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# Pedogenesis, Weathering Intensity, and Soil Development in the Northern Guinea Savanna of Zagga District, Northwestern Nigeria

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## Abstract

Understanding pedogenetic processes and weathering dynamics is fundamental to characterizing soil development and guiding sustainable land management in Guinea savannas. This study evaluated the pedogenic processes, weathering status, and stage of soil development in Zagga District. Field investigations of eight representative soil profiles were conducted and their morphological description, followed by laboratory analysis of their, physical, and chemical properties. The soils exhibited sandy loam to loamy sand textures, with silt/clay ratios generally <1, indicating advanced weathering and clay translocation. Bulk density ranged between 1.47–1.98 g cm$^{-3}$, while total porosity averaged 21–30%. Chemical analyses revealed acidic reactions (pH 5.2–6.1), low organic carbon (0.23–1.18 g kg$^{-1}$), low available phosphorus (<1.3 mg kg$^{-1}$), and moderate to high cation exchange capacity (9–37 cmol kg$^{-1}$), though base saturation was often below 20%, reflecting nutrient depletion and desilication. Dominant pedogenic processes included argilluviation, gleization, melanization, humification, and pedoturbation. Profiles such as ZG6 and ZG7 showed well-developed Bt horizons with evidence of clay illuviation, while coarse-textured profiles (ZG8, ZG9, ZG12, ZG13) reflected weak weathering, minimal clay translocation, and early-stage cambic development. Redoximorphic features, mottling, and grey matrix colors in several profiles confirmed the influence of fluctuating water tables and poor drainage. Overall, the soils of Zagga District represent a continuum from weakly developed Entisols to more weathered soils, shaped by seasonal wet–dry cycles and sandy parent materials. Their low fertility and resilience highlight the need for integrated soil fertility management, conservation practices, and land-use planning to sustain agricultural productivity.

**Keywords:** Pedogenesis, Soil development, Weathering, Northern Guinea Savanna, Zagga District

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## Introduction

The Nigerian Savanna comprises four major ecological zones: Southern Guinea (SG), Northern Guinea (NG), Sudan (SU), and Sahel Savanna (SA). Collectively, these agro-ecological regions span approximately 700,000 km², accounting for nearly three-quarters of Nigeria's total land mass (Malgwi & Abu, 2011). The soils of the Savanna are typically dominated by low-activity clays, with kaolinite and sesquioxides (FeOH) constituting about 80–90% of the clay fraction. They are highly weathered, with surface horizons ranging from loamy sand to sandy loam (Moberg & Esu, 1991).

Soil formation in tropical environments is driven by a dynamic interaction among climate, parent material, topography, biological activity, and time, all of which influence pedogenetic pathways and the degree of weathering (Buol *et al.,* 2011; Esu, 2010). In the Northern Guinea Savanna of Nigeria, these factors are shaped by a monomodal rainfall pattern, alternating wet–dry cycles, and the prevalence of sandy alluvial parent materials. Consequently, soils in this region exhibit variable horizon development, fluctuating drainage regimes, and weathering intensities ranging from weakly developed Entisols to more advanced Ultisols and Inceptisols (Yakubu & Ojanuga, 2009; Maniyunda *et al.,* 2014).

Soil is not merely a medium for plant anchorage but a dynamic natural body formed through physical, chemical, and biological weathering, resulting in the differentiation of soil horizons (Jenny, 1941; Schaetzl & Anderson, 2005). Understanding pedogenetic processes is central to evaluating soil resilience, nutrient cycling, and land sustainability—especially in tropical regions where high temperatures and intense seasonal rainfall accelerate weathering (Lal, 2015). Within Nigeria, the Guinea Savanna serves as the nation's primary grain-producing zone. The Northern Guinea Savanna, in particular, is marked by prolonged dry seasons and moisture stress, which strongly influence soil development and weathering trajectories (Jones & Wild, 1975; Kowal & Knabe, 1972). Most soils in this zone are derived from the ancient crystalline basement complex, resulting in deeply weathered profiles classified mainly as Alfisols, Inceptisols, and Ultisols under USDA Soil Taxonomy (Soil Survey Staff, 2014).

Pedogenesis in semi-arid savanna ecosystems typically involves eluviation–illuviation of clays, laterization, ferruginization in upland terrains, and gleization in poorly drained areas (Wilding & Eswaran, 1976; Barczok *et al.,* 2023). Seasonal leaching and redox fluctuations further enhance iron and manganese segregation, leading to mottling and other redoximorphic features (Glinski & Lipiec, 1990). Subsurface textural differentiation reflects ongoing eluviation–illuviation processes, while low base saturation and acidic reactions indicate advanced desilication and leaching (Obi *et al.,* 2009; Adesemuyi *et al.,* 2019). These processes collectively contribute to fertility decline, nutrient imbalance, and soil management challenges common to tropical environments (FAO, 2006).

Given the ecological vulnerability and importance of the Northern Guinea Savanna as Nigeria's food-producing hub, a deeper understanding of pedogenetic processes and weathering intensity processes is essential for sustainable soil use, fertility restoration, and improved taxonomic interpretation. This study therefore aims to examine the dominant pedogenetic processes, evaluate the degree of weathering, and assess the stage of soil development in the Zagga District, Northwestern Nigeria, thereby advancing pedological knowledge and informing sustainable land management strategies for the Northern Guinea Savanna.

## Materials and Methods

### Study Area: -

The research was conducted southwest of Zagga town, along the Dakingari–Koko Road in Bagudo Local Government Area of Kebbi State, Nigeria (Figure 1). The site lies between latitudes 11°27′20″ and 11°35′30″N and longitudes 40°00′ and 40°11′32″E, covering a total of 12,857 ha. For this study, a 170-ha section was delineated, while adjacent portions were reserved for parallel investigations.

Vegetation is predominantly Northern Guinea Savanna in the south and southeast, transitioning to Sudan Savanna in the north (Olayide *et al.,* 2023). The landscape is characterized by scattered trees such as *Adansonia digitata*, *Piliostigma reticulatum*, *Faidherbia albida*, and *Tamarindus indica*, interspersed with shrub species including *Guiera senegalensis*.

Geologically, Kebbi State is underlain by Precambrian Basement Complex rocks in the south and southeast and younger sedimentary formations in the north. The Basement Complex is dominated by ancient volcanic and metamorphic lithologies such as granites, schists, gneisses, quartzites, and migmatites.

### Field work and Soil Profile Description

A semi-detailed soil survey was undertaken at a scale of 1:25,000 following the procedures outlined by Kairis *et al*. (2020). Pegging was carried out on a fixed grid pattern, and representative soil profiles were opened within each identified mapping unit. Horizons were delineated based on observable variations in color, texture, structure, consistence, root distribution, and the occurrence of mottles or concretions. Morphological descriptions adhered to FAO (2006) guidelines; with soil colors determined using the Munsell soil color chart.

Soil samples were collected from each horizon, air-dried, gently crushed, and sieved through a 2-mm mesh for laboratory analysis. Undisturbed core samples were also obtained with a cylindrical steel sampler for bulk density and porosity determinations.

### Laboratory Analyses

Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962), with textural classes assigned using the USDA textural triangle. Bulk density was measured using the core method (Blake & Hartge, 1986). Total porosity was calculated from bulk density and particle density (assumed as 2.65 g $cm^{-3}$). Gravimetric moisture content was determined by oven-drying samples at 105°C to constant weight.

Soil pH was determined in 1:2.5 soil: water using a digital pH meter. Electrical conductivity (EC) was measured in a 1:2.5 soil–water extract. Organic carbon was determined by the Walkley–Black dichromate oxidation method (Nelson & Sommers, 1982) and converted to organic matter using a factor of 1.724. Total nitrogen was determined using the Kjeldahl digestion method (Bremner, 1996)). Available phosphorus was extracted by the Bray-1 method and determined colorimetrically ((Bray and Kurtz, 1965).). Exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$) were extracted with 1 *N* ammonium acetate (pH 7.0). The Ca and Mg were determined by atomic absorption spectrophotometry (AAS), while K and Na were determined using a flame photometer. Cation exchange capacity (CEC) was obtained by summation of exchangeable bases and exchangeable acidity. Base saturation (%) was calculated as (sum of exchangeable bases ÷ CEC) × 100.

## Data Analysis

Descriptive statistics (means, ranges, and standard deviations) were used to summarize soil physical and chemical properties. Pearson's correlation analysis was conducted to determine the linear relationship between soil physical and chemical properties.

## Results and Discussion

The eight identified mapping units were designated ZG6, ZG7, ZG8, ZG9, ZG10, ZG11, ZG12 and ZG 13.

### Soil Morphology and Horizon Differentiation

The soils were generally deep to very deep (Table 1). Previous studies (Raji, 1995; Idoga *et al.,* 2007; Maniyunda *et al.,* 2014) have attributed variations in soil depth to factors such as parent material, erosion, and the slope of the landscape. The dominance of brown colour in the subsoil horizon indicates that braunification is a prominent pedogenic process in these soils, consistent with the findings of Yakubu and Ojanuga (2009), Maniyunda *et al.* (2014), and Ande (2010).

The soils of Zagga District exhibit contrasting degrees of horizon differentiation, reflecting divergent pedogenic pathways (Table 1). Profiles ZG6 and ZG7 display well-formed Bt horizons with pronounced clay illuviation, indicative of argillic horizon development. By contrast, ZG8, ZG9, ZG10, and ZG13 retain sandy or loamy sand textures with weak horizon expression, suggesting limited weathering and early-stage profile development. Redoximorphic mottles in ZG6, ZG7, ZG9, and ZG10 further underscore the influence of fluctuating water tables and seasonal saturation, processes typical of gleization in savanna soils (Vepraskas, 1994; Sharu *et al.,* 2013).

**Table 1: Morphological Properties of the Soils**

**ZG 6**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | Mottles | | | | | | |
| 0-12 | Ap | 10YR7/2 | 10YR4/3 | 10YR6/8 | SL | 1fsbk | vs | MR | MP | CS |
| 12-35 | AB | 10YR6/3 | 10YR4/3 | 10YR5/8 | SL | 2fsbk | vs | MR | MP | GS |
| 35-69 | Bt1 | 10YR5/3 | 10YR5/3 | 5YR5/6 | SL | 3sbk | ss | VFR | MP | GS |
| 69-126 | Bt2 | 5YR7/1 | 5YR7/1 | 2.5YR3/6 | SL | 2fabk | ss | NR | FP | DS |
| 126-170+ | Bt3 | 10YR6/3 | 10YR5/2 | 5YR4/6 | SL | 2fabk | ss | NR | VFP | DS |

**ZG 7**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | Mottles | | | | | | |
| 0-27 | Ap | 10YR/7/2 | 10YR/5/3 | 10YR/6/8 | SL | 1sbk | vs | MR | MP | GS |
| 27-51 | Bw | 10YR 7/2 | 10YR 5/3 | 10YR 6/8 | SL | 2fsbk | s | MR | MP | GS |
| 51-107+ | Bt | - | 10YR 5/2 | 2.5YR 6/8 | S | 1fsbk | vs | MR | FP | DS |

**ZG 8**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | Mottles | | | | | | |
| 0-22 | Ap | - | 10YR5/2 | 10YR4/4 | LS | P | s | MR | FP | GS |
| 22-39 | Bt1 | - | 7.5 YR5/2 | 10 YR4/6 | LS | P | s | MR | FP | GS |
| 39-55 | Bt2 | - | 10YR6/2 | 10 YR5/8 | SL | P | vs | FR | FP | GS |
| 55-74+ | Cg | - | 10YR7/3 | - | S | P | - | MR | MP | GS |

**ZG 9**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | mottles | | | | | | |
| 0-14 | Ap | 10YR6/12 | 10 YR4/3 | - | LS | 2fsbk | s | MR | MP | GS |
| 14-28 | AB | 10 YR6/3 | 10YR5/3 | - | S | p | s | MR | MP | GS |
| 28-57 | Bt | - | 10 YR6/4 | 10YR 5/8 | LS | p | vs | MR | FP | GS |
| 57-84 | C1 | - | 7.5 YR7/4 | 10 YR 5/8 | S | p | vs | FR | FP | GS |

**ZG 10**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | mottles | | | | | | |
| 0-11 | Ap | - | 10YR5/6 | 7.5YR3/6 | LS | 2fsbk | ss | MR | MP | GS |
| 11-35 | Bt | - | 10YR6/9 | 2.5YR5/6 | LS | 3fsbk | ss | FR | MP | GS |
| 35-53 | C1 | - | 10YR5/6 | 2.5YR4/6 | LS | 2abk | vs | FR | MP | GS |
| 53-100 | C2 | - | 7.5YR5/6 | 5 YR5/4 | SL | 2fabk | vs | - | MP | GS |

**ZG 11**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | mottles | | | | | | |
| 0-18 | Ap | - | 10YR5/6 | - | SL | 1fsbk | s | MR | FP | GS |
| 18-53 | BC | - | 7.5YR5/8 | 2.5YR4/8 | SL | 2sbk | vs | MR | FP | GS |
| 53-103+ | C | - | 10YR4/4 | 2.5YR3/6 | SL | 3fsbk | vs | FR | - | |

**ZG 12**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | Mottles | | | | | | |
| 0-17 | Ap | - | 10YR4/6 | - | SL | 2msbk | S | MR | MP | GS |
| 17-41 | Bt1 | - | 10YR5/8 | - | SL | 1fsbk | vs | MR | MP | GS |
| 41-130 | Bt2 | - | 10 YR5/8 | 2.5YR6/8 | SL | 1fsbk | vs | VFR | MP | DS |
| 130-150 | Bt3 | - | 10 YR7/6 | - | LS | 2msbk | vs | VFR | FP | GS |
| 150-186 | C | - | 10 YR7/8 | - | LS | | vs | NR | FP | DS |

**ZG 13**

| Depth (cm) | Horizon Designation | Colour | | | Textual class | Structure | Consistence (wet) | Roots | Pores | Boundary form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dry | Moist | Mottles | | | | | | |
| 0-16 | Ap | - | 7.5YR6/6 | - | LS | 1fabk | ss | MR | MP | GS |
| 16-28 | AB | - | 7.5 YR5/8 | - | LS | 1fsbk | ss | MR | MP | GS |
| 28-81 | Bw1 | - | 5YR6/8 | - | LS | 1fsbk | ss | VF | MP | GS |
| 81-134 | Bw2 | - | 5YR6/8 | - | LS | 2fsbk | ss | NR | MP | GS |
| 134-200 | C | - | 7.5YR6/8 | - | LS | 1sbk | ss | - | MP | DS |

## Soil Physical Properties and Weathering Status

The descriptive statistics of the physical properties of the soils are presented in Table 2. Clay content exhibited marked variability across the profiles, ranging from 26–35% in ZG6–ZG7 to less than 10% in ZG8–ZG13. This wide range reflects fundamentally different pedogenic pathways operating within the study area. The higher clay contents observed in ZG6 and ZG7 are attributable to dominant argilluviation—the process of clay particle translocation from surface eluvial horizons to subsurface illuvial (Bt) horizons—coupled with secondary clay formation through in situ weathering of primary minerals (Buol *et al.,* 2011). In these profiles, the presence of well-developed Bt horizons with distinct clay films (as described in Table 3) provides direct field evidence of active clay illuviation. In contrast, the sandy profiles (ZG8–ZG13) exhibit clay contents below 10%, reflecting the dominance of physical weathering over chemical weathering, limited clay neoformation, and minimal clay translocation. In these soils, parent materials composed predominantly of quartz-rich sands have undergone only incipient pedogenesis, resulting in weakly expressed horizons and the absence of argillic development (Brady & Weil, 2017). Similar textural contrasts have been widely reported in Northern Guinea Savanna soils, where Alfisols and Ultisols typically display well-developed argillic horizons with clay accumulations exceeding 20%, while Entisols and Inceptisols remain coarser (sandy loam to sand) and weakly differentiated due to younger soil age, resistant parent materials, or erosional truncation of surface horizons (Yakubu & Ojanuga, 2009; Esu, 2010).

The relatively higher silt–clay ratios observed in the surface horizons compared to the subsoil horizons can be attributed to the eluviation of clay from the surface layers and its subsequent downslope movement from the crestal positions (Esu, 1987). In general, the surface horizons exhibited significantly higher silt–clay ratios than the subsoil horizons (with the exception of ZG11), indicating a greater degree of weathering in the subsoil relative to the surface layers. Furthermore, the mean silt–clay ratio values across all the soils exceeded the critical threshold of 0.15, which is commonly associated with highly weathered soils (Van Wambeke, 1962; Yakubu and Ojanuga, 2009; Maniyunda *et al.,* 2014). This suggests that the soils within the study area can be classified as fairly to moderately weathered.

Bulk density values ranged from 1.5 to 1.9 g cm$^{-3}$, generally falling within the threshold considered suitable for unrestricted root penetration and aeration (Reynolds *et al.,* 2002). However, the sandy horizons of ZG8 and ZG9 exhibited relatively higher porosity, consistent with coarse-textured parent materials and limited aggregation (Lal, 2015). These values align with findings by Sharu *et al.* (2013), who reported comparable bulk densities in sandy loam soils of Northwestern Nigeria, though slightly lower than those observed in more clayey Alfisols. These findings reinforce the central role of clay illuviation and weathering intensity in differentiating soil formation pathways in the Northern Guinea Savanna (Maniyunda *et al.,* 2014; Adesemuyi *et al.,* 2019).

**Table 2: Descriptive statistics of the Physical properties of soils in Zagga District**

| Property | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|
| Sand (%) | 34 | 47.8 | 94.9 | 71.6 | 14.2 |
| Silt (%) | 34 | 3.1 | 28.6 | 13.1 | 7.0 |
| Clay (%) | 34 | 2.0 | 35.3 | 13.8 | 10.3 |
| Silt/Clay ratio | 34 | 0.4 | 9.0 | 2.5 | 2.3 |
| Bulk density (g $cm^{-3}$) | 26 | 1.47 | 1.98 | 1.77 | 0.14 |
| Total porosity (%) | 26 | 13.9 | 36.9 | 23.9 | 5.1 |
| Gravimetric moisture content (%) | 34 | 11.1 | 28.0 | 20.0 | 5.5 |

**Table 3: Physical Properties of the Soils**

## ZG 6

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| | | | | **ZG 6** | | | | | | |
| 0-12 | Ap | 61.6 | 22.7 | 15.7 | SL | 1.4 | 1.86 | 2.00 | 27.4 | 17.5 |
| 12-35 | AB | 57.6 | 18.9 | 23.3 | SL | 0.8 | 1.89 | 2.00 | 28.2 | 17.3 |
| 35-69 | Bt1 | 53.7 | 16.9 | 29.4 | SL | 0.5 | 1.84 | 2.09 | 28.5 | 17.6 |
| 69-126 | Bt2 | 57.6 | 11.0 | 31.4 | SL | 0.4 | ---- | ---- | ---- | ---- |
| 126-170 | Bt3 | 55.7 | 12.9 | 31.4 | SL | 0.4 | ---- | ---- | ---- | ---- |
| | **Mean** | **57.4** | **16.2** | **26.2** | | **0.7** | **1.86** | **2.03** | **28.1** | **17.5** |

## ZG 7

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-27 | Ap | 61.6 | 22.7 | 15.7 | SL | 1.4 | 1.98 | 2.13 | 19.9 | 14.2 |
| 27-51 | Bw | 67.5 | 9.00 | 23.5 | SL | 0.4 | 1.68 | 2.13 | 22.9 | 19.7 |
| 51-107 | Bt | 47.8 | 16.9 | 35.3 | SL | 0.4 | 1.57 | 2.14 | 22.7 | 16.9 |
| | **Mean** | **59.0** | **16.0** | **25.0** | | **0.7** | **1.74** | **2.13** | **21.8** | **16.9** |

## ZG 8

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-22 | Ap | 73.3 | 24.7 | 2.00 | LS | 1.2 | 1.82 | 2.28 | 28.8 | 16.9 |
| 22-39 | Bt1 | 71.4 | 24.7 | 3.90 | LS | 6.3 | 1.83 | 2.23 | 26.8 | 18.5 |
| 39-55 | Bt2 | 67.5 | 28.6 | 3.90 | SL | 7.3 | 1.84 | 2.10 | 28.6 | 11.8 |
| 55-74 | Cg | 92.9 | 5.10 | 2.00 | S | 2.5 | ---- | ---- | ---- | 12.5 |
| | **Mean** | **76.0** | **21.0** | **3.00** | | **4.0** | **1.83** | **2.21** | **28.7** | **14.9** |

## ZG 9

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-14 | Ap | 87.0 | 11.0 | 2.00 | LS | 5.5 | 1.86 | 1.92 | 22.2 | 17.0 |
| 14-28 | AB | 90.9 | 7.10 | 2.00 | S | 3.5 | 1.75 | 2.04 | 24.3 | 14.8 |
| 28-57 | Bt | 89.0 | 3.20 | 7.80 | LS | 0.4 | 1.77 | 2.18 | 26.1 | 16.8 |
| 57-84 | C1 | 90.9 | 7.10 | 2.10 | S | 7.0 | ---- | ---- | ---- | 18.9 |
| 84-104+ | C2 | 94.9 | 3.10 | 2.00 | S | 1.5 | ---- | ---- | ---- | ---- |
| | **Mean** | **91.0** | **5.00** | **4.00** | | **3.5** | **1.79** | **2.05** | **24.2** | **16.9** |

## ZG 10

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-11 | Ap | 77.3 | 20.7 | 2.00 | LS | 9.0 | 1.69 | 2.00 | 22.2 | 26.3 |
| 11-35 | Bt | 81.2 | 12.9 | 5.90 | LS | 2.1 | 1.66 | 2.00 | 27.5 | 24.6 |
| 35-53 | C1 | 85.0 | 13.0 | 2.00 | LS | 6.5 | 1.77 | 2.09 | 13.9 | 27.0 |
| 53-100 | C2 | 67.5 | 20.7 | 11.8 | SL | 1.7 | ---- | ---- | ---- | 28.0 |
| | **Mean** | **77.7** | **16.8** | **6.4** | | **4.8** | **1.71** | **2.03** | **21.2** | **26.5** |

## ZG 11

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-18 | Ap | 57.6 | 11.0 | 31.4 | SL | 0.4 | 1.49 | 2.13 | 30.1 | 27.4 |
| 18-53 | BC | 61.6 | 12.9 | 25.5 | SL | 0.5 | 1.89 | 2.04 | 17.4 | 26.9 |
| 53-103 | C | 57.6 | 26.7 | 15.7 | SL | 1.7 | 1.89 | 2.04 | 16.4 | 23.4 |
| | **Mean** | **58.9** | **16.8** | **24.2** | | **0.8** | **1.76** | **2.07** | **21.3** | **25.9** |

## ZG 12

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-17 | Ap | 85.0 | 13.0 | 2.00 | LS | 6.5 | 1.77 | 2.23 | 20.7 | 23.4 |
| 17-41 | Bt1 | 87.0 | 7.10 | 5.90 | LS | 1.2 | 1.70 | 2.23 | 19.8 | 26.2 |
| 41-130 | Bt2 | 85.0 | 9.10 | 5.90 | LS | 1.5 | 1.98 | 2.28 | 17.0 | 26.5 |
| 130-150 | Bt3 | 90.9 | 7.10 | 5.90 | S | 1.2 | ---- | ---- | ---- | 28.0 |
| 150-186 | C | 92.9 | 5.10 | 2.00 | S | 2.5 | ---- | ---- | ---- | 26.5 |
| | **Mean** | **88.2** | **8.30** | **3.50** | | **6.4** | **1.82** | **2.25** | **19.2** | **26.0** |

## ZG 13

| Horizon | | Particle size distribution (%) | | | Textural Class | Silt/Clay Ratio | BD | PD | TP % | GMC |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Designation | Sand | Silt | Clay | | | (g/cm$^3$) | | | |
| 0-16 | Ap | 87.0 | 7.10 | 5.90 | LS | 1.2 | 1.47 | 2.33 | 36.9 | 23.1 |
| 16-28 | AB | 90.9 | 3.20 | 5.90 | LS | 0.5 | 1.91 | 2.23 | 18.1 | 18.1 |
| 28-81 | Bw1 | 83.1 | 5.10 | 11.8 | LS | 0.4 | 1.86 | 2.33 | 20.2 | 19.1 |
| 81-134 | Bw2 | 77.3 | 10.9 | 11.8 | LS | 0.9 | ---- | ---- | ---- | 11.1 |
| 134-200 | C | 89.0 | 5.10 | 5.90 | LS | 0.8 | ---- | ---- | ---- | 13.1 |
| | **Mean** | **85.5** | **6.30** | **8.30** | **LS** | **0.7** | **1.75** | **2.33** | **25.1** | **16.9** |

## Soil Chemical Properties and Nutrient Dynamics

The descriptive statistics of the chemical properties of the soils are presented in Table 4, while horizon-level variations are shown in Table 5. The soils of the study area are generally acidic, with pH values ranging from 5.2 to 6.1 across all horizons. This moderately to strongly acidic condition is consistent with leached savanna soils where long-term weathering under high seasonal rainfall has resulted in the progressive depletion of exchangeable bases and the accumulation of hydrogen and aluminum ions on the exchange complex (Lal, 2015; Brady & Weil, 2017). The slightly higher pH values (6.0–6.1) recorded in the sandy profiles (ZG8, ZG9) likely reflect their lower weathering intensity and reduced leaching due to coarser texture and shallower depth, whereas the more acidic conditions (pH 5.2–5.6) in clay-rich profiles (ZG6, ZG7, ZG11) are consistent with advanced pedogenesis and longer residence time of soil water in finer-textured horizons. Organic carbon contents were characteristically low, ranging from 0.10 to 2.63 g $kg^{-1}$, with most profiles recording values below 1.0 g $kg^{-1}$ (Table 4). Total nitrogen followed a similar pattern (0.007–0.15 g $kg^{-1}$), reflecting the strong coupling between organic carbon and nitrogen dynamics in these soils. The low organic matter status is attributable to several interacting factors: (i) rapid decomposition rates driven by high temperatures and alternating wet–dry cycles typical of tropical savanna ecosystems; (ii) limited organic matter inputs from natural vegetation, which is dominated by sparse trees and shrubs with low biomass production; and (iii) sustained leaching losses that remove soluble organic compounds from the rooting zone (Sanchez, 2019; Maniyunda *et al.,* 2014). The slightly higher organic carbon values observed in surface horizons (Ap) compared to subsurface horizons (Bt, BC, C) confirm that organic matter accumulation is largely restricted to the uppermost soil layer, with minimal translocation of organic colloids to depth. This surface stratification of organic carbon has important implications for nutrient cycling: most biological activity and nutrient mineralization are concentrated in the top 0–20 cm, leaving subsurface horizons depleted of organic substrates and dependent on clay mineralogy for nutrient retention.

Exchangeable bases were modest across all profiles, with calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) dominating the exchange complex, as shown in Table 5, while potassium ($K^{+}$) and sodium ($Na^{+}$) remained minimal (Table 4). Mean exchangeable Ca ranged from 0.60 to 1.40 cmol $kg^{-1}$, while Mg ranged from 0.15 to 0.85 cmol $kg^{-1}$, reflecting the typical weathering sequence in which Ca and Mg are released more readily from primary minerals than K and Na (Esu, 2010). The low $K^{+}$ (0.05–0.33 cmol $kg^{-1}$) and $Na^{+}$ (0.06–2.30 cmol $kg^{-1}$) values indicate that feldspars and other K-bearing minerals are either absent in the parent material or have been extensively weathered, with released K rapidly taken up by vegetation or lost through leaching. This pattern—Ca > Mg >> K > Na—is characteristic of highly weathered tropical soils and is consistent with findings from other parts of the Northern Guinea Savanna (Sharu *et al.,* 2013). The relatively higher $Na^{+}$ values observed in ZG11 (0.50 cmol $kg^{-1}$) and ZG6 (0.70–2.30 cmol $kg^{-1}$) may reflect localized influence of sodic parent materials or groundwater influence, though exchangeable sodium percentage (ESP) values remained below the threshold for sodicity (ESP < 15% in all profiles except ZG11, where ESP reached 17.2% in one horizon).

Cation exchange capacity (CEC) showed strong textural dependence across the profiles (Table 5), confirming that clay content is the primary determinant of nutrient retention capacity in these soils. The clay-rich profiles

ZG6 (22–28 cmol kg$^{-1}$) and ZG7 (19–21 cmol kg$^{-1}$) maintained relatively high CEC values, consistent with their higher clay content (26% and 25%, respectively) and the presence of illuvial Bt horizons (Table 3). Profile ZG11 recorded the highest CEC values (36–37 cmol kg$^{-1}$) despite having only 24% clay on average, suggesting that the clay fraction in this profile may be dominated by more reactive clay minerals (e.g., smectite or vermiculite) compared to the predominantly kaolinitic clays typical of other profiles. In contrast, sandy profiles such as ZG8–ZG10 and ZG13 recorded much lower CEC values (9–12 cmol kg$^{-1}$), reflecting their low clay content (<8%) and the dominance of quartz sand, which possesses negligible negative charge and therefore minimal nutrient retention capacity (Sanchez, 2019). Profile ZG12 presented an interesting case: despite having only 3.5% mean clay content, it recorded moderate CEC values (11–35 cmol kg$^{-1}$), with the highest values (35 cmol kg$^{-1}$) occurring in the Ap horizon where organic matter (0.80 g kg$^{-1}$) likely contributed additional exchange sites. This observation highlights the dual contribution of clay and organic matter to CEC in surface horizons, a finding consistent with Brady & Weil (2017).

Base saturation and nutrient depletion**:** Base saturation was consistently below 20% across all profiles (range: 8.5–25.0%, mean: 15.5%; Table 4), highlighting advanced leaching, progressive desilication, and severe nutrient depletion (Yakubu & Ojanuga, 2009; Adesemuyi *et al.,* 2019). Base saturation values below 20% indicate that more than 80% of the exchange complex is occupied by acidic cations ($H^+$ and $Al^{3+}$), which can impair root growth, reduce nutrient availability, and increase the solubility of potentially toxic aluminum (Sharma *et al.,* 2025) The lowest base saturation values were recorded in ZG9 (8.5–11.8%) and ZG10 (10.5–12.2%), both of which are sandy profiles with low CEC and minimal buffering capacity. Even the clay-rich profiles (ZG6, ZG7, ZG11) exhibited base saturation below 20%, indicating that their higher CEC is largely occupied by acidic cations rather than exchangeable bases. This finding has critical implications for soil fertility management: liming is necessary not only to raise pH but also to displace $Al^{3+}$ and $H^+$ from the exchange complex, thereby increasing base saturation and improving nutrient availability (Lal, 2015). The consistently low base saturation across all profiles underscores that soil fertility decline is not restricted to sandy soils but extends to clay-rich profiles as well, albeit with different mechanisms: sandy soils suffer from low CEC and rapid leaching, while clay-rich soils suffer from base depletion despite adequate CEC. Both scenarios require integrated nutrient management strategies that combine liming, organic matter enrichment, and balanced fertilization to restore and sustain productivity.

**Table 4: Descriptive statistics of Chemical properties of soils in Zagga District**

| Property | N | Minimum | Maximum | Mean | Standard Deviation |
|---|---|---|---|---|---|
| pH ($H_2O$) | 34 | 5.2 | 6.2 | 5.5 | 0.3 |
| EC (dS $m^{-1}$) | 34 | 0.001 | 0.082 | 0.015 | 0.019 |
| Organic carbon (g $kg^{-1}$) | 34 | 0.10 | 2.63 | 0.52 | 0.53 |
| Organic matter (g $kg^{-1}$) | 34 | 0.20 | 4.51 | 0.94 | 0.90 |
| Total nitrogen (g $kg^{-1}$) | 34 | 0.007 | 0.15 | 0.10 | 0.04 |
| Available P (mg $kg^{-1}$) | 34 | 0.55 | 1.30 | 0.87 | 0.21 |
| Exchangeable Ca (cmol $kg^{-1}$) | 34 | 0.60 | 1.40 | 0.81 | 0.19 |
| Exchangeable Mg (cmol $kg^{-1}$) | 34 | 0.15 | 0.85 | 0.48 | 0.20 |
| Exchangeable K (cmol $kg^{-1}$) | 34 | 0.05 | 0.33 | 0.12 | 0.09 |
| Exchangeable Na (cmol $kg^{-1}$) | 34 | 0.06 | 2.30 | 0.48 | 0.45 |
| CEC (cmol $kg^{-1}$) | 34 | 6.0 | 37.0 | 22.0 | 9.2 |
| Exchangeable sodium percentage (%) | 34 | 0.22 | 17.2 | 6.6 | 5.2 |
| Base saturation (%) | 34 | 8.5 | 25.0 | 15.5 | 3.7 |

**Table 5: Chemical Properties of the Soils**
**ZG 6**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (dSm$^{-1}$) | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟷ | (cmol/kg) | ⟷ | | | | (%) |
| 0-12 | Ap | 5.2 | 0.0013 | 0.50 | 0.95 | 0.140 | 1.25 | 0.75 | 0.60 | 0.05 | 2.30 | 20 | 11.5 | 18.5 |
| 12-35 | AB | 5.2 | 0.0086 | 0.35 | 0.50 | 0.120 | 1.25 | 0.85 | 0.15 | 0.10 | 0.70 | 19 | 3.68 | 19.5 |
| 35-69 | Bt1 | 5.3 | 0.0760 | 0.25 | 0.35 | 0.130 | 1.25 | 0.60 | 0.45 | 0.13 | 0.70 | 19 | 3.68 | 19.8 |
| 69-126 | Bt2 | 5.6 | 0.0820 | 0.15 | 0.20 | 0.009 | 1.10 | 0.70 | 0.80 | 0.26 | 0.70 | 23 | 3.04 | 16.9 |
| 126-170 | Bt3 | 5.7 | 0.0045 | 0.72 | 1.20 | 0.007 | 1.30 | 0.70 | 0.45 | 0.28 | 0.95 | 28 | 3.39 | 18.5 |
| **Mean** | | **5.4** | **0.034** | **0.39** | **0.64** | **0.081** | **1.23** | **0.72** | **0.49** | **0.16** | **1.07** | **22** | **3.88** | **18.6** |

**ZG 7**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (dS/m$^{-1}$) | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟷ | (cmol/kg) | ⟷ | | | | (%) |
| 0-27 | Ap | 5.5 | 0.0023 | 0.55 | 0.90 | 0.14 | 0.90 | 0.80 | 0.19 | 0.08 | 0.35 | 20 | 1.75 | 17.1 |
| 27-51 | Bw | 5.3 | 0.0062 | 1.10 | 1.90 | 0.13 | 0.80 | 0.65 | 0.60 | 0.28 | 0.45 | 19 | 2.37 | 14.2 |
| 51-107 | Bt | 5.4 | 0.0062 | 0.50 | 0.90 | 0.13 | 0.80 | 0.75 | 0.55 | 0.33 | 0.50 | 21 | 2.38 | 14.8 |
| **Mean** | | **5.4** | **0.0049** | **0.72** | **1.23** | **0.13** | **0.80** | **0.73** | **0.45** | **0.23** | **0.43** | **20** | **2.00** | **15.3** |

**ZG 8**

| Depth (cm) | Horizon Designation | pH 1:1 | EC | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (H$_2$O) | (dS/m$^{-1}$) | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟶ | (cmol/kg) | ⟵ | | | | (%) |
| 0-22 | Ap | 6.0 | 0.0180 | 0.50 | 0.90 | 0.12 | 1.10 | 0.70 | 0.15 | 0.05 | 0.06 | 12 | 5.00 | 12.5 |
| 22-39 | Bt1 | 5.9 | 0.0110 | 0.40 | 0.75 | 0.12 | 1.10 | 0.85 | 0.45 | 0.05 | 0.30 | 12 | 2.50 | 13.8 |
| 39-55 | Bt2 | 6.0 | 0.0083 | 0.20 | 0.35 | 0.11 | 0.70 | 0.70 | 0.25 | 0.05 | 0.40 | 10 | 4.00 | 14.0 |
| 55-74 | Cg | 6.1 | 0.0084 | 0.10 | 0.25 | 0.09 | 0.80 | 0.90 | 0.25 | 0.05 | 0.30 | 6.0 | 5.00 | 25.0 |
| **Mean** | | **6.0** | **0.0110** | **0.30** | **0.56** | **0.11** | **0.93** | **0.77** | **0.28** | **0.05** | **0.40** | **09** | **3.80** | **16.3** |

**ZG 9**

| Depth (cm) | Horizon Designation | pH 1:1 | EC | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (H$_2$O) | (dSm$^{-1}$) | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟶ | (cmol/kg) | ⟵ | | | | (%) |
| 0-14 | Ap | 5.5 | 0.0086 | 0.40 | 0.70 | 0.14 | 0.80 | 1.40 | 0.20 | 0.05 | 0.56 | 20 | 2.80 | 11.1 |
| 14-28 | AB | 5,5 | 0.0066 | 0.50 | 0.70 | 0.13 | 0.70 | 1.36 | 0.15 | 0.05 | 0.44 | 18 | 2.40 | 11.8 |
| 28-57 | Bt | 6.2 | 0.0110 | 0.40 | 0.90 | 0.090 | 0.66 | 0.95 | 0.30 | 0.05 | 0.22 | 18 | 1.20 | 8.5 |
| 57-84 | C1 | 5.9 | 0.0096 | 0.40 | 0.70 | 0.007 | 0.55 | 0.94 | 0.15 | 0.05 | 0.25 | 15 | 1.70 | 9.2 |
| 84-104 | C2 | 5.9 | 0.0087 | 0.10 | 0.25 | 0.050 | 0.75 | 0.95 | 0.25 | 0.05 | 0.25 | 9.2 | 0.22 | 16.3 |
| **Mean** | | **5.8** | **0.0089** | **0.36** | **0.65** | **0.083** | **0.69** | **1.12** | **0.21** | **0.05** | **0.34** | **16** | **1.88** | **11.4** |

**ZG 10**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC ($dSm^{-1}$) | OC ⟵ | OM (g/kg) | TN ⟶ | AP (mg/kg) | Ca ⟶ | Mg (cmol/kg) | K ⟵ | Na | CEC | ESP | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-11 | Ap | 6.1 | 0.0065 | 0.25 | 0.30 | 0.10 | 0.83 | 0.75 | 0.45 | 0.05 | 0.30 | 18 | 8.6 | 12.2 |
| 11-35 | Bt | 5.6 | 0.0078 | 0.54 | 0.92 | 0.10 | 1.04 | 0.65 | 0.60 | 0.05 | 0.30 | 18 | 8.9 | 11.4 |
| 35-53 | C1 | 5.5 | 0.0068 | 2.63 | 4.51 | 0.09 | 1.04 | 0.60 | 0.60 | 0.05 | 0.30 | 18 | 8.6 | 10.5 |
| 53-100 | C2 | 5.4 | 0.0070 | 1.30 | 2.26 | 0.13 | 1.10 | 0.85 | 0.45 | 0.10 | 0.45 | 23 | 8.5 | 10.8 |
| **Mean** | | **5.7** | **0.0070** | **1.18** | **2.00** | **0.11** | **1.00** | **0.71** | **0.53** | **0.063** | **0.34** | **19** | **8.7** | **11.2** |

**ZG 11**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC ($dS/m^{-1}$) | OC ⟵ | OM (g/kg) | TN ⟶ | AP (mg/kg) | Ca ⟶ | Mg (cmol/kg) | K ⟵ | Na | CEC | ESP | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-18 | Ap | 5.3 | 0.0630 | 0.30 | 0.55 | 0.15 | 0.70 | 0.90 | 0.40 | 0.28 | 0.50 | 36 | 17.2 | 14.5 |
| 18-53 | BC | 5.3 | 0.0290 | 0.25 | 1.55 | 0.14 | 0.70 | 0.90 | 0.40 | 0.28 | 0.50 | 36 | 17.2 | 13.6 |
| 53-103 | C | 5.6 | 0.0220 | 0.15 | 0.29 | 0.14 | 0.71 | 0.85 | 0.40 | 0.26 | 0.50 | 37 | 15.4 | 14.5 |
| **Mean** | | **5.4** | **0.0380** | **0.23** | **0.79** | **0.14** | **0.70** | **0.88** | **0.40** | **0.27** | **0.50** | **36** | **16.6** | **14.2** |

**ZG 12**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC ($dSm^{-1}$) | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟶ | (cmol/kg) | ⟵ | | | | (%) |
| 0-17 | Ap | 5.3 | 0.0210 | 0.80 | 1.45 | 0.11 | 0.71 | 0.60 | 0.44 | 0.05 | 0.30 | 35 | 13.9 | 15.8 |
| 17-41 | Bt1 | 5.2 | 0.0140 | 0.45 | 0.75 | 0.08 | 0.64 | 0.60 | 0.74 | 0.05 | 0.35 | 34 | 14.1 | 14.6 |
| 41-130 | Bt2 | 5.2 | 0.0110 | 0.40 | 0.70 | 0.08 | 0.75 | 0.60 | 0.65 | 0.05 | 0.33 | 35 | 14.0 | 16.2 |
| 130-150 | Bt3 | 5.3 | 0.0096 | 0.53 | 0.93 | 0.04 | 0.60 | 0.60 | 0.85 | 0.05 | 0.29 | 19 | 14.8 | 16.5 |
| 150-186 | C | 5.4 | 0.0099 | 0.53 | 0.94 | 0.03 | 0.63 | 0.60 | 0.84 | 0.05 | 0.28 | 11 | 14.9 | 15.8 |
| **Mean** | | **5.3** | **0.0131** | **0.55** | **0.95** | **0.068** | **0.67** | **0.60** | **0.71** | **0.05** | **0.31** | **27** | **14.3** | **15.8** |

**ZG 13**

| Depth (cm) | Horizon Designation | pH 1:1 ($H_2O$) | EC ($dSm^{-1}$) | OC | OM | TN | AP | Ca | Mg | K | Na | CEC | ESP | BS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ⟵ | (g/kg) | ⟶ | (mg/kg) | ⟶ | (cmol/kg) | ⟵ | | | | (%) |
| 0-16 | Ap | 5.4 | 0.0096 | 3.00 | 0.51 | 0.10 | 0.70 | 0.76 | 0.28 | 0.13 | 0.30 | 36 | 14.0 | 15.6 |
| 16-28 | AB | 5.3 | 0.0079 | 0.35 | 0.53 | 0.09 | 0.70 | 0.70 | 0.37 | 0.13 | 0.30 | 36 | 16.1 | 17.2 |
| 28-81 | Bw1 | 5.3 | 0.0160 | 0.27 | 0.34 | 0.08 | 0.70 | 0.79 | 0.71 | 0.05 | 0.33 | 35 | 5.4 | 15.2 |
| 81-134 | Bw2 | 5.3 | 0.0110 | 0.35 | 0.52 | 0.08 | 0.64 | 0.83 | 0.54 | 0.05 | 0.32 | 35 | 4.9 | 14.9 |
| 134-200 | C | 5.4 | 0.0050 | 0.43 | 0.73 | 0.06 | 0.63 | 0.81 | 0.55 | 0.05 | 0.34 | 35 | 5.0 | 14.8 |
| **Mean** | | **5.3** | **0.0099** | **0.34** | **0.53** | **0.08** | **0.67** | **0.78** | **0.49** | **0.082** | **0.32** | **35** | **7.1** | **15.5** |

## Relationship between physical and chemical properties

The Pearson's correlation matrix among selected soil properties is presented in Table 6. **Clay vs. Sand ($r = -0.88, p < 0.001$):** The strong negative relationship between clay and sand content confirms a fundamental textural dichotomy within the study area. This inverse association indicates that as sand content decreases, clay content increases proportionally, reflecting the progressive physical and chemical weathering of parent materials (Liu *et al,* 2022) Such a strong negative correlation is typical of soils where eluviation–illuviation processes are active, with clay particles translocating downward from surface horizons and accumulating in subsurface Bt horizons (Buol *et al.,* 2011). In the context of Zagga District, this relationship underscores the contrasting pedogenic pathways: profiles such as ZG6, ZG7, and ZG11 have undergone significant clay enrichment through illuviation, while profiles ZG8, ZG9, ZG12, and ZG13 remain sand-dominated due to limited weathering and minimal clay translocation. This strong negative correlation ($r = -0.88$) is among the highest reported for similar savanna soils in northern Nigeria (Sharu *et al.,* 2013; Maniyunda *et al.,* 2014).

**Clay vs. CEC ($r = 0.81, p < 0.001$):** The strong positive correlation between clay content and cation exchange capacity (CEC) demonstrates that clay-sized particles are the primary determinant of nutrient retention capacity in these soils (Brevik & Sadeghpour 2026). This relationship is expected because clay minerals, particularly the 1:1 kaolinite and sesquioxides typical of highly weathered tropical soils, possess negatively charged surfaces that retain exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$) (Brady & Weil, 2017). The magnitude of this correlation ($r = 0.81$) indicates that approximately 66% of the variability in CEC can be explained by clay content alone. Profiles with higher clay content, such as ZG6 (26% clay, 22 cmol $kg^{-1}$ CEC), ZG7 (25% clay, 20 cmol $kg^{-1}$ CEC), and ZG11 (24% clay, 36 cmol $kg^{-1}$ CEC), consequently exhibit superior nutrient retention and fertility potential. Conversely, sandy profiles with clay content below 8% (ZG8, ZG9, ZG12, ZG13) recorded CEC values below 20 cmol $kg^{-1}$, reflecting their limited ability to retain essential plant nutrients. This finding aligns with previous studies in the Nigerian savanna, where clay content was identified as the single most important predictor of soil fertility status (Yakubu & Ojanuga, 2009; Adesemuyi *et al.,* 2019).

**Sand vs. CEC ($r = -0.79, p < 0.001$):** The strong negative correlation between sand content and CEC provides complementary evidence that sandy soils are inherently infertile due to their low surface area and limited negative charge density (Schapel *et al.,* 2023). Sand-sized particles (2.0–0.05 mm) are dominated by quartz and other resistant minerals that lack significant cation exchange capacity, resulting in minimal nutrient retention (Sanchez, 2019). The magnitude of this correlation ($r = -0.79$) confirms that as sand content increases, CEC declines almost linearly. Profiles with sand content exceeding 85%, such as ZG8 (76–93% sand, 6–12 cmol $kg^{-1}$ CEC), ZG9 (87–95% sand, 9–20 cmol $kg^{-1}$ CEC), and ZG12 (85–93% sand, 11–35 cmol $kg^{-1}$ CEC), consistently recorded the lowest CEC values across all horizons. This relationship has profound implications for soil management: sandy soils in Zagga District require frequent organic matter amendments and careful nutrient management to sustain crop productivity, as they lack the intrinsic nutrient retention capacity of clay-rich soils (Lal, 2015). The strong negative sand–CEC relationship observed here is consistent with findings from other savanna ecosystems in West Africa, where sandy surface horizons are typically associated with rapid nutrient leaching and low fertilizer use efficiency (Jones & Wild, 1975; Moberg & Esu, 1991).

**Clay vs. Silt (r = -0.50, p < 0.05):** The moderate negative correlation between clay and silt content reflects contrasting depositional environments and weathering histories within the study area. Silt-sized particles (0.05–0.002 mm) are often considered intermediate in the weathering sequence, representing partially weathered primary minerals that have not yet been fully transformed into clay-sized secondary minerals (Schaetzl & Anderson, 2005). The negative relationship (r = -0.50) suggests that profiles with advanced pedogenic development (ZG6, ZG7, ZG11) have undergone sufficient weathering to convert silt into clay, resulting in lower silt/clay ratios (typically <1). In contrast, weakly developed profiles (ZG8, ZG9, ZG12, ZG13) retain higher silt/clay ratios (often >3), indicating limited mineral transformation and the dominance of physical over chemical weathering. This interpretation is supported by the silt/clay ratio data presented in Table 2, where ZG8 (silt/clay = 4.0–7.3) and ZG9 (silt/clay = 3.5–7.0) exhibit the highest ratios, while ZG6 (silt/clay = 0.4–1.4) and ZG7 (silt/clay = 0.4–1.4) show the lowest. The clay–silt correlation thus serves as a useful indicator of relative weathering intensity, with more negative values (approaching -1) suggesting advanced pedogenesis (Buol *et al.,* 2011; Esu, 2010).

**Table 6: Pearson's correlation matrix among selected soil properties (n = 34 horizons)**

| Variable | pH | OC | TN | AP | Clay | Silt | Sand | CEC | BS |
|---|---|---|---|---|---|---|---|---|---|
| pH | 1.00 | | | | | | | | |
| OC | 0.07 | 1.00 | | | | | | | |
| TN | -0.10 | 0.31 | 1.00 | | | | | | |
| AP | -0.04 | 0.18 | 0.21 | 1.00 | | | | | |
| Clay | -0.21 | 0.18 | 0.11 | 0.10 | 1.00 | | | | |
| Silt | 0.19 | -0.19 | -0.13 | 0.04 | **-0.50*** | 1.00 | | | |
| Sand | -0.03 | -0.06 | -0.03 | -0.09 | **-0.88***** | -0.19 | 1.00 | | |
| CEC | -0.25 | 0.14 | 0.16 | 0.11 | **0.81***** | -0.33 | **-0.79***** | 1.00 | |
| BS | 0.16 | 0.18 | -0.16 | 0.17 | -0.05 | 0.21 | 0.00 | -0.12 | 1.00 |

*Significance levels: *p < 0.05; **p < 0.01; ***p < 0.001*

## Humification, Melanization, and Pedoturbation

Organic matter dynamics also contributed to soil differentiation. Humification and melanization were moderate in profiles ZG6 and ZG7, where relatively higher organic carbon supported darker surface horizons, but were limited in the sandy profiles (ZG8–ZG13) due to rapid organic matter decomposition and low retention capacity. This pattern is consistent with reports that melanization in savanna soils is closely tied to stabilized humus accumulation in finer-textured horizons (Maniyunda *et al.,* 2014; Schaetzl & Anderson, 2005). Evidence of pedoturbation was observed in the form of root channels and diffuse horizon boundaries, particularly in ZG7 and ZG11, suggesting biological mixing and soil turnover by roots and fauna. Such processes enhance soil aggregation, porosity, and nutrient cycling, but are often restricted to the surface horizons in sandy soils where rooting depth and organic matter inputs are limited (Fey and Schaetzl, 2017). From a management perspective, sustaining humification and melanization requires consistent organic matter inputs, such as manure, compost, or cover crops, which also reinforce bioturbation-driven soil mixing. In sandy soils with inherently low nutrient retention, such practices are critical for improving structural stability and long-term fertility.

## Pedogenic Processes

**Table7: Summary of Soil Properties and Pedogenic Interpretations of Zagga District Soils**

| Profile | Clay (%) | Silt/Clay | CEC (cmol/kg) | Base Sat. (%) | OC (%) | Pedogenic Interpretation |
|---|---|---|---|---|---|---|
| ZG6 | 26.2 | 0.7 | 22 | 18.6 | 0.39 | Argilluviation, Gleization |
| ZG7 | 25.0 | 0.7 | 20 | 15.3 | 0.72 | Argilluviation, Humification |
| ZG8 | 3.0 | 4.0 | 9 | 16.3 | 0.30 | Weak illuviation, Sandy weathering |
| ZG9 | 4.0 | 3.5 | 16 | 11.4 | 0.36 | Gleization, Weak clay illuviation |
| ZG10 | 6.4 | 4.8 | 19 | 11.2 | 1.18 | Gleization, Weak argilluviation |
| ZG11 | 24.2 | 0.8 | 36 | 14.2 | 0.23 | Argilluviation, Strong weathering |
| ZG12 | 3.5 | 6.4 | 27 | 15.8 | 0.55 | Sandy weathering, Weak illuviation |
| ZG13 | 8.3 | 0.7 | 35 | 15.5 | 0.34 | Cambic horizon, Weak argilluviation |

A summary of the major soil properties and their pedogenic interpretations is presented in Table 7. Across the transect, five key pedogenic processes were evident:

- **Argilluviation**: Strong in ZG6 and ZG7, confirmed by clay increases with depth and Bt horizon formation.
- **Gleization**: Widespread, as indicated by mottling in ZG6, ZG7, ZG9, and ZG10, reflecting alternating redox conditions.
- **Humification and Melanization**: Moderate in ZG6 and ZG7, but limited in sandy ZG8–ZG13 due to low OM retention.
- **Pedoturbation**: Evident from root channels and gradual boundaries, particularly in ZG7 and ZG11.

- **Physical Weathering**: Dominant in ZG8–ZG13, producing sandy horizons with weak pedogenic features.

## Implications for Soil Development and Management

The study confirms that soil development in the Northern Guinea Savanna is heterogeneous, largely influenced by parent material, drainage regimes, and the degree of pedogenic processes (Buol *et al.,* 2011; Esu, 2010). Profiles such as ZG6 and ZG7 exhibit advanced pedogenesis with argillic horizons and relatively higher nutrient retention, characteristics aligning them with Alfisols or Ultisols. In contrast, the sandy and weakly developed profiles (ZG8–ZG13) show limited clay accumulation and low chemical fertility, resembling Entisols and Inceptisols (Soil Survey Staff, 2014; Yakubu & Ojanuga, 2009).

From a management perspective, clay-rich soils offer greater fertility potential due to higher cation exchange capacity (CEC), but are prone to compaction and structural decline if subjected to intensive tillage or continuous cropping without organic matter replenishment (Lal, 2015; Reynolds *et al.,* 2002). Sandy soils, by contrast, are inherently fragile, with low nutrient- and water-holding capacity, requiring careful interventions to sustain productivity (Sanchez, 2019; Adesemuyi *et al.,* 2019).

Liming is necessary in the more acidic profiles (pH 5.2–5.6) to raise pH into the optimal range for crop production and enhance nutrient availability (Fageria & Baligar, 2008). Incorporation of crop residues, compost, or manure should be prioritized, especially in sandy soils (ZG8–ZG13), to improve nutrient retention, microbial activity, and structural stability (Sanchez, 2019). Mulching and cover cropping are critical in sandy profiles to reduce evaporation losses and enhance soil moisture storage, thereby offsetting their low water-holding capacity (Lal, 2015). For clay-rich soils (ZG6, ZG7), reduced tillage and controlled traffic farming are recommended to maintain structure and prevent compaction, while crop rotations with legumes can replenish nitrogen (Reynolds *et al.,* 2002). Balanced fertilization strategies—integrating mineral fertilizers with organic inputs—should be tailored to soil texture and CEC to ensure efficient nutrient use and long-term sustainability (Yakubu & Ojanuga, 2009).

## Conclusion

The soils of Zagga District in the Northern Guinea Savanna exhibit considerable variability in pedogenic development, reflecting the combined influence of parent material, drainage conditions, and weathering intensity. Profiles ZG6 and ZG7 are comparatively more developed, characterized by well-expressed Bt horizons, higher clay accumulation, greater cation exchange capacity (CEC), and distinct redoximorphic features, all of which indicate active argilluviation and seasonal gleization. Conversely, profiles such as ZG8, ZG9, ZG10, and ZG13 remain weakly developed, with coarse sandy textures, low organic matter content, poor nutrient reserves, and minimal clay translocation, suggesting dominance of physical weathering and early-stage soil formation processes.

The generally low base saturation, acidic reaction, and low organic carbon contents across the profiles confirm that the soils are highly leached and inherently low in fertility. Nevertheless, the observed variability in clay content, weathering status, and nutrient-retention capacity demonstrates that soil development within the study area follows multiple pedogenic pathways rather than a single uniform process. Clay-rich soils possess relatively greater nutrient-holding capacity but are susceptible to compaction and structural degradation under continuous cultivation, whereas sandy soils are fragile, drought-prone, and highly vulnerable to nutrient leaching.

Overall, the integration of morphological, physical, chemical, and statistical evidence provided a comprehensive understanding of pedogenesis, weathering intensity, and soil development in Zagga District. The findings emphasize the importance of site-specific soil management strategies tailored to the contrasting properties of the soils in order to sustain agricultural productivity and ecological stability in the Northern Guinea Savanna.

## Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. **Integrated Soil Fertility Management (ISFM):** Organic amendments such as farmyard manure, compost, green manure, and crop residues should be incorporated regularly to improve soil organic matter, nutrient retention, and microbial activity, particularly in sandy soils with low CEC.
2. **Liming of Acidic Soils:** The acidic nature of the soils (pH 5.2–5.6 in several profiles) necessitates periodic liming to reduce soil acidity, improve base saturation, and enhance nutrient availability for crop production.
3. **Moisture Conservation Practices:** Mulching, cover cropping, and conservation tillage should be promoted, especially in sandy profiles (ZG8–ZG13), to reduce evaporation losses, improve infiltration, and enhance soil water-holding capacity.
4. **Reduced Tillage and Controlled Traffic Farming:** In the clay-rich profiles (ZG6 and ZG7), reduced tillage and controlled traffic practices are recommended to minimize soil compaction, preserve soil structure, and maintain pore continuity.
5. **Balanced Fertilizer Application:** Fertilizer use should be tailored to the nutrient-retention capacity of each soil type. Sandy soils require split fertilizer applications to reduce leaching losses, while clay-rich soils may benefit from balanced nutrient formulations combined with organic inputs.
6. **Crop Rotation and Legume Integration:** Rotations involving legumes should be encouraged to improve nitrogen status, enhance biological activity, and sustain soil fertility under continuous cultivation.
7. **Drainage Management:** Areas affected by seasonal waterlogging and gleization should be provided with appropriate drainage measures to minimize prolonged saturation and improve root aeration.
8. **Land Capability–Based Soil Management:** Agricultural land-use planning in Zagga District should consider soil variability and pedogenic differences to ensure that management practices are matched with the capability and limitations of each soil unit.
9. **Further Mineralogical and Micromorphological Studies:** Additional studies involving clay mineralogy, micromorphology, and geochemical weathering indices are recommended to better understand the mineral transformation processes

and long-term evolution of the soils in the Northern Guinea Savanna.

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