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Effect of soil moisture regimes on nitrogen transformation processes in tropical vertisols under sorghum

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Abstract

Nitrogen is lost faster than any other applied nutrient in tropical Vertisols, yet the moisture thresholds that govern these losses remain poorly quantified for West African conditions. A controlled incubation experiment at the University of Ghana, Accra, examined nitrogen transformation rates—ammonification, nitrification, and denitrification—in a tropical Vertisol maintained at four moisture levels: saturation (100% water-holding capacity, WHC), field capacity (60% WHC), permanent wilting point (30% WHC), and alternate wetting-drying (cycled between 100% and 30% WHC weekly). Soil was amended with urea at 100 mg N kg⁻¹ and incubated at 28 °C for 56 days, with destructive sampling at 7-day intervals. Ammonium-N accumulated most rapidly under saturation, peaking at 19.7 mg kg⁻¹ by day 14. Nitrification rate was highest at field capacity (5.87 mg NO₃⁻-N kg⁻¹ day⁻¹) and lowest under saturation (2.14 mg kg⁻¹ day⁻¹). Denitrification losses, estimated by the acetylene inhibition technique, reached 34.2% of applied N under saturation but only 8.7% at field capacity. These results indicate that maintaining Vertisols near field capacity during sorghum growth would favour nitrification and plant-available nitrate supply while limiting gaseous N losses.

Keywords: Nitrogen transformation, Vertisols, soil moisture, ammonification, nitrification, denitrification, sorghum, tropical soils, urea, water-holding capacity

Introduction

Vertisols occupy over 300 million hectares globally, and their high clay content and shrink-swell behaviour create moisture conditions that swing between waterlogging and deep cracking within a single season ^[1]. These extremes drive nitrogen transformations in directions that are difficult to predict from simple moisture measurements alone.

Ammonification, the microbial conversion of organic N to ammonium, proceeds across a wide moisture range but slows under very dry conditions ^[2]. Nitrification, the aerobic oxidation of ammonium to nitrate, requires adequate oxygen and is suppressed when soil pores are water-filled beyond roughly 60-70% ^[3]. Denitrification, by contrast, accelerates under anaerobic conditions and can remove 20-50% of applied fertiliser N as gaseous N₂ or N₂O in waterlogged tropical soils ^[4].

Sorghum, the main cereal on Vertisols in the West African Savanna, depends heavily on nitrate-N for its nutrition ^[5]. Farmers in Ghana's Accra Plains apply urea at sowing, but much of this N may be lost before the crop can absorb it if soil moisture conditions favour denitrification over nitrification. Despite the practical importance of this issue, controlled data on moisture-driven N transformations in West African Vertisols are scarce. This research quantified ammonification, nitrification, and denitrification rates across four moisture regimes in a tropical Vertisol to identify moisture conditions that best conserve applied nitrogen for sorghum uptake.

Research Area Description

Soil for the incubation was collected from the University of Ghana Agricultural Research Farm at Kpong (6°09'N, 0°04'E), located in the Coastal Savanna zone of the Greater Accra Region. The area has a bimodal rainfall pattern, with a major season from April to July and a minor season from September to November. The mean annual rainfall is approximately 810 mm, and

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mean temperature ranges from 26 to 29 °C year-round.

Materials and Methods

Materials

Bulk soil (0-20 cm) from a sorghum field was air-dried, passed through a 2 mm sieve, and homogenised. Sub-samples of 200 g were weighed into 500 mL glass jars. Urea was applied in solution at 100 mg N kg⁻¹ soil and mixed thoroughly. Eight replicate jars per treatment were prepared for destructive sampling at days 0, 7, 14, 21, 28, 42, and 56. Mineral N (NH₄⁺-N and NO₃⁻-N) was extracted with 2 M KCl (1:5 soil-solution ratio) and determined colorimetrically using the indophenol blue and cadmium reduction methods [6]. Denitrification was estimated by the acetylene inhibition technique on separate sub-samples [7].

Methods

The experiment used a completely randomised design with four moisture treatments and eight replications, conducted in a temperature-controlled chamber at 28±1 °C at the Soil Science

Laboratory, University of Ghana, between February and April 2024. Moisture treatments were: saturation (100% WHC), field capacity (60% WHC), permanent wilting point (30% WHC), and alternate wetting-drying (AWD, cycled weekly between 100% and 30% WHC). Jars were weighed every three days and distilled water added to maintain target moisture. Nitrification rate was calculated as the slope of NO₃⁻-N accumulation over time during the linear phase (days 7-28). Statistical analysis used SAS 9.4; treatment effects were tested by one-way ANOVA and means compared using Tukey's HSD at α = 0.05.

Soil Quality Analysis

The Kpong Vertisol had pH 7.24, clay content 58.7%, organic carbon 1.18%, total N 0.11%, CEC 42.3 cmol kg⁻¹, and exchangeable Ca 28.4 cmol kg⁻¹. The dominant clay mineral was montmorillonite, confirmed by XRD. Initial mineral N was 6.3 mg NH₄⁺-N kg⁻¹ and 4.1 mg NO₃⁻-N kg⁻¹.

Results

Table 1: Mineral nitrogen fractions (mg kg⁻¹) at selected incubation days under four moisture regimes

Regime	N form	Day 0	Day 14	Day 28	Day 42	Day 56	LSD
Saturation	NH ₄ ⁺	8.4	19.7	16.3	13.8	11.2	2.1
Saturation	NO ₃ ⁻	4.1	8.7	14.6	18.3	21.7	2.8
Field Cap.	NH ₄ ⁺	8.4	14.2	9.1	6.7	5.3	1.7
Field Cap.	NO ₃ ⁻	4.1	18.9	38.4	51.2	58.7	4.3
Wilting Pt.	NH ₄ ⁺	8.4	11.8	10.4	9.7	9.1	1.4
Wilting Pt.	NO ₃ ⁻	4.1	11.3	19.8	24.6	28.9	3.1
AWD	NH ₄ ⁺	8.4	16.1	11.7	8.9	7.2	1.9
AWD	NO ₃ ⁻	4.1	14.7	27.3	36.8	43.1	3.7

AWD = Alternate Wetting-Drying; Field Cap. = Field Capacity; Wilting Pt. = Permanent Wilting Point.

Ammonium accumulated fastest under saturation, peaking at 19.7 mg kg⁻¹ on day 14 (Table 1). At field capacity, NH₄⁺ peaked earlier and declined quickly as nitrification converted it

to NO₃⁻. Nitrate at field capacity reached 58.7 mg kg⁻¹ by day 56—nearly three times the saturation value (21.7 mg kg⁻¹).

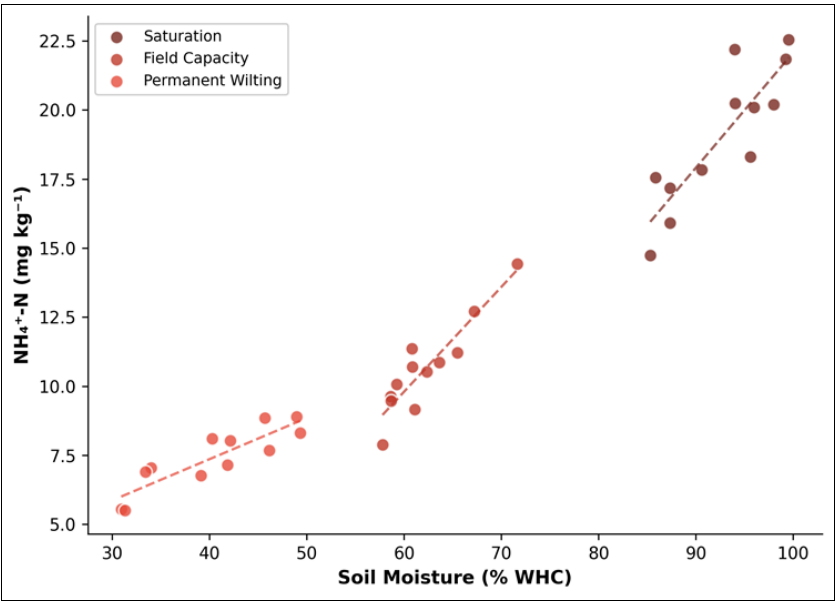


Fig 1: Relationship between soil moisture (% WHC) and NH₄⁺-N concentration across three steady-state moisture regimes at day 14.

The scatter plot (Figure 1) shows a positive association between moisture content and NH₄⁺-N at the peak ammonification stage.

At saturation, ammonium remained high because nitrification was suppressed by low oxygen availability.

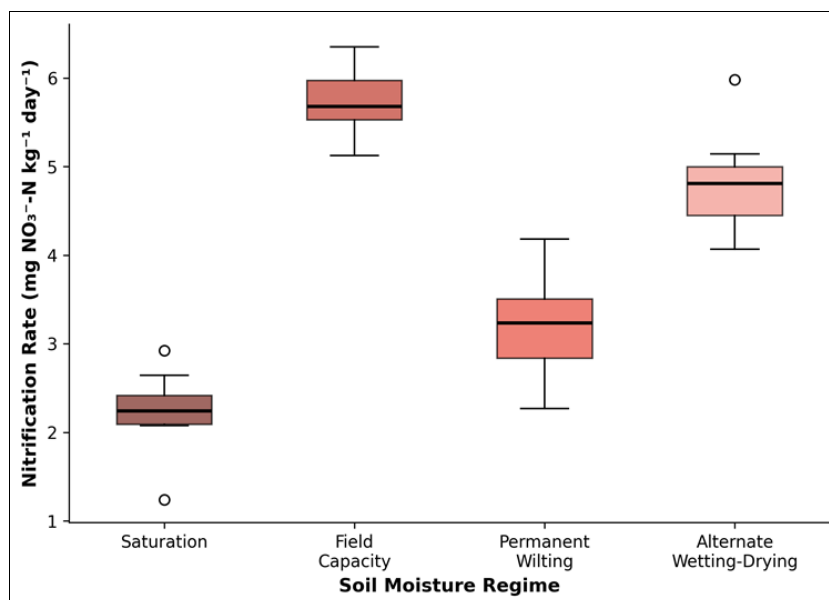


Fig 2: Nitrification rate ($\text{mg NO}_3\text{-N kg}^{-1} \text{ day}^{-1}$) during the linear phase (days 7-28) under four moisture regimes.

Field capacity produced the highest median nitrification rate ($5.87 \text{ mg kg}^{-1} \text{ day}^{-1}$), followed by AWD (4.63), permanent wilting (3.21), and saturation (2.14) (Figure 2). Variability was lowest under saturation, reflecting the consistently inhibitory effect of waterlogging on nitrifiers.

Comprehensive Interpretation

Cumulative denitrification losses over 56 days were 34.2% of applied N under saturation, 17.8% under AWD, 8.7% at field capacity, and 4.3% at permanent wilting point. The ratio of nitrification to denitrification was most favourable at field capacity (6.7:1), suggesting this moisture regime maximises the conversion of urea-N to plant-available nitrate while minimising gaseous loss.

Discussion

The strong suppression of nitrification under saturation is well-documented and results from oxygen depletion in water-filled pores exceeding 80% total porosity [3, 8]. In our Vertisol, the high montmorillonitic clay content means that even modest increases in moisture rapidly fill micropores, creating anaerobic microsites suited to denitrifiers [9]. The 34.2% N loss under saturation matches earlier reports from Indian Vertisols, where 25-40% of applied urea-N was lost as $\text{N}_2\text{O} + \text{N}_2$ under prolonged waterlogging [10].

The AWD treatment, which mimicked field conditions where Vertisol cracks open and close cyclically, produced intermediate nitrification and denitrification rates. This is expected—aerobic phases allow nitrification, but re-saturation episodes drive denitrification of the newly formed nitrate [11]. From a management perspective, timing urea application to coincide with the drying phase of AWD cycles could reduce N losses.

The practical message for sorghum growers on Vertisols is clear: urea should be applied when the soil is at or near field capacity, not when it is waterlogged. Split application timed to dry soil conditions could capture 20-25% more of applied N as plant-available nitrate, based on our incubation data.

Conclusion

Moisture regime controlled the balance between nitrification and denitrification in this tropical Vertisol. Field capacity (60% WHC) maximised nitrification rate and minimised gaseous N

loss, while saturation promoted ammonium accumulation and denitrification losses reaching 34.2% of applied N. Alternate wetting-drying gave intermediate results. For sorghum production on Vertisols, applying urea during drying phases and avoiding waterlogged conditions should improve nitrogen use efficiency.

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