustrates the progression of NH_4^+, NO_3^-, and N min concentrations across the four growth stages and nitrogen doses for each tillage system. Nitrogen applications were subdivided in two parts: the first between stages 1 and 2 and the second between stages 2 and 3, applied at the 50, 100, and 150 kg/ha doses. The concentration trends were analyzed variable by variable.

The NH_4^+ concentrations were disclosed, the second stage marked with the peak of concentrations. Under CT, the high mean concentrations are assigned to the dose of 150 kg/ha (56 mg/kg), succeeded by the doses, 50 kg/ha (50 mg/kg),100 kg/ha (45.2 mg/kg), and 0 kg/ha (39.3 mg/kg). Under NT, the NH_4^+concentrations were elevated at the dose 100 kg/ha (57.1 mg/kg), pursued by the dose, 50 kg/ha (51.2 mg/kg), and equal mean concentrations for the doses, 0 and 150 kg/ha (46.4 mg/kg).

The third stage, is affected by a general decline in NH_4^+ concentrations. Under CT, the dose of 50 kg/ha maintained the highest mean (46.4 mg/kg), followed by the doses,0 kg/ha (39.3 mg/kg), 150 kg/ha (28.6 mg/kg), and 100 kg/ha (27.4 mg/kg). Conversely, under NT, means were highest for the dose of,0 kg/ha (46.4 mg/kg), succeeded

Table 6. Tukey's HSD post-hoc test for stage and dose factors

Parameter		NH_4^+	NO_3^-	N min
Stage	1	43.6(a)	37.1(b)	80.7(b)
	2	49.0(a)	53.7 (a)	102.7(a)
	3	36.9(b)	33.8(b)	70.7(b)
	4	19.8 (c)	16.1(c)	35.9(c)
Dose (kg/ha)	0	36.9 (ab)	33.3(a)	70.2 (a)
	50	41.4 (a)*	35.1(a)	76.5(a)
	100	35.9 (ab)	36.8(a)	72.6(a)
	150	35.1 (b)	35.4(a)	70.5(a)

Note: * p-value < 0.05.

Table 7. The evolution of NH_4^+, NO_3^-, and N min, mean concentrations under CT and NT depending on stages (1, 2, 3 and 4) and doses (0, 50, 100 and 150 kg/ha)

Parameter			Stages			
Dose (kg/ha)	Tillage system	Variables (mg/kg)	1	2	3	4
0	CT	NH_4^+	42.9	39.3	39.3	31.0
		NO_3^-	35.7	50.0	34.5	17.9
		N min	78.6	89.3	73.8	48.8
	NT	NH_4^+	36.9	46.4	46.4	13.1
		NO_3^-	28.6	39.3	42.9	17.9
		N min	65.5	85.7	89.3	31.0
50	CT	NH_4^+	63.1	50.0	46.4	25.0
		NO_3^-	34.5	63.1	27.4	25.0
		N min	97.6	113.1	73.8	50.0
	NT	NH_4^+	46.4	51.2	35.7	13.1
		NO_3^-	39.3	56.0	26.2	9.5
		N min	85.7	107.1	61.9	22.6
100	CT	NH_4^+	40.5	45.2	27.4	21.4
		NO_3^-	31.0	47.6	41.7	14.3
		N min	71.4	92.9	69.0	35.7
	NT	NH_4^+	42.9	57.1	40.5	11.9
		NO_3^-	44.0	67.9	33.3	14.3
		N min	86.9	125.0	73.8	26.2
150	CT	NH_4^+	42.9	56.0	28.6	21.4
		NO_3^-	41.7	51.2	29.8	11.9
		N min	84.5	107.1	58.3	33.3
	NT	NH_4^+	33.3	46.4	31.0	21.4
		NO_3^-	41.7	54.8	34.5	17.9
		N min	75.0	101.2	65.5	39.3

by the doses, 100 kg/ha (40.5 mg/kg), 50 kg/ha (35.7 mg/kg), and 150 kg/ha (31 mg/kg).

The last stage, reflected further reductions. Under CT, NH_4^+ was highest in order at the dose of 0 kg/ha (31 mg/kg), 50 kg/ha (25 mg/kg), and equal mean concentrations obtained for 100 and 150 kg/ha (21.4 mg/kg). Under NT, the dose of 150 kg/ha led (21.4 mg/kg), followed by equal mean concentrations for the doses, 0 and 50 kg/ha (13.1 mg/kg), and finally 100 kg/ha (11.9 mg/kg).

These stage-by-stage process delimit how both, dose and tillage system could influence the nitrogen evolution over time. The decline in NH_4^+ concentrations after the second stage corresponds to increased plant growth and the non-disturbance soil effect, in consistency with the nitrogen mineralization dynamics for the wheat cereal.

The NO_3^- mean concentrations provide valuable nitrogen management valorization. The evaluation is interesting to prospect if the intentional dose support is ranging between 50 kg/ha and 100 kg/ha, as detected for the NH_4^+. The mean concentrations for the NO_3^- at the second stage exposed (Table 6), under CT, a highest NO_3^- level was obtained in order of superiority at the doses of, 50kg/ha (63.1 mg/kg), then 150 kg/ha (51.0mg/kg), 0 kg/ha (50.0 mg/kg), and 100 kg/ha (47.6mg/kg). Relative to the NT, NO_3^- concentrations were the maximum at the dose of 100kg/ha (67.9 mg/kg), then 50 kg/ha (56.0 mg/kg), 150 kg/ha (54.8 mg/kg), and 0 kg/ha (39.3 mg/kg).

The third stage is concerned with a diminished concentrations mensuration retained. The NO_3^- concentrations under CT, were the highest at the dose of 100 kg/ha (41.7 mg/kg), then 0 kg/ha (34.5mg/kg), 150 kg/ha (29.8 mg/kg), and at last 50 kg/ha (27.4 mg/kg). The NT case, the important concentration is obtained for the dose of 0 kg/ha (42.9 mg/kg), 150 kg/ha (34.5 mg/kg), 100 kg/ha (33.3 mg/kg), and 50 kg/ha (26.2 mg/kg).

The last stage, the NO_3^- concentrations had further declined. Under CT, the dose of 50 kg/ha maintained the elevated mean value (25.0 mg/kg), 0 kg/ha (17.9 mg/kg),100 kg/ha (14.3 mg/kg), and 150 kg/ha (11.9 mg/kg). Under NT, concentrations were highest and equal at 0 kg/ha and 150 kg/ha (17.9 mg/kg), followed by 100 kg/ha (14.3 mg/kg), and 50 kg/ha (9.5 mg/kg).

These results reveal that the NO_3^- availability peaks depending on the initial fertilization. The 100 kg/ha dose under NT consistently promoted higher NO_3^- availability during the active growth phase, aligning with the agronomic target of synchronizing nitrogen release with crop demand, compared to the CT.

The monitoring of NO_3^- dynamics reinforces the efficient utilization of this nitrogen form by the wheat crop, with the 50 kg/ha dose demonstrating the most favorable performance, closely followed by 100 kg/ha, particularly under the NT system when compared to CT. These observations underscore the role of optimal nitrogen dosing in maximizing nutrient uptake while minimizing potential losses. To provide a comprehensive overview, Figure 5 summarizes the behavior of N min concentrations. This representation combined the effects of both NO_3^- and NH_4^+, reflecting their cumulative contribution to the mineral nitrogen cycle availability for plant uptake.

The variability highlighted in Figure 5, illustrates how N min utilization differs between tillage systems, emphasizing the potential to reduce nitrogen losses through informed management practices. The data reveal clear differentiation in N min dynamics between CT and NT, aligning with the interaction patterns identified in the ANOVA analysis. This expectation, affirms the relevance of considering all influencing factors: tillage system, nitrogen dose, soil depth, and crop growth stage, when designing nutrient management strategies.

The capacity of N min to a sustain nitrogen availability throughout the cropping cycle is fundamental for optimizing wheat growth and yield. These achievements provide a solid foundation, for refining fertilization practices in conservation agriculture systems.

The results obtained from the analysis of NH_4^+, NO_3^-, and N min clearly reveal that NT outperforms CT in terms of the nitrogen use efficiency, as indicated by, the significant differences reliable to the growth stage, and the interactions between the factors. Through the use of Tukey's test, the NT system significantly enhances the practical retention and mineralization of nitrogen, particularly at 50 and 100 kg/ha fertilizer doses. These manifest, the importance of understanding the interplay between nitrogen fertilizer doses, soil depth, tillage systems, and crop growth stages for optimizing the nitrogen performances.

Variability of ammonium (NH_4^+ Var), nitrate (NO_3^- Var), and mineral nitrogen (N min Var) between the two tillage systems, CT and NT.

The analysis of N min, NO_3^-, and NH_4^+ variability provided insights into the differential behavior of these nutrients under NT and CT systems. This variability was calculated in Table 8, inspired by the meta-analyses of Su et al. (2021), Pittelkow et al. (2014), and Ponisio et al. (2015), highlights the effectiveness of nitrogen use based on the soil-plant relationship under the two tillage practices. For all the variables, the equations used were:

a) b)

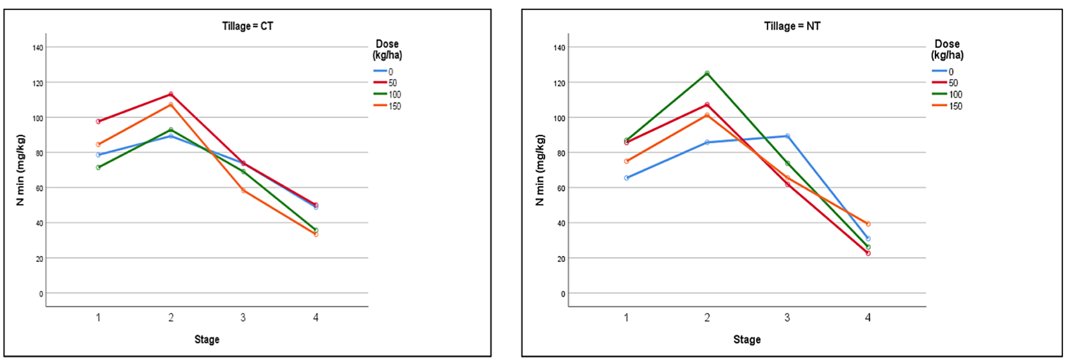

Figure 5. The curves evolution of N min concentrations under CT (a) and NT(b) depending on stages (1, 2, 3 and 4) and doses. (0, 50, 100 and 150 kg/ha)

$$N\ min\ Var = [(N\ minNT - N\ minCT) / N\ minCT] \times 100 \quad (1)$$

$$NO_3^-\ Var = [(NO_3^-NT - NO_3^-CT) / NO_3^-CT] \times 100 \quad (2)$$

$$NH_4^+\ Var = [(NH_4^+NT - NH_4^+CT) / NH_4^+CT] \times 100 \quad (3)$$

The achievements demonstrate, that the NT promotes greater mineralization of nitrogen, resulting in more efficiency nitrogen use. The percentage differences in N min at the two depths (63% at 0–10 cm and 40% at 10–20 cm) further validate the importance of NT for long-term soil nitrogen management. This efficiency is even more notable when compared to conventional systems, confirming that NT fosters superior nitrogen conservation. The approaches were conformed with previous research by Zhang et al. (2016), Sadiq et al. (2021), and Jat et al. (2017), which suggested the NT system could have an improvement in terms of nitrogen mineralization by up to 50% compared to CT. Thus, supporting its application for a sustainable agricultural practice. Additionally, the variability observed between tillage systems is more pronounced under NT, indicating its greater adaptation in nitrogen conservation and mineralization.

Table 8. Evaluation of wheat variability (%) for NH_4^+ Var, NO_3^- Var, and N min Var under NT and CT

Stage	Dose (kg/ha)	Depth	NH_4^+ Var	NO_3^- Var	N min Var
1	0	0–10	-25.0	-20.0	-22.9
		10–20	0.0	-20.0	-9.7
	50	0–10	-11.5	0.0	-7.1
		10–20	-40.7	30.8	-17.5
	100	0–10	35.7	35.7	35.7
		10–20	-15.0	50.0	9.4
	150	0–10	0.0	12.5	6.7
		10–20	-36.4	-10.5	-24.4
2	0	0–10	33.3	-28.6	-2.8
		10–20	5.6	-14.3	-5.1
	50	0–10	13.0	-18.5	-4.0
		10–20	-10.5	-3.8	-6.7
	100	0–10	43.8	65.0	55.6
		10–20	13.6	20.0	16.7
	150	0–10	-12.0	-20.0	-15.6
		10–20	-22.7	30.4	4.4
3	0	0–10	5.9	66.7	31.0
		10–20	31.3	-5.9	12.1
	50	0–10	-31.3	-23.1	-27.6
		10–20	-17.4	20.0	-6.1
	100	0–10	63.6	-5.6	20.7
		10–20	33.3	-35.3	-6.9
	150	0–10	44.4	100.0	68.8
		10–20	-13.3	-16.7	-15.2
4	0	0–10	-64.3	12.5	-36.4
		10–20	-50.0	-14.3	-36.8
	50	0–10	-60.0	-66.7	-63.0
		10–20	-16.7	-55.6	-40.0
	100	0–10	-50.0	-14.3	-36.8
		10–20	-33.3	20.0	-9.1
	150	0–10	-28.6	75.0	-5.6
		10–20	100.0	33.3	60.0

NT proves to be more valuable to enhance nitrogen mineralization and minimize the nitrogen losses, which are essential for improving the wheat production while reducing environmental impacts. The results focused the necessity for a precise nitrogen management, with a perspicacity nitrogen dose between 50 kg/ha and 100 kg/ha, and suggest that further research into long-term nitrogen dynamics under conservation tillage systems will be instrumental to develop sustainable agriculture.

In the same field, studies conducted by Maher et al. (2023) and Sellami et al. (2023) demonstrated a high degree of consistency under NT, capitalizing on climatic variability during drought years. They are part of an integral Maghreb NT research initiative. NT is considered as an intelligent agricultural practice that improves both crop productivity and the structuring of soil nutrients. The quantification of doses is significant, as beyond 100 kg/ha, the effectiveness of mineral nitrogen (N min) used is reduced (Table 6). This directly impacts soil quality and preservation. These directives are fully conformed to those reported by Cui et al. (2022). The soils under NT exhibit more variable concentrations, depending on crop residue management and nitrogen availability in the surface layers. In this context, NT appears to enhance the ongoing potential for NO_3^- and NH_4^+ utilization in the soil compared to CT, at the 0-20 cm depth. NT tends to maintain, a more stable N min level due to a reduced, volatilization, denitrification, and leaching, compared to the CT. These results contribute to the growing knowledge base supporting NT practices and provide actionable directives for nitrogen fertilization management in the Maghreb, encouraging further research and development in sustainable agricultural practices.

CONCLUSIONS

The present study defined an efficient nitrogen dose efficacy of 50 kg/ha under both tillage systems (NT and CT). It underscored the significant advantages of NT over CT in terms of nitrogen retention, mineralization, and overall soil health. The experimental research conducted under controlled greenhouse conditions at INRA's Rabat, highlighted the influence of tillage type, nitrogen dose, soil depth, and growth stages on nitrogen dynamics. The ANOVA results based on the data collected every three weeks regarding NH_4^+, NO_3^- and N min, described the nitrogen fertilization as valuable under the dose of 50 kg/ha, with respective mean values for NH_4^+, NO_3^-, and N min of 41.4 mg/kg, 35.1 mg/kg, and 76.5 mg/kg as projected in Tukey's test. However, NT demonstrated an active nitrogen use efficiency until the end of the wheat crop cycle, with notable gains, compared to CT. Also, the ANOVA confirmed the influence of tillage type, stages, nitrogen dose, and depths on the importance of N mineralization, with significant interactions among these factors. Furthermore, NT improved the N min potentiality by 63% at 0–10 cm and 40% at 10–20 cm depths attributed to the relevant dose of 50 kg/ha. Beyond a dose of 100 kg/ha, nitrogen losses were detected. Revealing the substantial benefits of NT, including increased nitrogen mineralization, soil structure, and reduced fertilizer dependency, NT should be promoted as a preferred practice for sustainable wheat production in Morocco and other similar regions. By optimizing nitrogen management through the appropriate dose, farmers can in this directive reduce the environmental deterioration, preserve soil and water resources, improve their production and contribute to an ecological resilience.

Acknowledgments

The present article is integrated as part of a project between MCGP, EIA, and CAMA. We would like to sincerely thank the National Institute of Agricultural Research (INRA, Rabat),the International Center for Agricultural Research in the Arid Zones (ICARDA),and the Faculty of Sciences of Kenitra for their essential support.

REFERENCES

1. Alburquerque, M.A., Dieckow, J., Sordi, A., Piva, J.T., Bayer, C., Molin, R., Pergher, M., Ribeiro-Junior, P.J. (2015). Carbon and nitrogen in a Ferralsol under zero-tillage rotations based on cover, cash or hay crops. *Soil Use and Management,31*(1),1–9. https://doi.org/10.1111/sum.12173
2. Bartaula, S., Panthi, U., Adhikari, A., Mahato, M., Joshi, D., Aryal, K. (2020). Effect of different tillage practices and nitrogen level on wheat production under inner terai of Nepal. *Journal of Agriculture and Natural Resources, 3*(1),233–239. https://doi.org/10.3126/janr.v3i1.27177

3. Cui, S., Zhu, X., Cao, G. (2022). Effects of tillage on soil nitrogen and its components from rice-wheat fields in subtropical regions of China. *International Journal of Agricultural and Biological Engineering, 15*(3),146–152. https://doi.org/10.25165/j.ijabe.20221503.5661
4. Devita, P., Dipaolo, E., Fecondo, G., Difonzo, N., Pisante, M. (2006). No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. *Soil and Tillage Research,92*(1–2), 69–78. https://doi.org/10.1016/j.still.2006.01.012
5. Farooq, M., Flower, K., Jabran, K., Wahid, A., Siddique, K.H. (2011). Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research, 117*, 172–183. https://doi.org/10.1016/j.still.2011.10.001
6. Franchini, J., Crispino, C., Souza, R., Torres, E., Hungria, M. (2006). Microbiological parameters as indicators of soil quality under various soil management and crop rotation systems in southern Brazil. *Soil and Tillage Research, 92*(1–2),18–29. https://doi.org/10.1016/j.still.2005.12.010
7. Han, Y., Ma, W., Zhou, B., Yang, X., Salah, A., Li, C., Cao, C., Zhan, M., Zhao, M. (2020). Effects of Straw-Return method for the Maize–Rice rotation system on soil properties and crop yields. *Agronomy, 10*(4),461. https://doi.org/10.3390/agronomy10040461
8. Hirzel, J., Undurraga, P., León, L., Panichini, M., Carrasco, J., González, J., Matus, I. (2019). Different residues affect wheat nutritional composition. *Journal of Soil Science and Plant Nutrition, 20*(1),75–82. https://doi.org/10.1007/s42729-019-00102-2
9. Hungria, M., Franchini, J. C., Brandão-Junior, O., Kaschuk, G. Souza, R. A. (2009). Soil microbial activity and crop sustainability in a long-term experiment with three soil-tillage and two crop-rotation systems. *Applied Soil Ecology, 42*(3), 288–296. https://doi.org/10.1016/j.apsoil.2009.05.005
10. INRA. (2024). New Varietal Obtention By INRA,6. https://www.inra.org.ma/sites/default/files/LIVRET_obtentions_vari%C3%A9tales_2024.pdf (in French)
11. Jat, H. S., Datta, A., Sharma, P. C., Kumar, V., Yadav, A. K., Choudhary, M., Choudhary, V., Gathala, M. K., Sharma, D. K., Jat, M. L., Yaduvanshi, N. P. S., Singh, G., McDonald, A. (2017). Assessing soil properties and nutrient availability under conservation agriculture practices in a reclaimed sodic soil in cereal-based systems of North-West India. *Archives of Agronomy and Soil Science, 64*(4), 531–545. https://doi.org/10.1080/03650340.2017.1359415
12. Kadiri Hassani, K., Moussadek, R., Baghdad, B., Zouahri, A., Dakak, H., Maher, H., Bouabdli, A. (2024). Effect of no tillage and conventional tillage on wheat grain yield Variability: A review. *Journal of Environmental & Earth Sciences, 6*(1), 57–70. https://doi.org/10.30564/jees.v6i1.6172
13. Maher, H., Moussadek, R., Ghanimi, A., Zouidi, O., Douaik, A., Dakak, H.,Amenzou, N. E., Zouahri, A. (2023). Effect of tillage and nitrogen fertilization on soil properties and yield of five durum wheat germoplasms in a dry area of Morocco. *Applied Sciences, 13*(2), 910. https://doi.org/10.3390/app13020910
14. Maynard, D. G., Kalra, Y. P., Crumbaugh, J. A. (2007). *Nitrate and exchangeable ammonium nitrogen.* In Soil sampling and methods of analysis 71–80. Carter, M. R., Gregorich, E. G. CRC Press, Boca Raton, FL. https://doi.org/10.1201/9781420005271
15. Moussadek, R. (2012). Impacts of Conservation Agriculture on the Properties and Productivity of Vertisols in Central Morocco. *AVRUG-bulletin/Afrika Focus,25*(2). https://doi.org/10.21825/af.v25i2.4957 (in French)
16. Moussadek, R., Laghrour, M., Mrabet, R., Van Ranst, E. (2023). Crop yields under climate variability and no-tillage system in dry areas of Morocco. *Ecological Engineering & Environmental Technology, 24*(1), 221–232. https://doi.org/10.12912/27197050/155024
17. Mrabet, R. (2011). *No-Tillage agriculture in West Asia and North Africa.* In Springer eBooks, 1015–1042. https://doi.org/10.1007/978-1-4020-9132-2_40
18. Mrabet, R., Bahri, H., Zaghouane, O., M'Hamed, H. C., El-Areed, S. R. M., El-Enin, M. M. A. (2022). Adoption and spread of conservation agriculture in North Africa. In *Burleigh Dodds series in agricultural science,* 185–246. https://doi.org/10.19103/as.2021.0088.06
19. Mrabet, R., Moussadek, R., Fadlaoui, A., Van Ranst, É. (2012). Conservation agriculture in dry areas of Morocco. *Field Crops Research, 132*, 84–94. https://doi.org/10.1016/j.fcr.2011.11.017
20. NASA POWER | DAV. (2024). Retrieved July 15, 2024, from https://power.larc.nasa.gov/data-access-viewer/
21. Neufeld, J. L. (2020). *The State of Food and Agriculture 2020*. In FAO eBooks. https://doi.org/10.4060/cb1447en
22. Olfs, H., Blankenau, K., Brentrup, F., Jasper, J., Link, A., Lammel, J. (2005). Soil- and plant-based nitrogen-fertilizer recommendations in arable farming. *Journal of Plant Nutrition and Soil Science, 168*(4), 414–431. https://doi.org/10.1002/jpln.200520526
23. Oorts, K. (2006). *Effect of tillage systems on soil organic matter stocks and C and N fluxes in cereal cropping systems on a silt loam soil in Northern France*. Earth Sciences. National Institute of Agronomy Paris-Grignon - INA P-G; Catholic University of Louvain. NNT: fftel-00011985. https://theses.hal.science/file/index/docid/63101/filename/These_Katrien_Oorts.pdf (in French)

24. Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M., Van Gestel, N., Six, J., Venterea, R. T., Van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature, 517*(7534), 365–368. https://doi.org/10.1038/nature13809
25. Ponisio, L. C., M'Gonigle, L. K., Mace, K., Palomino, J., De Valpine, P., Kremen, C. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences, 282*(1799), 20141396. https://doi.org/10.1098/rspb.2014.1396
26. Robinson, J. M., Liddicoat, C., Muñoz-Rojas, M., Breed, M. F. (2024). Restoring soil biodiversity. *Current Biology, 34*(9), R393–R398. https://doi.org/10.1016/j.cub.2024.02.035
27. Sadiq, M., Li, G., Rahim, N., Tahir, M. (2021). Effect of conservation tillage on yield of spring wheat (*Triticum aestivum* L.) and soil mineral nitrogen and carbon content. *International Agrophysics, 35*(1),83–95. https://doi.org/10.31545/intagr/132363
28. Sellami, W., Daoui, K., Ibriz, M., Bendidi, A. (2023,October 23). *Optimization of nitrogen fertilization of soft wheat in a direct seeding system.* By INRA Meknès Magazine. Retrieved October 23,2023,from https://mag.inrameknes.info/?p=3403 (in French)
29. Su, Y., Gabrielle, B., Makowski, D. (2021). A global dataset for crop production under conventional tillage and no tillage systems. *Scientific Data, 8*(1). https://doi.org/10.1038/s41597-021-00817-x
30. Yang, H., Xu, M., Koide, R. T., Liu, Q., Dai, Y., Liu, L., Bian, X. (2015). Effects of ditch-buried straw return on water percolation, nitrogen leaching and crop yields in a rice–wheat rotation system. *Journal of the Science of Food and Agriculture, 96*(4), 1141–1149. https://doi.org/10.1002/jsfa.7196
31. Zhang, H., Zhang, Y., Yan, C., Liu, E., Chen, B. (2016). Soil nitrogen and its fractions between long-term conventional and no-tillage systems with straw retention in dryland farming in northern China. *Geoderma, 269*,138–144. https://doi.org/10.1016/j.geoderma.2016.02.001
32. Zihlmann, U., Weisskopf, P., Müller, M., Schafflützel, R., Chervet, A., Sturny, W. G. (2006). Nitrogen dynamics in soils under direct seeding or conventional seeding. *Swiss Review Agric. 38*(5): 262–268. https://no-till.ch/wp-content/uploads/2023/04/Stickstoffdynamik-im-Boden-bei-Direktsaat-und-Pflug_fr.pdf (in French)