Comparative Effects of Poultry Manure and Urea on Soil Physicochemical Properties in Semi-Arid Terrace Soils of Northern Sudan

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Research Article

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Abstract

Soil fertility decline is a central constraint to forage production in semi-arid terrace landscapes, where low organic carbon, alkaline reaction and salinity may interact with weak soil structure. This field study evaluated the effects of untreated poultry manure, pre-composted poultry manure and urea on selected physicochemical properties of low- and high-terrace soils under *Clitoria ternatea L.*, *Chloris gayana Kunth* and their mixture at the Demonstration Farm of Nile Valley University, northern Sudan, during 2019–2021. The experiment followed a split-plot arrangement with three replications. Treatments comprised an unfertilized control, urea-N, untreated poultry manure at two rates and pre-composted poultry manure at two rates. Soil samples were collected from 0–30 cm after harvest and analyzed for apparent particle-size fractions, soil organic carbon, soil organic nitrogen, pH and electrical conductivity. The two terraces differed strongly at baseline: the low terrace was silty clay with higher organic carbon and lower salinity, whereas the high terrace was sandy clay loam, alkaline and more saline. Poultry manure showed more favorable terrace-specific responses than urea for several soil fertility indicators, although the direction and magnitude of response depended on terrace position. In the high terrace, untreated manure at the higher rate produced the highest mean soil organic carbon (1.85%) and organic nitrogen (375.5 mg kg^{-1}), while also reducing electrical conductivity to 1.07 dS m^{-1}. In the low terrace, organic nitrogen reached its highest treatment mean under pre-composted poultry manure at the lower rate. Mixed Clitoria-Rhodes stands strengthened the interpretation that legumes and fibrous-rooted grasses can provide complementary functional benefits. The findings support terrace-specific nutrient management based on organic inputs, legume inclusion and careful salinity monitoring.

1. INTRODUCTION

Sustaining soil fertility in semi-arid agriculture requires management practices that rebuild organic matter while maintaining nutrient availability and salt balance. In dryland and irrigated semi-arid systems, soil organic carbon is a core indicator of soil function because it influences aggregation, nutrient retention, biological activity and water dynamics [1–4]. These functions are especially relevant in terrace landscapes, where topographic position, sediment sorting, runoff redistribution and irrigation history may create strong contrasts in texture, salinity and fertility over short distances.

Organic amendments are widely recognized as practical inputs for improving degraded or low-carbon soils. Long-term field evidence shows that manures and composts can increase soil organic carbon, enhance biological activity, improve aggregate formation and support more resilient nutrient cycling when application rates are agronomically appropriate [5–9]. Poultry manure is particularly relevant because it supplies organic carbon together with nitrogen, phosphorus, potassium and base cations. Its effects, however, depend on decomposition stage, salinity, soil texture, initial soil organic matter and water management [10–12].

Mineral nitrogen fertilizers such as urea provide immediately available nitrogen and can increase crop growth, but their effect on soil quality is less stable when used without organic inputs. The nitrification of ammoniacal nitrogen may contribute to proton production and pH decline in some systems, although the direction of response depends on soil buffering capacity, carbonate content, irrigation and crop uptake [13–15]. Therefore, a simple comparison between manure and urea is insufficient; the more relevant question is how each input performs under contrasting soil positions and forage functional types.

Legume-grass systems offer an additional pathway for improving soil function. *Clitoria ternatea L.* is a tropical forage legume with nodulation capacity, deep rooting and value as fodder and green manure [16–18]. *Chloris gayana Kunth* is a fibrous-rooted perennial grass known for adaptation to warm environments and moderate salinity, and its root system can contribute to surface stabilization and soil structure [19, 20]. Combining these species may integrate biological nitrogen inputs with root-driven physical stabilization, a mechanism that is valuable in fragile terrace soils.

Despite extensive literature on organic amendments, fewer field studies have examined the joint effects of manure form, mineral nitrogen, terrace position and forage functional type in semi-arid Sudan. This study was designed to address that gap by testing whether untreated poultry manure, pre-composted poultry manure and urea differentially affect physical and chemical indicators in low- and high-terrace soils. The specific objectives were to: (i) quantify treatment effects on apparent particle-size fractions, soil organic carbon, soil organic nitrogen, pH and electrical conductivity; (ii) compare responses between low- and high-terrace soils; and (iii) interpret the role of Clitoria, Rhodes grass and their mixture in integrated fertility management.

2. MATERIALS AND METHODS

2.1. Study area and soil setting

The field experiment was conducted during three consecutive growing seasons from 2019 to 2021 at the Demonstration Farm of the Faculty of Agriculture, Nile Valley University, Darmali, River Nile State, Sudan (17°48' N, 34°00' E; 346.5 m above sea level) (Fig. 1). The study site is located near Darmali (Dar Mali) within the Nile River corridor in River Nile State, northern Sudan. This location represents a semi-arid terrace landscape where alluvial landforms, irrigation influence and local topographic variation create contrasting soil conditions over short distances.

The area lies within a semi-arid agroecological zone characterized by low rainfall, high evaporative demand and marked seasonal temperature fluctuation. These conditions make soil water retention, salt movement and organic matter turnover critical determinants of amendment performance.

Two terrace positions were examined. The low-terrace soil was silty clay, moderately alkaline and low in salinity. The high-terrace soil was sandy clay loam, more alkaline and more saline at baseline. These two soil positions provided a useful field contrast for testing whether the same amendment produces similar or different responses across terrace environments.

Table 1
Baseline physicochemical properties of the two terrace soils at 0–30 cm depth.

Property	Low terrace soil	High terrace soil
Texture class	Silty clay	Sandy clay loam
Clay (%)	42.12	26.26
Silt (%)	51.00	19.37
Sand (%)	11.54	56.19
pH	7.60	8.80
Soil organic carbon (%)	0.260	0.067
Soil organic nitrogen (mg kg^{-1})	344	178
Electrical conductivity (dS m^{-1})	0.66	4.00

2.2. Experimental design, crops and treatments

The experiment followed a split-plot arrangement with three replications. The main plots were assigned to forage crop systems: pure *Clitoria ternatea L.*, pure *Chloris gayana Kunth* and a Clitoria-Rhodes mixture. The fertilizer treatments were assigned to sub-plots and applied under both terrace positions. The treatment structure was designed to compare organic amendment form and rate with mineral nitrogen and an unfertilized control.

Untreated poultry manure was incorporated directly before sowing. Pre-composted poultry manure was prepared through aerobic composting in soil pits for three weeks, with regular moistening and covering to promote partial decomposition. Urea was band-applied two weeks after emergence. Supplemental irrigation, manual weed control and field management were maintained uniformly across treatments.

Table 2
Fertilizer treatments and codes.

Code	Treatment description used in the harmonized manuscript
C0	Unfertilized control
N	Urea nitrogen at 40 kg N ha^{-1}
UM1	Untreated poultry manure at 2 t ha^{-1}
UM2	Untreated poultry manure at 4 t ha^{-1}
TM1	pre-composted poultry manure at 2 t ha^{-1}
TM2	pre-composted poultry manure at 4 t ha^{-1}

2.3. Soil sampling and laboratory analysis

Composite soil samples were collected from 0–30 cm depth after harvest from each experimental plot. Soil physical analysis included apparent particle-size fractions for clay, silt and sand. The term apparent particle-size fractions is used here because short-term organic amendment effects may influence dispersion and aggregation during analysis rather than mineral particle formation itself.

Soil organic carbon was determined by wet oxidation, soil organic nitrogen by Kjeldahl digestion, pH in a soil-water suspension and electrical conductivity in a soil-water extract. The selected indicators represent carbon status, nitrogen enrichment, soil reaction and salt-related constraints, which are widely used in soil quality assessment and fertility interpretation [2, 3, 21].

2.4. Statistical analysis

Data were analyzed using a split-plot ANOVA model with crop system as the main-plot factor and fertilizer treatment as the subplot factor within each terrace position. Season was included as a fixed factor, and interaction effects were evaluated where applicable. Mean separation was performed using LSD at $p \leq 0.05$, following the original statistical analysis.

3. RESULTS AND DISCUSSION

The LSD-based summaries in Tables 3a and 3b indicate that treatment responses were terrace-specific rather than uniform across the whole experiment. The high terrace showed the clearest favorable response to UM2, particularly for SOC, SON and EC. In contrast, the low terrace showed smaller chemical contrasts among treatments, reflecting its finer texture, lower salinity and stronger baseline fertility status. Therefore, the following discussion emphasizes terrace-specific treatment patterns rather than broad pooled treatment effects.

Table 3
a. LSD-based interpretation of treatment effects on soil physical indicators.

Soil indicator	Terrace	Key treatment mean or contrast	LSD-based interpretation	Agronomic interpretation	Supporting references
Clay fraction (%)	Low terrace	UM1 = 35.72	UM1 ranked among the highest clay-fraction treatments; TM1 recorded the lowest mean clay fraction.	Untreated manure at the lower rate showed the strongest apparent fine-fraction retention in the low terrace, probably through improved aggregation and reduced dispersion.	[6, 7, 9, 24]
Silt fraction (%)	High terrace	UM2 = 28.22	UM2 recorded the highest mean silt fraction and was placed among the higher statistical groups.	Untreated manure at the higher rate showed the clearest apparent silt-fraction response in the high terrace, reflecting better stabilization of fine particles.	[6, 7, 22, 24]
Sand fraction (%)	Low terrace	TM1 = 26.78	TM1 recorded the highest mean sand fraction in the low terrace.	This supports a cautious interpretation of particle-size shifts as aggregation, dispersion and laboratory-separation effects rather than rapid mineral transformation.	[7, 9, 22, 24]

Values are treatment means summarized from the original crop-system and season-specific statistical tables. LSD-based interpretation follows the original mean-separation letters reported at $p \leq 0.05$. Means sharing the same letter within the original comparison column were considered not significantly different.

Table 3
b. LSD-based interpretation of treatment effects on soil chemical and functional indicators.

Soil indicator	Terrace	Key treatment mean or contrast	LSD-based interpretation	Agronomic interpretation	Supporting references
SOC (%)	Low terrace	UM1 = 2.98	UM1 was placed in the highest overall statistical group, while UM2 and TM2 were placed in lower groups.	SOC response in the low terrace was modest because the soil already had stronger baseline fertility and finer texture.	[1, 5, 6, 8, 22]
SOC (%)	High terrace	UM2 = 1.85	UM2 was statistically separated as the highest overall treatment group; TM1 recorded the lowest mean.	Untreated manure at the higher rate produced the clearest carbon-building response in the high terrace, where baseline SOC was low.	[1, 5, 6, 8, 25]
SON (mg kg^{-1})	Low terrace	TM1 = 542.7	TM2 was separated in the lowest group, while C0, UM1 and TM1 were within higher statistical groups.	Pre-composted poultry manure at the lower rate supported the highest nitrogen mean in the low terrace, likely through mineralizable organic N and improved nutrient cycling.	[5, 6, 13, 26]
SON (mg kg^{-1})	High terrace	UM2 = 375.5	UM2 was statistically separated from the other treatments in the overall mean comparison.	Untreated manure at the higher rate produced the strongest nitrogen response in the high terrace, with potential support from legume-derived N inputs.	[16, 17, 18, 26]
pH	Low terrace	N and UM1 = 7.9	C0 was the lowest group; N and UM1 were in the highest group.	Treatment effects on pH were small and remained within alkaline ranges, suggesting strong buffering capacity.	[9, 13, 14, 15]

Soil indicator	Terrace	Key treatment mean or contrast	LSD-based interpretation	Agronomic interpretation	Supporting references
pH	High terrace	C0 and UM2 = 8.4	UM1 recorded the lowest mean pH, while C0 and UM2 remained in the highest group.	Carbonate buffering likely constrained large pH shifts, while organic acid production may explain minor pH reduction under some manure treatments.	[10, 13, 14, 15]
EC (dS m^{-1})	Low terrace	N, UM1 and UM2 = 0.33	EC remained low across treatments; differences were small but detectable in the original LSD grouping.	Salinity was not a major limiting factor in the low terrace, so treatment effects on EC had limited agronomic importance.	[10, 11, 12, 23]
EC (dS m^{-1})	High terrace	UM2 = 1.07	UM2 was statistically separated as the lowest EC treatment; N and TM1 recorded the highest means.	Untreated manure at the higher rate produced the most favorable salinity-related response in the high terrace, likely through improved porosity, infiltration and salt redistribution under irrigation.	[10, 11, 12, 23]
Forage functional role	Mixed system	Clitoria-Rhodes mixture	Crop effects were interpreted through functional complementarity rather than a single chemical indicator.	Clitoria may contribute biological N input, while Rhodes grass may support surface stabilization through fibrous roots.	[16, 17, 18, 19, 20, 26]

Values are treatment means summarized from the original crop-system and season-specific statistical tables. LSD-based interpretation follows the original mean-separation letters reported at $p \leq 0.05$. Means sharing the same letter within the original comparison column were considered not significantly different. SOC = soil organic carbon; SON = soil organic nitrogen; EC = electrical conductivity. Supporting references correspond to the reference list of the manuscript.

3.1. Baseline terrace contrast and implications for amendment response

The two terrace soils started from very different fertility conditions (Table 1 and Fig. 2). The low terrace had a finer texture, higher organic carbon and lower electrical conductivity. The high terrace had higher sand content, lower organic carbon and higher salinity. This contrast explains why the same amendment did not produce identical responses in the two terrace positions. Fine-textured soils usually have greater capacity to protect organic matter through organo-mineral associations, while sandy soils often show faster but less buffered responses to organic inputs [7, 8, 22].

The high initial pH and EC of the high terrace indicate a more constrained root environment than the low terrace. Under such conditions, organic amendments may act through multiple pathways: carbon supply, nutrient release, improvement of pore continuity, stronger aggregate formation and enhanced salt leaching under irrigation [10–12, 23].

3.2. Treatment effects on apparent particle-size fractions

The physical data showed terrace-dependent shifts in measured particle-size fractions (Table 4). In the low terrace, the highest mean clay fraction occurred under UM1 (35.72%), whereas TM1 showed the highest mean sand fraction (26.78%). In the high terrace, UM2 produced the highest mean silt fraction (28.22%), while clay varied within a narrow range across treatments. These patterns should not be interpreted as a rapid transformation of mineral particles. A more defensible interpretation is that manure affected aggregation, dispersion and the stability of fine particles during laboratory separation.

This interpretation is consistent with the literature showing that organic inputs can alter aggregate stability, pore-size distribution and the protection of fine particles through microbial binding agents and organo-mineral interactions [6, 7, 9, 24]. The higher response of the sandy high terrace to untreated manure at the higher rate suggests that coarse-textured soils may show clearer short-term structural signals when organic substrates are supplied.

Table 4
Treatment means for apparent particle-size fractions (%) in low- and high-terrace soils.

Treatment	Low clay	Low silt	Low sand	High clay	High silt	High sand
C0	34.22	41.77	22.67	35.45	27.43	46.11
N	34.30	42.59	25.07	35.16	26.82	47.53
UM1	35.72	41.72	24.12	35.50	25.37	47.32
UM2	35.15	42.01	25.11	35.41	28.22	46.75
TM1	32.57	41.74	26.78	34.28	27.24	47.77
TM2	34.46	42.24	25.26	34.41	27.64	46.66

3.3. Soil organic carbon response

Soil organic carbon responded differently across terrace positions (Table 5 and Fig. 3). In the low terrace, SOC was highest under UM1 (2.98%) and close to the control mean, indicating that the finer baseline soil already had relatively stronger carbon retention. In the high terrace, the highest SOC occurred under UM2 (1.85%), followed by urea (1.74%) and UM1 (1.69%). This suggests that untreated manure at the higher rate showed the most favorable LSD-supported response for improving carbon status in the more degraded high terrace.

The result agrees with evidence that repeated manure additions increase SOC more consistently than unfertilized or mineral-only systems, particularly where initial organic carbon is low [5, 6, 8]. Organic carbon gains in sandy or low-carbon soils may be rapid at the beginning of rehabilitation, but they require continued organic inputs and plant cover to become stable [1, 4, 7]. The stronger response under UM2 also reflects the value of less decomposed organic materials as a source of both labile and particulate organic matter, although pre-composted poultry manure may provide more stabilized carbon over longer periods [6, 25].

It should be noted that baseline SOC values were derived from pre-experimental composite samples, whereas post-harvest SOC values represent plot-level treatment means summarized across crop systems and seasons. Therefore, baseline-to-post-treatment differences should be interpreted cautiously as they reflect both treatment effects and differences in sampling structure.

3.4. Soil organic nitrogen response and crop functional effects

Soil organic nitrogen was sensitive to both amendment type and crop system (Table 5). In the low terrace, the highest treatment mean was observed under TM1 (542.7 mg kg^{-1}), while UM1 maintained a high mean value (505.7 mg kg^{-1}). In the high terrace, UM2 produced the highest organic nitrogen mean (375.5 mg kg^{-1}), clearly exceeding the control (316.5 mg kg^{-1}).

The response is biologically plausible. Poultry manure supplies organic and mineralizable nitrogen, while Clitoria can contribute biologically fixed nitrogen through nodulation and root turnover [16–18]. Rhodes grass, by contrast, contributes a dense fibrous root system that can strengthen soil structure and promote carbon inputs near the surface. The mixture therefore offers a functional complementarity: the legume supports nitrogen enrichment, and the grass contributes root-driven stabilization. Such complementarity is increasingly recognized as a pathway for reducing reliance on mineral nitrogen in forage systems [18, 20].

Table 5
Treatment means for selected chemical indicators in low- and high-terrace soils.

Treatment	Low SOC	Low SON	Low pH	Low EC	High SOC	High SON	High pH	High EC
C0	2.96	504.5	7.6	0.36	1.58	316.5	8.4	1.27
N	2.88	477.5	7.9	0.33	1.74	319.2	8.3	1.51
UM1	2.98	505.7	7.9	0.33	1.69	317.5	8.2	1.20
UM2	2.74	452.3	7.7	0.33	1.85	375.5	8.4	1.07
TM1	2.90	542.7	7.7	0.35	1.41	332.0	8.3	1.51
TM2	2.73	430.3	7.8	0.34	1.64	329.7	8.3	1.49

3.5. Soil reaction and electrical conductivity

The pH response was moderate and remained within alkaline ranges in both terrace soils (Table 5). In the low terrace, pH ranged from 7.6 to 7.9, while in the high terrace it ranged from 8.2 to 8.4. These values indicate that carbonate buffering likely constrained large pH shifts in both terrace soils. Nevertheless, the slightly lower pH under UM1 in the high terrace may reflect organic acid production during decomposition and local rhizosphere processes.

Electrical conductivity showed the clearest fertility constraint in the high terrace (Table 5 and Fig. 4). The control mean was 1.27 dS m^{-1}, urea increased the mean to 1.51 dS m^{-1}, and UM2 reduced it to 1.07 dS m^{-1}. This supports the interpretation that organic amendments, when combined with irrigation, can improve pore continuity and salt redistribution beyond the active root zone [10–12, 23]. The low terrace had low EC across all treatments, so treatment differences were less agronomically limiting.

The urea response should be interpreted with care. Mineral nitrogen can increase plant growth where nitrogen is limiting, but mineral-only fertilization does not directly rebuild carbon pools or improve structure unless it increases residue returns [13–15]. In the high terrace, where salinity and low carbon were both constraints, untreated manure at the higher rate provided a more balanced improvement than urea alone.

The marked difference between baseline EC and post-harvest treatment means should be interpreted in the context of supplemental irrigation, seasonal salt redistribution and the different sampling structure between initial composite samples and plot-level post-harvest samples.

3.6. Integrated interpretation for terrace-specific fertility management

The combined results show that amendment performance depended on the initial condition of the terrace soil. The low terrace already had better carbon status and lower salinity, so treatment benefits were more visible in nitrogen and aggregation-related indicators. The high terrace had lower baseline organic carbon and higher salinity, so it responded more clearly to untreated manure, particularly UM2. This terrace-specific response is consistent with soil quality frameworks that emphasize interpretation by soil function, threat and local constraint rather than by a single universal threshold [2, 3].

A practical interpretation is that untreated poultry manure at the higher rate is most promising for the high terrace, where carbon deficiency and salinity are stronger constraints. In the low terrace, a lower pre-composted poultry manure rate may be sufficient for maintaining fertility while reducing risks associated with excessive nutrient loading. The crop mixture is agronomically attractive because it combines nitrogen input from Clitoria with root reinforcement from Rhodes grass (Fig. 5).

Table 6
Terrace-specific interpretation of the main findings.

Terrace condition	Most relevant constraint	Best-supported treatment trend	Management implication
Low terrace	Maintaining fertility and structure under low salinity	TM1 or UM1 with forage cover	Use moderate organic inputs and avoid unnecessary mineral-only fertilization.
High terrace	Low SOC, higher alkalinity and higher EC	UM2 with Clitoria or Clitoria-Rhodes mixture	Prioritize organic carbon rebuilding and salinity monitoring.
Mixed forage system	Need for N input and surface stabilization	Clitoria-Rhodes mixture	Combine biological N input with fibrous-root soil stabilization.

4. CONCLUSIONS

This study demonstrates that poultry manure can improve selected soil physicochemical indicators in semi-arid terrace soils, but its effect is strongly conditioned by terrace position and initial soil status. The high terrace, which started with lower organic carbon and higher salinity, showed the clearest response to untreated poultry manure at the higher rate. This treatment showed the most favorable LSD-supported pattern, with higher mean soil organic carbon and organic nitrogen and lower electrical conductivity relative to the control and urea treatments.

The low terrace showed smaller salinity-related responses because its baseline EC was low. In this soil, moderate manure application may be more appropriate for maintaining organic nitrogen and structure without excessive nutrient addition. The results also support the functional value of including *Clitoria* ternatea *L.*, in forage systems because of its nitrogen-related role, while Chloris gayana may contribute to root-driven soil stabilization.

Under the conditions of this study, poultry manure should not be treated as a uniform amendment across terrace positions. A terrace-specific strategy is therefore recommended. The higher untreated manure rate appears most promising for the more degraded high terrace, whereas moderate pre-composted or untreated poultry manure rates appear more appropriate for the low terrace. Further multi-location trials should test residual effects, manure nutrient composition, crop yield response, salt-ion dynamics and economic feasibility before large-scale recommendation.

Declarations

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References

1. Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627
2. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman M, Sukkel W, van Groenigen JW (2018) Brussaard, L. Soil quality - A critical review. Soil Biol Biochem 120:105–125
3. Karlen DL, Andrews SS, Doran JW (2001) Soil quality: Current concepts and applications. Adv Agron 74:1–40
4. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A et al (2017) Soil carbon 4 per mille. Geoderma 292:59–86
5. Edmeades DC (2003) The long-term effects of manures and fertilisers on soil productivity and quality: A review. Nutr Cycl Agrosyst 66:165–180
6. Diacono M, Montemurro F (2010) Long-term effects of organic amendments on soil fertility. A review. Agron Sustain Dev 30:401–422
7. Larney FJ, Angers DA (2012) The role of organic amendments in soil reclamation: A review. Can J Soil Sci 92:19–38
8. Maillard É, Angers DA (2014) Animal manure application and soil organic carbon stocks: A meta-analysis. Glob Change Biol 20:666–679
9. Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. Nutr Cycl Agrosyst 51:123–137
10. Tejada M, Garcia C, Gonzalez JL, Hernandez MT (2006) Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil. Soil Biol Biochem 38:1413–1421
11. Oo AN, Iwai CB, Saenjan P (2015) Soil properties and maize growth in saline and nonsaline soils using cassava-industrial waste compost and vermicompost. Land Degrad Dev 26:300–310
12. Chaganti VN, Crohn DM, Šimůnek J (2015) Leaching and reclamation of a biochar and compost amended saline-sodic soil with moderate SAR reclaimed water. Agric Water Manage 158:255–265

13. Geisseler D, Scow KM (2014) Long-term effects of mineral fertilizers on soil microorganisms - A review. Soil Biol Biochem 75:54–63
14. Hao T, Zhu Q, Zeng M, Shen J, Shi X, Liu X, Zhang F, de Vries W (2020) Impacts of nitrogen fertilizer type and application rate on soil acidification rate under a wheat-maize double cropping system. J Environ Manage 270:110888
15. Schroder JL, Zhang H, Girma K, Raun WR, Penn CJ, Payton ME (2011) Soil acidification from long-term use of nitrogen fertilizers on winter wheat. Soil Sci Soc Am J 75:957–964
16. Laranjo M, Alexandre A, Oliveira S (2014) Legume growth-promoting rhizobia: An overview on the Mesorhizobium genus. Microbiol Res 169:2–17
17. Oguis GK, Gilding EK, Jackson MA, Craik DJ (2019) Butterfly pea (Clitoria ternatea), a cyclotide-bearing plant with applications in agriculture and medicine. Front Plant Sci 10:645
18. Traill S, Peoples MB, Sykes J, Swan AD, Liu DL, Hunt JR (2018) Tropical forage legumes provide large nitrogen benefits to succeeding crops in a subtropical farming system. Crop Pasture Sci 69:290–303
19. Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59:651–681
20. Annicchiarico P, Barrett B, Brummer EC, Julier B, Marshall AH (2015) Achievements and challenges in improving temperate perennial forage legumes. CRC Crit Rev Plant Sci 34:327–380
21. Wander MM, Drinkwater LE (2000) Fostering soil stewardship through soil quality assessment. Appl Soil Ecol 15:61–73
22. Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol Biochem 32:2099–2103
23. Lakhdar A, Hafsi C, Rabhi M, Debez A, Montemurro F, Abdelly C, Jedidi N, Ouerghi Z (2008) Application of municipal solid waste compost reduces the negative effects of saline water in Hordeum maritimum L. Bioresour Technol 99:7160–7167
24. Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. J Soil Sci 33:141–163
25. Pan G, Smith P, Pan W (2009) The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. Agric Ecosyst Environ 129:344–348
26. Palm CA, Myers RJK, Nandwa SM (2000) Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. Nutr Cycl Agrosyst 56:155–164

Figures

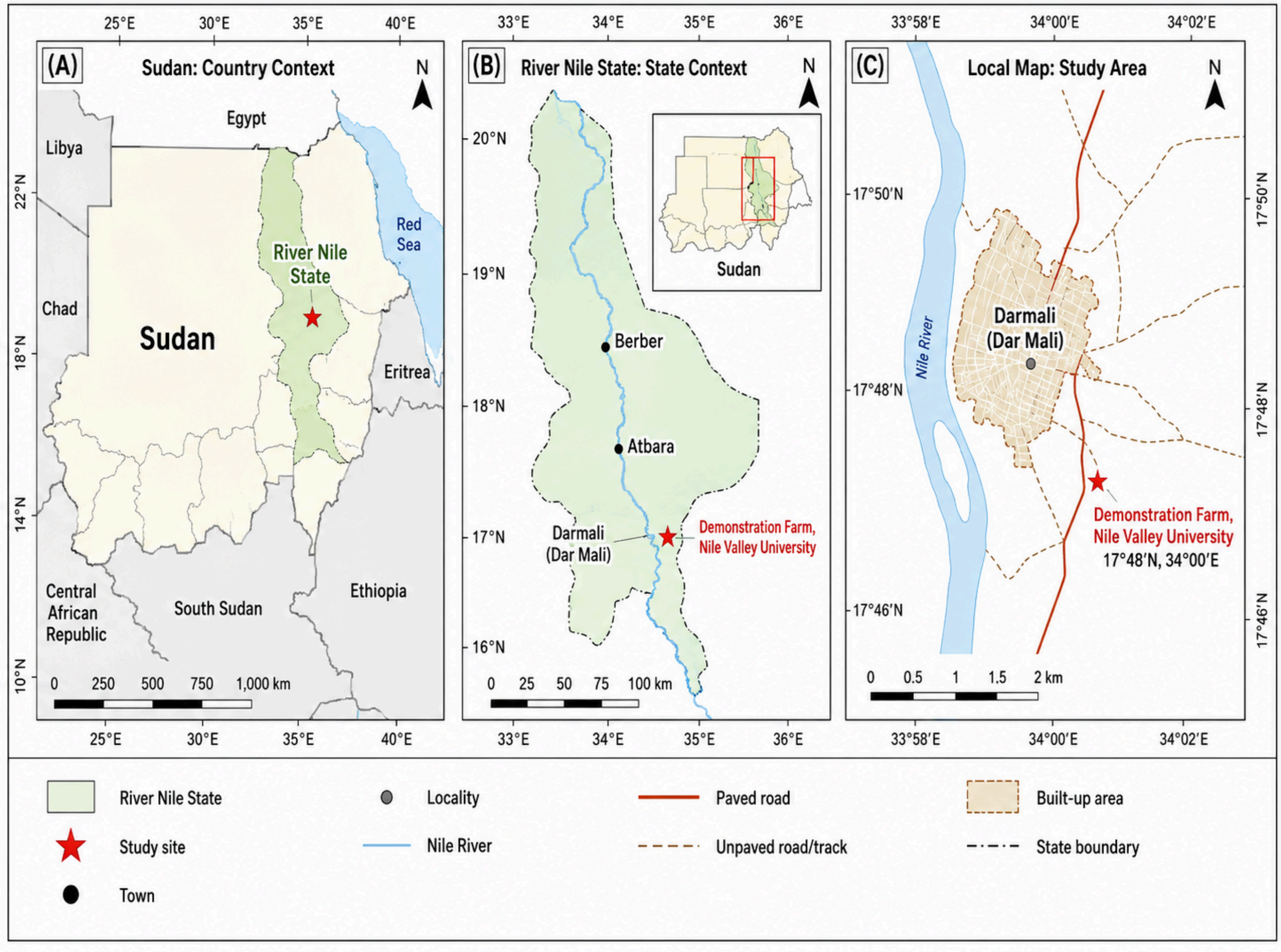

Figure 1

Location of the study area at the Demonstration Farm of the Faculty of Agriculture, Nile Valley University, Darmali, River Nile State, Sudan. The figure shows: (A) the position of River Nile State within Sudan; (B) the regional location of Darmali within River Nile State; and (C) the local position of the study site near the Nile River corridor.

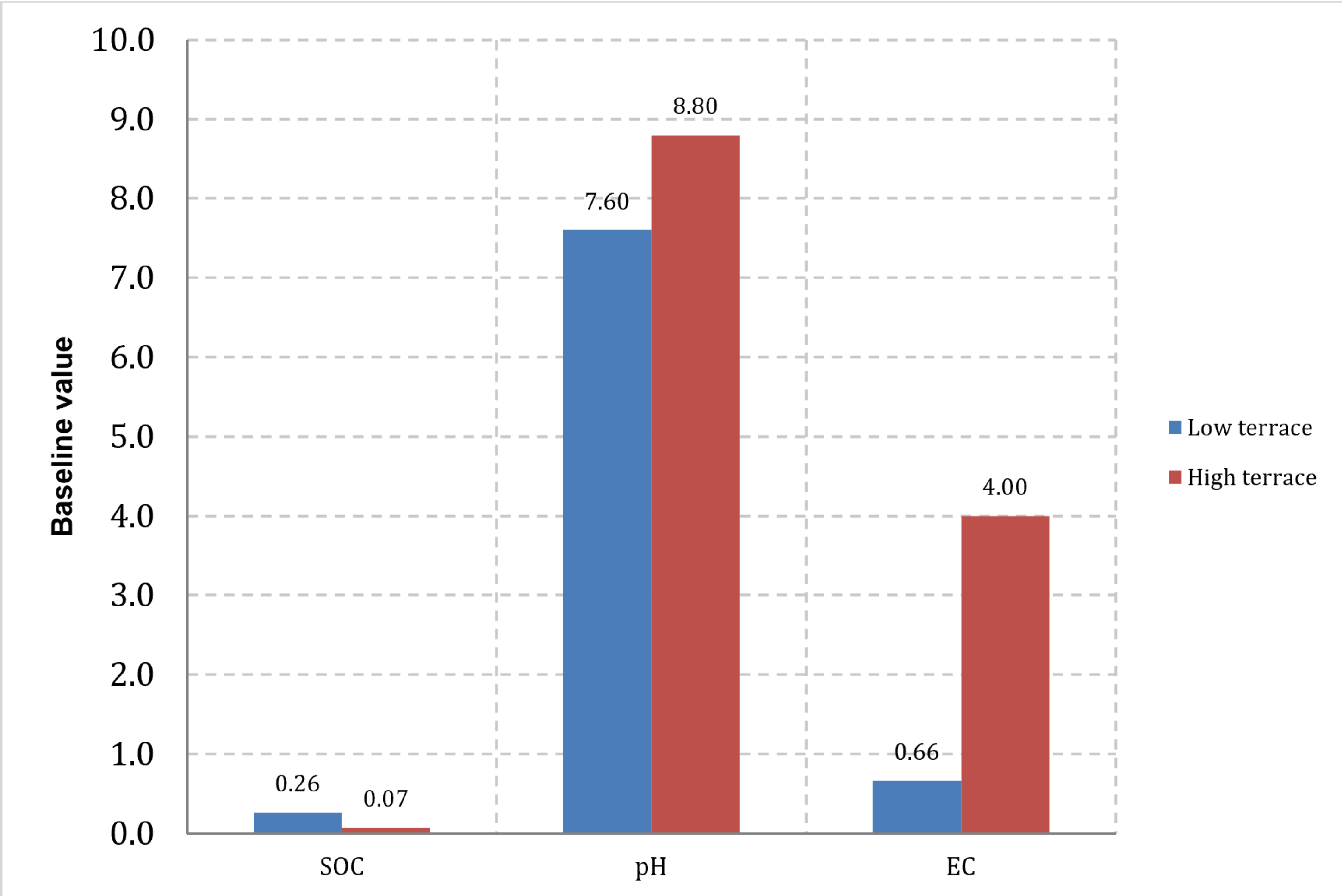

Figure 2

Baseline contrast between low- and high-terrace soils before treatment application.

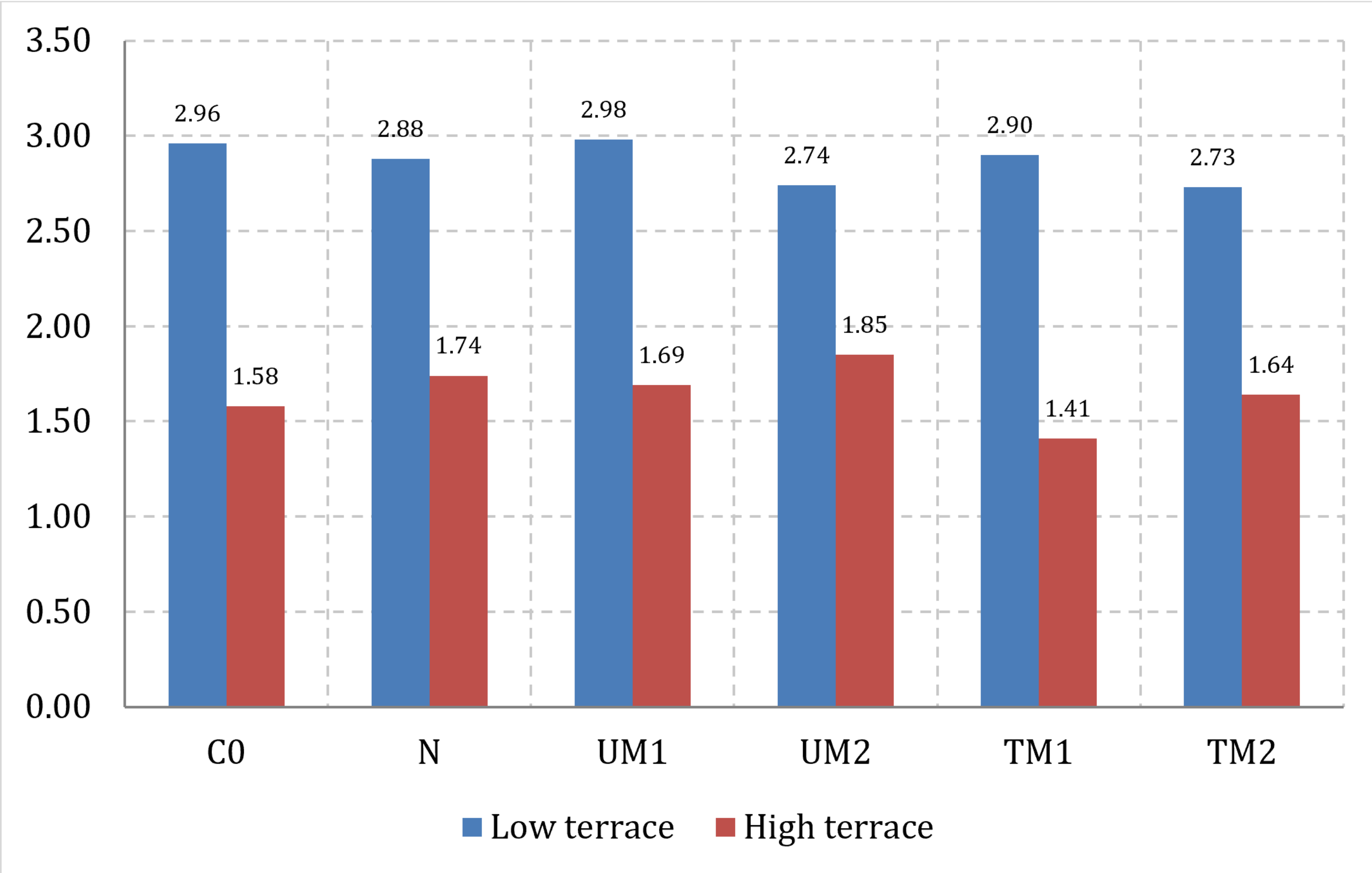

Figure 3

Mean soil organic carbon response to fertilizer treatments in low- and high-terrace soils.

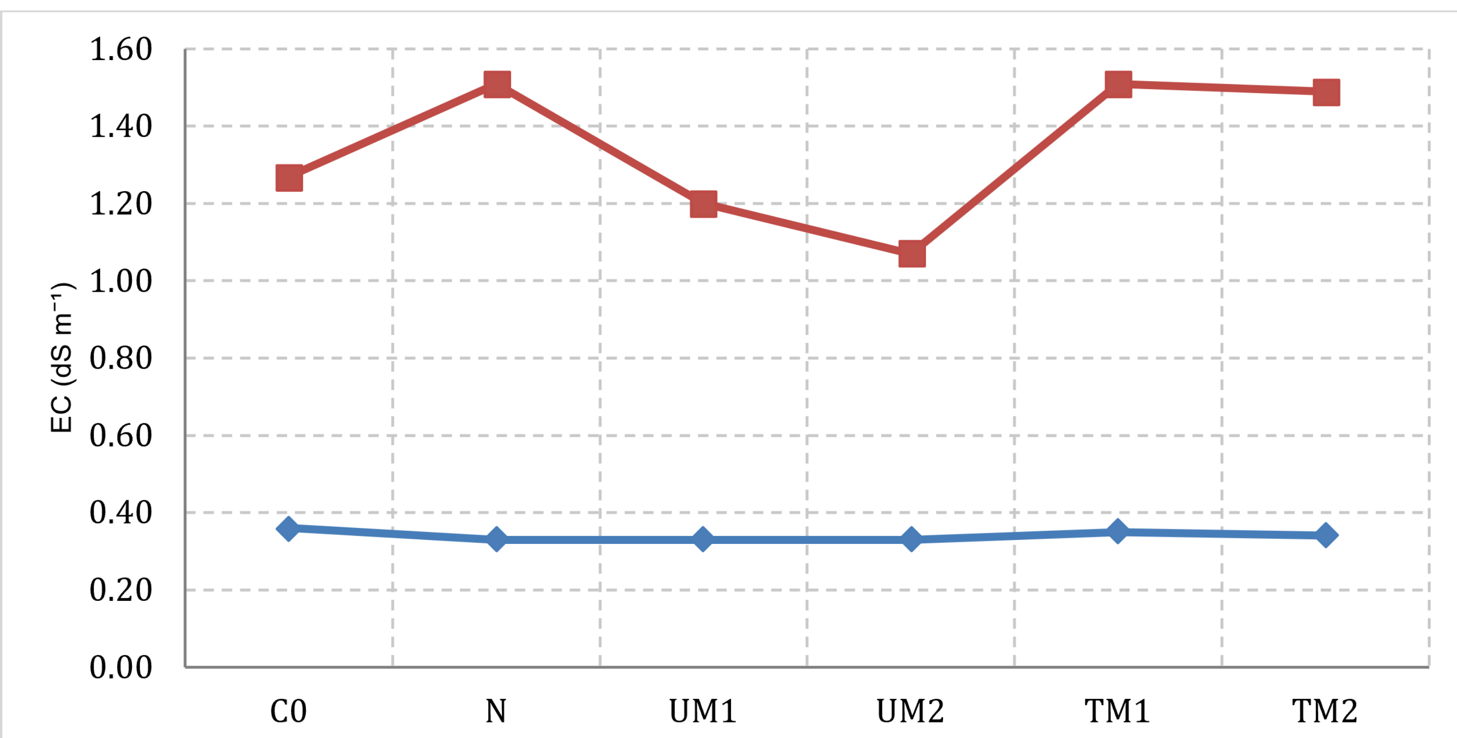

Figure 4

Mean electrical conductivity response to fertilizer treatments in low- and high-terrace soils.

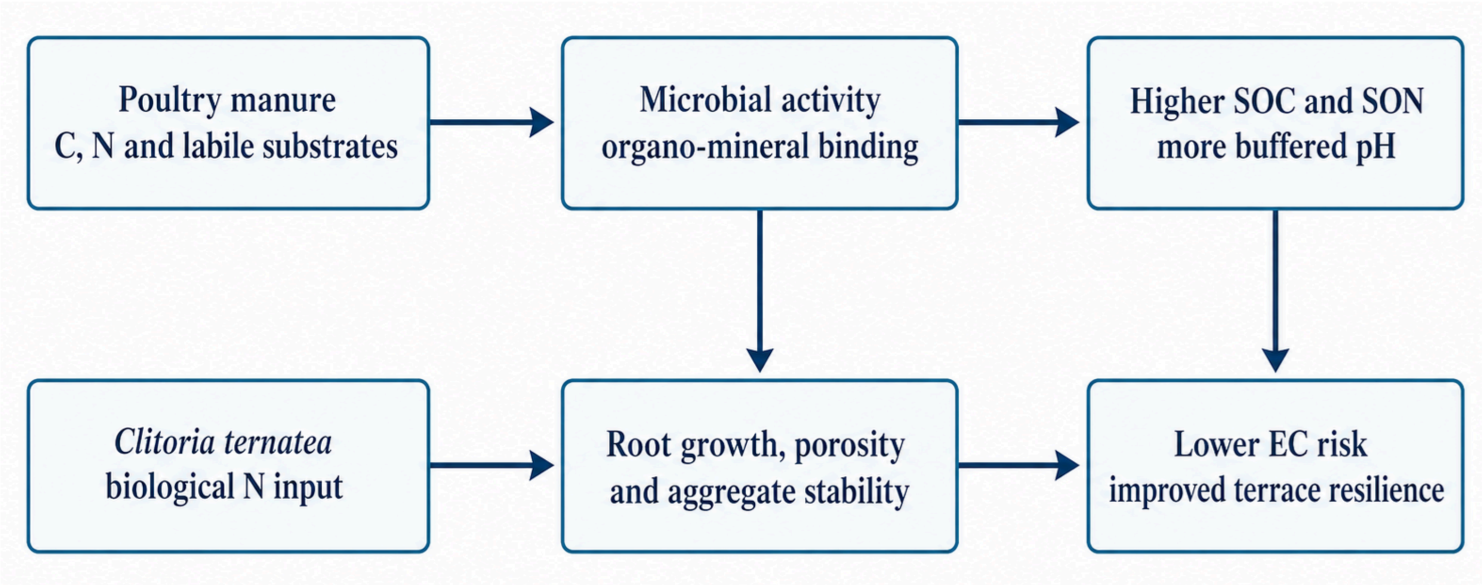

Figure 5

Mechanistic interpretation of amendment effects in semi-arid terrace soils.