



Distribution and Availability of Nitrogen Forms in Soils Containing Ferromanganese Concretion Nodules under Contrasting Land Use Systems in Southern Guinea Savannah

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Abstract

This study investigated the distribution and availability of nitrogen forms (total N, organic N, nitrate, and ammonium) in concretion-rich Ferric Luvisols under contrasting land use systems (intensive cultivation vs. forest) across three soil depths (0–15, 15–30, and 30–45 cm). A factorial experimental design (2×3×3) with three replications examined soil only (SOL), concretion only (CON), and soil plus concretion (SCN) samples. Results revealed that land use exerted a stronger influence on nitrogen dynamics than concretion presence. Forest soils maintained significantly higher organic nitrogen (0.95 vs. 0.74 g kg⁻¹), total nitrogen, and nitrate (0.92 vs. 0.39 g kg⁻¹) levels compared to those under intensive cultivation, reflecting nitrogen capital depletion due to continuous cropping. Intensive land use exhibited 53.5% higher bulk density (1.09 g cm⁻³), lower pH (4.87), and reduced organic matter, creating unfavourable conditions for nitrogen cycling. Findings revealed that concretion nodules contained significantly lower organic and total nitrogen than the soil matrix but exhibited 3–4-fold higher ammonium concentrations, suggesting fixation within oxide structures. Soil plus concretion mixtures showed 30–45% enhancement in total nitrogen compared to soil alone, indicating beneficial interactive effects through organo-mineral associations. Nitrogen distribution remained relatively uniform across depths (0–45 cm), suggesting active vertical movement and leaching vulnerability. Both land use types exhibited low nitrogen fertility status (total N < 1.0 g kg⁻¹), with organic nitrogen dominating (>85% of total N). The study demonstrates that sustainable nitrogen management in concretion-rich Savannah soils require integrated approaches emphasising organic matter conservation, pH amelioration, and practices that address physical, chemical, and biological constraints simultaneously. These findings provide essential baseline information for developing site-specific fertility management strategies in tropical Savannah agro-ecosystems.

Keywords: Ferromanganese concretions; Nitrogen forms; Land use change; Ferric Luvisols; Southern Guinea Savannah; Soil fertility management; Tropical soils; Organic nitrogen; West Africa.

1. Introduction

Nitrogen availability remains a critical constraint to agricultural productivity in tropical agro-ecosystems, particularly in the Savannah regions of West Africa, where intensive cultivation has led to substantial nutrient depletion (Vanlauwe et al., 2017). The soils of Nigeria's Southern Guinea Savannah, predominantly

classified as Ferric Luvisols, are characterised by inherent fertility limitations, including multiple nutritional deficiencies, high acidity, and low organic matter content (Adnan et al., 2017). These constraints are further compounded by the presence of ferromanganese (Fe-Mn) concretion nodules, which are abundant in

weathered Savannah soils and significantly influence nutrient dynamics and availability (Agbenin, 2003). Understanding the complex interactions between these concretion nodules, land use management, and nitrogen cycling is essential for developing sustainable soil fertility management strategies in this critical agricultural zone.

Ferromanganese concretion nodules represent a distinctive feature of tropical and subtropical soils, particularly those with imperfect internal drainage subjected to alternating wet and dry cycles (Gasparatos et al., 2004; Zhang and Karathanasis, 1997). These redoximorphic features, formed through successive oxidation-reduction processes, concentrate iron and manganese oxides along with other elements, creating discrete cemented structures that can occupy substantial portions of the soil profile (Chan et al., 2005; Rhoton et al., 1993). While considerable research has documented the role of Fe-Mn concretions as reservoirs for micronutrients and heavy metals (Timofeeva, 2008; Zhang and Karathanasis, 1997), their influence on major nutrient dynamics, particularly nitrogen transformation and availability, remains poorly understood. This gap is particularly critical given that nitrogen limitation represents the primary factor constraining crop productivity in Savannah soils (Batjes, 1996; Kowal and Kassam, 1978).

The nitrogen cycle in tropical soils is governed by complex microbial-mediated processes including mineralisation, immobilisation, nitrification, and denitrification, which are sensitive to soil physical and chemical properties (Robertson and Groffman, 2015). In soils containing substantial quantities of Fe-Mn concretions, these processes may be significantly altered due to the unique physicochemical properties of concretion materials, including their surface

chemistry, redox characteristics, and nutrient content (Gasparatos et al., 2005). Iron and manganese oxides present in concretions possess high surface reactivity and can influence the sorption and desorption of various ionic species, potentially affecting the distribution and plant availability of nitrogen forms (Arai and Sparks, 2007). However, the specific mechanisms through which concretion nodules influence the distribution of organic nitrogen, ammonium (NH_4^+), and nitrate (NO_3^-) in tropical soils remain inadequately investigated.

Land use change represents another critical factor influencing nitrogen dynamics in tropical agro-ecosystems (Sugihara et al., 2010). The conversion of natural forest to intensive agricultural systems typically results in accelerated organic matter decomposition, increased nitrogen mineralisation rates, and enhanced susceptibility to nitrogen losses through leaching and gaseous emissions (Robertson, 2000). In the Southern Guinea Savannah of Nigeria, demographic pressures have driven the expansion of intensive cultivation into marginal lands often characterised by high concretion content and inherently low fertility (Doetterl et al., 2015). The interactive effects of land use intensification and concretion presence on nitrogen availability have not been systematically evaluated, despite their obvious importance for agricultural sustainability and food security in the region.

Previous studies have established that concretion nodules can significantly affect soil chemical properties at high concentrations, depending on their mineralogy and elemental composition (Verlaan et al., 2004; Feng, 2011). Research has shown that concretions typically contain higher concentrations of Fe and Mn oxides and lower silica content compared to the surrounding soil matrix, with implications for cation exchange

capacity and nutrient retention (Saleque et al., 2004). However, most investigations have focused on geochemical characterisation of concretions or their role in micronutrient and heavy metal dynamics, with limited attention to their influence on macronutrient availability, particularly nitrogen.

The vertical distribution of nitrogen forms in soil profiles is influenced by multiple factors including root activity, water movement, microbial activity, and the physical and chemical properties of different soil horizons (Mehnatkesh et al., 2013). In concretion-rich soils, depth-related variations in concretion abundance and characteristics may create distinct nitrogen distribution patterns that differ from those in concretion-free soils. Elucidating these depth-related patterns is essential for developing depth-specific management recommendations and understanding the long-term sustainability of different land use systems.

Despite the recognised importance of both concretion nodules and land use management in determining soil fertility, no comprehensive study has simultaneously examined their effects on the distribution and availability of different nitrogen forms in Southern Guinea Savannah soils. This knowledge gap limits our ability to develop effective nitrogen management strategies for these inherently challenging soils. The objective of this study was therefore to quantify the distribution of total nitrogen, organic nitrogen, nitrate, and ammonium in soils containing ferromanganese concretion nodules under contrasting land use systems (intensive cultivation versus forest), and to evaluate the relative contributions of concretion nodules, land use type, and soil depth to variations in nitrogen form distribution. The study hypothesised that land use type would exert a greater influence on nitrogen form distribution than concretion presence, with forest soils

retaining higher nitrogen stocks across all forms.

2. Experimental Design and Soil Sampling

The study was conducted in Iwu, Isin Local Government Area of Kwara State, Nigeria (latitude 8°16'51" N; longitude 5°01'09" E; elevation \approx 686 m a.s.l.), within the Southern Guinea Savannah ecological zone. The climate is tropical with mean annual precipitation of approximately 1,600 mm and mean annual temperature of 25–32°C. Soils are classified as Ferric Luvisols (FAO-UNESCO, 1988), formed on basement complex rocks and dominated by kaolinite clay minerals with abundant Fe-Mn oxide concretions. The two contrasting land use systems sampled were: (i) intensive arable cultivation with continuous cropping of maize (

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A factorial experimental design ($2 \times 3 \times 3$) with three replications was employed. Factors were: (i) land use type — intensive cultivation and forest; (ii) soil depth — 0–15, 15–30, and 30–45 cm; and (iii) sample type — soil only (SOL), concretion only

(CON), and soil plus concretion (SCN). Soil sampling was conducted during the dry season (December 2024) using a systematic random sampling approach. At each site, composite samples were collected from nine randomly located auger points within a 50 m × 50 m plot. Undisturbed core samples (5 cm diameter × 5 cm height) were also collected for bulk density determination. A total of 54 composite samples (2 land uses × 3 depths × 3 sample types × 3 replicates) were collected for analysis.

Soil samples were air-dried, gently crushed, and sieved at 2 mm to separate the fine earth fraction from coarse materials. Concretion nodules retained on the 2-mm sieve were hand-picked, cleaned by brushing to remove adhering soil particles, air-dried, and ground for chemical analysis. The soil plus concretion (SCN) treatment was prepared by mixing fine earth with ground concretion material in proportions reflecting field occurrence (approximately 30% concretion by weight). All prepared samples were stored at room temperature in airtight plastic containers until analysis.

2.1 Physical and Chemical Analyses

Particle size distribution was determined by the hydrometer method (Ibitoye, 2005) and bulk density by the core sampling method (Abu-Hamdeh and Al-Jalil, 1999). Soil pH was measured potentiometrically in a 1:2 soil-to-water suspension (Davis and Freitas, 1970). Organic carbon was determined by the Walkley-Black wet oxidation method (Nelson and Sommers, 1982) and organic matter calculated using the Van Bemmelen factor (×1.724). Total nitrogen was determined by the Micro-

Kjeldahl digestion method (Nelson and Bremner, 1972). Available phosphorus was extracted using the Bray-1 method (Bray and Kurtz, 1945) and determined colorimetrically at 882 nm. Exchangeable cations (K, Na, Ca, Mg) were extracted with 1 N neutral ammonium acetate (pH 7.0) and determined by flame photometry (K, Na) and EDTA titration (Ca, Mg). Exchange acidity and CEC were determined by standard KCl extraction and titration methods.

2.2 Nitrogen Forms Determination

Exchangeable ammonium (NH₄⁺-N) and nitrate (NO₃⁻-N) were extracted using Morgan's reagent. Ammonium-N was determined colorimetrically using Nessler's reagent at 410 nm (Schuffelen et al., 1961). Nitrate-N was determined by the phenoldisulfonic acid method at 410 nm. Organic nitrogen was calculated as the difference between total nitrogen and inorganic nitrogen (sum of NH₄⁺-N and NO₃⁻-N).

2.3 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using the General Linear Model procedure in Minitab 17.0 to assess main and interaction effects of land use, depth, and sample type. Mean separation was performed using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$. Pearson correlation analysis was conducted to examine relationships among soil properties and nitrogen forms. Data normality and homogeneity of variance were verified prior to ANOVA using Shapiro-Wilk and Levene's tests, respectively.

3. Results and Discussion

3.1 Physical Properties of Soils under the Influence of Concretion Nodules

3.1.1 Effect of Land Use on Physical Properties

Table 1. Effect of land use on physical properties of the soil

Variable	Sand	Silt	Clay	Texture	BD (g cm ⁻³)	PD (g cm ⁻³)	Total Porosity	MC (cm)
	%	%	%					
Land use								
Intensive	73.26a	8.01a	18.78a	SL	1.09a	2.39a	0.54b	0.77b
Forest	72.08a	8.44a	19.47a	SL	0.71b	2.32a	0.69a	1.42a

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test. BD = bulk density; PD = particle density; MC = moisture content; SL = sandy loam.

Particle size analysis revealed that both land use types had a sandy loam texture, with sand fraction dominating. Bulk density was significantly higher ($p < 0.05$) in intensive land use (1.09 g cm⁻³) compared to forest land use (0.71 g cm⁻³), representing a 53.5% increase. Total

porosity was significantly lower in intensive soils (0.54) than in forest soils (0.69). Moisture content was significantly higher in forest soils (1.42 cm) than in intensive soils (0.77 cm). Particle size fractions and particle density did not differ significantly between land use types.

3.1.2 Effect of Soil Depth on Physical Properties

Table 2. Effect of soil depth on physical properties of the soil

Depth (cm)	Sand	Silt	Clay	Texture	BD (g cm ⁻³)	PD (g cm ⁻³)	Total Porosity	MC (cm)
0–15	73.85a	8.26a	18.88a	SL	0.88a	2.32a	0.61a	1.08a
15–30	72.30a	8.87a	19.79a	SL	0.92a	2.39a	0.61a	1.02a
30–45	71.86a	7.55a	18.71a	SL	0.90a	2.36a	0.62a	1.18a

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

Across the three depth intervals (0–15, 15–30, and 30–45 cm), no significant differences ($p > 0.05$) were observed for any of the measured physical properties. Sand content ranged from 71.86 to

73.85%, bulk density averaged approximately 0.90 g cm⁻³ across all depths, and total porosity showed minimal variation (0.61–0.62).

3.1.3 Interaction Effects of Land Use and Depth

Table 3. Interaction effect of land use and depth on selected physical properties of the soil

Land Use	Depth (cm)	Sand %	Silt %	Clay %	Texture	BD (g cm ⁻³)	PD (g cm ⁻³)	Total Porosity	MC (cm)
Intensive	0–15	74.21a	8.06a	17.74a	SL	1.07a	2.32a	0.53b	0.60b
	15–30	71.67a	8.69a	19.56a	SL	1.13a	2.47a	0.54b	0.81ab
	30–45	73.90a	7.28a	19.04a	SL	1.08a	2.38a	0.55b	0.91ab
Forest	0–15	71.51a	8.47a	20.22a	SL	0.70b	2.31a	0.69a	1.57a
	15–30	70.93a	9.04a	20.02a	SL	0.71b	2.32a	0.69a	1.23ab

	30–45	73.80a	7.82a	18.38a	SL	0.73b	2.33a	0.68a	1.46a
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Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

The interaction between land use and soil depth significantly affected bulk density, total porosity, and moisture content ($p < 0.05$). In intensive land use, bulk density remained consistently high across all depths (1.07–1.13 g cm⁻³), whereas in forest land use, bulk density was uniformly low (0.70–0.73 g cm⁻³) throughout the profile. Total porosity exhibited an inverse

relationship, with intensive soils maintaining low values (0.53–0.55) and forest soils consistently higher values (0.68–0.69) across all depths.

3.2 Chemical Properties of Soils under the Influence of Concretion Nodules

3.2.1 Chemical Properties of Soil Only (SOL)

Table 4. Effect of land use on selected chemical properties of soil only (SOL)

Land Use	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
Intensive	4.87b	0.49a	0.50a	0.53a	1.66a	0.44a	3.01a	0.58a	6.72a	0.74b	1.28b
Forest	5.31a	0.07b	0.24b	0.35b	1.23b	0.54a	2.10b	0.44a	4.90b	0.95a	1.64a

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test. ns = not significant; * $p < 0.05$.

Forest land use exhibited significantly higher pH (5.31) compared to intensive land use (4.87). Available phosphorus was significantly higher ($p < 0.05$) in intensive soils (0.49 mg kg⁻¹) compared to forest soils (0.07 mg kg⁻¹), representing a seven-fold increase. Exchangeable potassium and sodium were also higher in intensive soils (0.50 and 0.53 cmol kg⁻¹) compared to forest soils (0.24 and 0.35 cmol kg⁻¹). Exchangeable calcium was significantly higher in intensive soils (1.66 cmol kg⁻¹) compared to forest soils (1.23 cmol kg⁻¹),

while magnesium showed no significant difference. Exchange acidity (hydrogen) was significantly higher in intensive soils (3.01 cmol kg⁻¹) compared to forest soils (2.10 cmol kg⁻¹). CEC was significantly higher in intensive soils (6.72 cmol kg⁻¹) compared to forest soils (4.90 cmol kg⁻¹). Organic carbon and organic matter were significantly higher ($p < 0.05$) in forest soils (0.95 g kg⁻¹ and 1.64 g kg⁻¹) compared to intensive soils (0.74 g kg⁻¹ and 1.28 g kg⁻¹).

Table 5. Effect of depth on selected chemical properties of soil only (SOL)

Depth (cm)	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
0–15	4.84a	0.11a	0.33a	0.36a	1.38a	0.59a	3.0a	0.37a	6.03a	1.0a	1.73a
15–30	5.31a	0.08ab	0.43a	0.51a	1.41a	0.48a	2.40a	0.61a	5.84a	0.79a	1.36ab
30–45	5.11a	0.06b	0.34a	0.44a	1.55a	0.40a	2.27a	0.55a	5.55a	0.75a	1.29b

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

The effect of soil depth on chemical properties showed significant variation only for available phosphorus and organic

matter. Phosphorus decreased significantly with depth from 0.11 mg kg⁻¹ at 0–15 cm to 0.06 mg kg⁻¹ at 30–45 cm. Organic

matter similarly declined from 1.73 g kg⁻¹ at the surface to 1.29 g kg⁻¹ in the deepest layer.

Table 6. Interaction effect of land use and depth on selected chemical properties of soil only (SOL)

Land Use	Depth (cm)	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
Intensive	0–15	4.83b	0.09b	0.45ab	0.41ab	1.47a	0.51a	3.12a	0.38a	6.34ab	0.86ab	1.51ab
	15–30	4.96ab	0.11b	0.64a	0.68a	1.64a	0.48a	2.83a	0.66a	6.93a	0.78ab	1.34ab
	30–45	4.82b	1.29a	0.42bc	0.49ab	1.88a	0.32a	3.09a	0.71a	6.91a	0.57b	0.98b
Forest	0–15	4.86b	0.12b	0.21c	0.32b	1.30a	0.67a	2.88a	0.37a	5.74ab	1.13a	1.95a
	15–30	5.66a	0.05b	0.23bc	0.35b	1.18a	0.48a	1.97a	0.56a	4.76ab	0.81ab	1.37ab
	30–45	5.40ab	0.05b	0.27bc	0.38ab	1.22a	0.48a	1.46a	0.39a	4.20b	0.93ab	1.60ab

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

The interaction between land use and depth revealed significant effects on most chemical properties except magnesium, aluminium, and CEC. In intensive land use, the highest phosphorus content (1.29

mg kg⁻¹) occurred at 30–45 cm depth, while in forest land use, phosphorus was uniformly low across all depths.

3.2.2 Chemical Properties of Concretion Only (CON)

Table 7. Effect of land use on selected chemical properties of concretion only (CON)

Land Use	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
Intensive	5.01b	0.09a	0.51a	0.55a	1.63a	0.39a	2.01a	1.61a	6.70a	0.65b	1.04a
Forest	5.42a	0.06a	0.33b	0.44a	1.17b	1.62a	2.68a	0.34b	6.58a	1.09a	1.88b

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

Forest-derived concretions had significantly higher pH (5.42) compared to intensive land concretions (5.01). Exchangeable aluminium was significantly higher ($p < 0.05$) in concretions from intensive land use (1.61 cmol kg⁻¹) compared to forest concretions (0.34 cmol kg⁻¹). Organic carbon and organic matter

were significantly higher in forest concretions (1.09 and 1.88 g kg⁻¹) compared to intensive concretions (0.65 and 1.04 g kg⁻¹). Available phosphorus, exchangeable potassium, calcium, and total organic matter showed no significant differences between land use types in concretion materials.

Table 8. Interaction effect of land use and depth on selected chemical properties of concretion only (CON)

Land Use	Depth (cm)	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
Intensive	0–15	4.83b	0.09b	0.45ab	0.41ab	1.47a	0.51a	3.12a	0.38a	6.34ab	0.86ab	1.51ab
	15–30	4.96ab	0.11b	0.64a	0.68a	1.64a	0.48a	2.83a	0.66a	6.93a	0.78ab	1.34ab
	30–45	4.82b	1.29a	0.42bc	0.49ab	1.88a	0.32a	3.09a	0.71a	6.91a	0.57b	0.98b
Forest	0–15	4.86b	0.12b	0.21c	0.32b	1.30a	0.67a	2.88a	0.37a	5.74ab	1.13a	1.95a
	15–30	5.66a	0.05b	0.23bc	0.35b	1.18a	0.48a	1.97a	0.56a	4.76ab	0.81ab	1.37ab
	30–45	5.40ab	0.05b	0.27bc	0.38ab	1.22a	0.48a	1.46a	0.39a	4.20b	0.93ab	1.60ab

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test. This table is presented in landscape format for clarity in the original submission.

Soil depth had no significant effect ($p > 0.05$) on any chemical property of concretion nodules, indicating uniform chemical characteristics of concretions

throughout the soil profile. The interaction between land use and depth was significant for pH, potassium, calcium, aluminium, organic carbon, and organic matter.

3.2.3 Chemical Properties of Soil Plus Concretion (SCN)

Table 9. Effect of land use on selected chemical properties of soil plus concretion (SCN)

Land Use	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
Intensive	4.91b	0.08a	0.53a	0.55a	2.28a	0.34a	2.01a	1.90a	6.96a	0.83b	1.43b
Forest	5.64a	0.20a	0.30b	0.44a	1.37b	0.58a	2.68a	2.78a	6.58a	1.30a	2.24a

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

Forest SCN samples had significantly higher pH (5.64), organic carbon (1.30 g kg⁻¹), and organic matter (2.24 g kg⁻¹) compared to intensive SCN (pH 4.91, OC 0.83 g kg⁻¹, OM 1.43 g kg⁻¹), representing a 56.6% increase in organic carbon.

Intensive SCN exhibited significantly higher exchangeable potassium (0.53 cmol kg⁻¹) compared to forest SCN (0.30 cmol kg⁻¹), while forest SCN had higher exchangeable magnesium (0.58 cmol kg⁻¹ vs. 0.34 cmol kg⁻¹).

Table 10. Effect of depth on selected chemical properties of soil plus concretion (SCN)

Depth (cm)	pH (H ₂ O)	P (mg/kg)	K	Na	Ca	Mg	H	Al	CEC	OC (g/kg)	OM (g/kg)
0–15	5.06a	0.09a	0.34a	0.44a	1.11a	2.01a	2.51a	0.34a	6.75a	0.95a	1.64a
15–30	5.34a	0.07a	0.45a	0.57a	1.49a	0.40a	2.60a	2.32a	7.83a	0.77a	1.27a
30–45	5.24a	0.07a	0.47a	0.48a	1.59a	0.61a	1.91a	0.31a	5.37a	0.89a	1.47a

Means with the same superscript in the same column are not significantly different ($p > 0.05$) based on Tukey's test.

Soil depth had no significant effect on any chemical property of SCN samples, similar to the pattern observed in concretion-only samples. The interaction between land use and depth significantly affected pH, potassium, calcium, aluminium, organic carbon, and organic matter in SCN samples.

3.3 Nitrogen Forms and Correlation Analysis

Total nitrogen showed highly significant positive correlations with organic nitrogen ($r = 0.532$, $p < 0.001$) and nitrate ($r = 0.961$, $p < 0.001$). Organic nitrogen exhibited a

significant positive correlation with nitrate ($r = 0.290$, $p < 0.05$). Both total nitrogen and organic nitrogen showed significant positive correlations with soil depth ($r = 0.540$ and 0.331 , respectively), as did nitrate ($r = 0.509$, $p < 0.001$). Ammonium showed no significant correlations with other nitrogen forms or with depth. Land use type showed a significant negative correlation with organic nitrogen ($r = -0.316$, $p < 0.05$), confirming higher organic nitrogen content in forest compared to intensive land use.

Table 11. Correlation coefficients (r)

	Total N	Org. N	NO ₃ ⁻ -N	NH ₄ ⁺ -N	Depth
Org. N (g kg ⁻¹)	0.532***	–			
NO ₃ ⁻ -N (g kg ⁻¹)	0.961***	0.290*	–		
NH ₄ ⁺ -N (g kg ⁻¹)	-0.087ns	-0.071ns	-0.167ns	–	
Depth	0.540***	0.331*	0.509***	-0.209ns	–
Land use	-0.095ns	-0.316*	0.011ns	-0.093ns	0.000ns

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns = not significant.

4. Conclusion

Land use type exerts a more profound influence on nitrogen dynamics in ferromanganese concretion-rich Ferric Luvisols than concretion presence itself. Forest land use maintained significantly higher organic nitrogen (28% increase), total nitrogen, and nitrate (136% increase) compared to intensive cultivation, reflecting unsustainable nitrogen capital depletion under continuous cropping.

Contrary to the initial hypothesis, concretion nodules contained significantly lower organic nitrogen, total nitrogen, and nitrate than the surrounding soil matrix; however, they exhibited 3–4-fold higher ammonium concentrations, likely through fixation involving iron and manganese oxide surfaces. Soil plus concretion mixtures showed 30–45% enhancement in total and organic nitrogen, attributable to organo-mineral associations rather than direct nitrogen contribution from

concretions. The uniform nitrogen distribution throughout the 0–45 cm profile indicates active vertical movement and vulnerability to leaching losses during intense rainfall events.

Both land use types fall within the low nitrogen fertility classification (total N < 1.0 g kg⁻¹), with organic nitrogen dominating (>85% of total N). Sustainable nitrogen management in these soils requires: (i) integration of organic amendments to rebuild depleted nitrogen

stocks; (ii) lime application to raise pH above 5.5; (iii) adoption of legume-based rotations for biological nitrogen fixation; (iv) conservation tillage to reduce physical degradation; and (v) split nitrogen fertiliser applications to minimise leaching losses. Future research should investigate temporal nitrogen dynamics across seasons, microbial processes in concretion-influenced microsites, and the long-term effectiveness of organic amendments.

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