

Assessment of Soil Buffering Capacity in Benue Farmlands and its Role in Mitigating Soil Acidity

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ABSTRACT

This study assessed the buffering capacity of selected farmlands across six locations (Gwer East, Otukpo, Konshisha, Ukum, Tarka, and Oju) using physicochemical analyses and a simulated acid rain experiment. Soil samples were analyzed for pH, organic matter, cation exchange capacity (CEC), particle-size distribution, and base saturation, and buffering capacity was determined using the ΔpH method. Results showed that soils were generally slightly to moderately acidic (pH 5.20–6.85), with notable spatial variability in key fertility indicators. Organic matter (2.60–4.68%) and CEC (5.60–11.30 cmol kg⁻¹) were highest in Gwer East and Oju, corresponding with higher base saturation and stronger buffering capacity, while Tarka and Otukpo recorded lower values and weaker resistance to pH change. Buffering capacity ranged from high ($\Delta\text{pH} = 1.00$) in Gwer East to very low ($\Delta\text{pH} > 4.0$) in several locations. Simulated acid rain exposure confirmed that soils with low organic matter, low CEC, and high sand content experienced greater material loss (up to 3.19%), whereas more clay- and organic-rich soils showed reduced degradation. Correlation patterns indicated that organic matter, clay fraction, CEC, and base saturation collectively govern soil resistance to acidification. The study demonstrates that soil buffering capacity in Benue farmlands is highly variable and strongly dependent on soil composition, highlighting the need for organic matter enhancement, liming, and improved nutrient management to sustain soil quality and agricultural productivity in the region.

KEYWORDS: Soil buffering capacity; Acid rain; Cation exchange capacity; Organic matter; Benue State; Soil acidity

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1. INTRODUCTION

Benue State occupies a strategic position in Nigeria's agricultural economy, owing to its vast arable land, favorable climate, and long-standing reputation as a major producer of staple crops. The region supports the cultivation of yam, cassava, maize, rice, and legumes at both subsistence and commercial scales, contributing significantly to national food security. This productivity is largely associated with its location within the Southern Guinea savanna agroecological zone, which provides moderate rainfall and relatively fertile soils suitable for diverse cropping systems (Ojanuga, *et.al.*, 2003; FAO, 2015). However, increasing population pressure and continuous land use without adequate soil management practices are gradually undermining the sustainability of agricultural production in the region.

The soils of Benue State are predominantly derived from sedimentary parent materials, resulting in profiles that are typically loamy to sandy in texture. These soils are generally well-drained and easy to cultivate, characteristics that favor agricultural use. Yet, they often possess low organic matter content and weak structural stability, making them vulnerable to nutrient depletion and leaching losses (Esu, 2010; Ojanuga *et al.*, 2003). The inherent properties of these soils, particularly their coarse texture and low cation exchange capacity, limit their ability to retain essential nutrients, thereby predisposing them to fertility decline under intensive cultivation.

A major constraint associated with these soils is the prevalence of soil acidity, which has become increasingly pronounced in many parts of Benue farmlands. Soil acidification in tropical environments is driven by several factors, including high rainfall that promotes leaching of base cations (Ca²⁺, Mg²⁺, K⁺), continuous cropping, and the application of acid-forming fertilizers such as

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ammonium-based nitrogen sources (Brady & Weil, 2016). Acidic soil conditions reduce the availability of key nutrients, particularly phosphorus, while increasing the solubility of potentially toxic elements such as aluminum and manganese. These changes negatively affect root development, microbial activity, and overall crop productivity (Fageria & Baligar, 2008).

Closely linked to soil acidity dynamics is the concept of soil buffering capacity, which refers to the ability of soil to resist changes in pH when subjected to acidic or alkaline inputs. Soil buffering capacity is governed by factors such as clay content, organic matter, and the presence of exchangeable base cations. Soils with high buffering capacity can moderate fluctuations in pH, thereby maintaining a stable chemical environment for plant growth, whereas soils with low buffering capacity are more susceptible to rapid acidification and associated fertility constraints (Brady & Weil, 2016; Sparks, 2003). In this context, understanding the buffering behavior of soils is essential for designing effective soil amendment strategies, including liming and integrated nutrient management.

In addition to agricultural practices, atmospheric deposition has emerged as an important contributor to soil acidification. Acid rain, formed primarily from sulfur dioxide (SO₂) and nitrogen oxides (NO_x) released during fossil fuel combustion and industrial activities, can significantly alter soil chemical properties. In regions of Nigeria, including parts of the North-Central and adjoining areas, these emissions contribute to the formation of acidic precipitation, which accelerates the leaching of base cations and further lowers soil pH (Galloway et al., 2008; Akpan & Akpan, 2012). The cumulative effect of these processes poses a serious threat to soil health and agricultural sustainability.

Despite the recognized importance of soil buffering capacity in managing soil acidity, there remains a paucity of empirical data on the buffering characteristics of soils in Benue State. Most existing studies have focused on general soil fertility assessments without adequately addressing the soil's resistance to acidification. This knowledge gap limits the development of location-specific soil management strategies and hampers efforts to mitigate the adverse effects of soil acidity on crop production. Therefore, a comprehensive assessment of soil buffering capacity in Benue farmlands is necessary to inform sustainable soil management practices and enhance long-term agricultural productivity in the region.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in three major agricultural zones of Benue State, Nigeria: Gwer East, Otukpo, Konshisha, Ukum, Tarkaa, and Oju. These areas represent the state's intensive farming systems and diverse soil conditions. Benue State lies within the Southern Guinea savanna agroecological zone, characterized by a tropical climate with distinct wet and dry seasons. Annual rainfall ranges between 1,200 and 1,800 mm, with peak precipitation occurring between June and September. Temperatures are generally high throughout the year, averaging between 25°C and 32°C. The region supports extensive cultivation of staple crops such as yams, cassava, maize, and rice, making it a critical agricultural hub in Nigeria (Ojanuga, et.al., 2003; FAO, 2015).

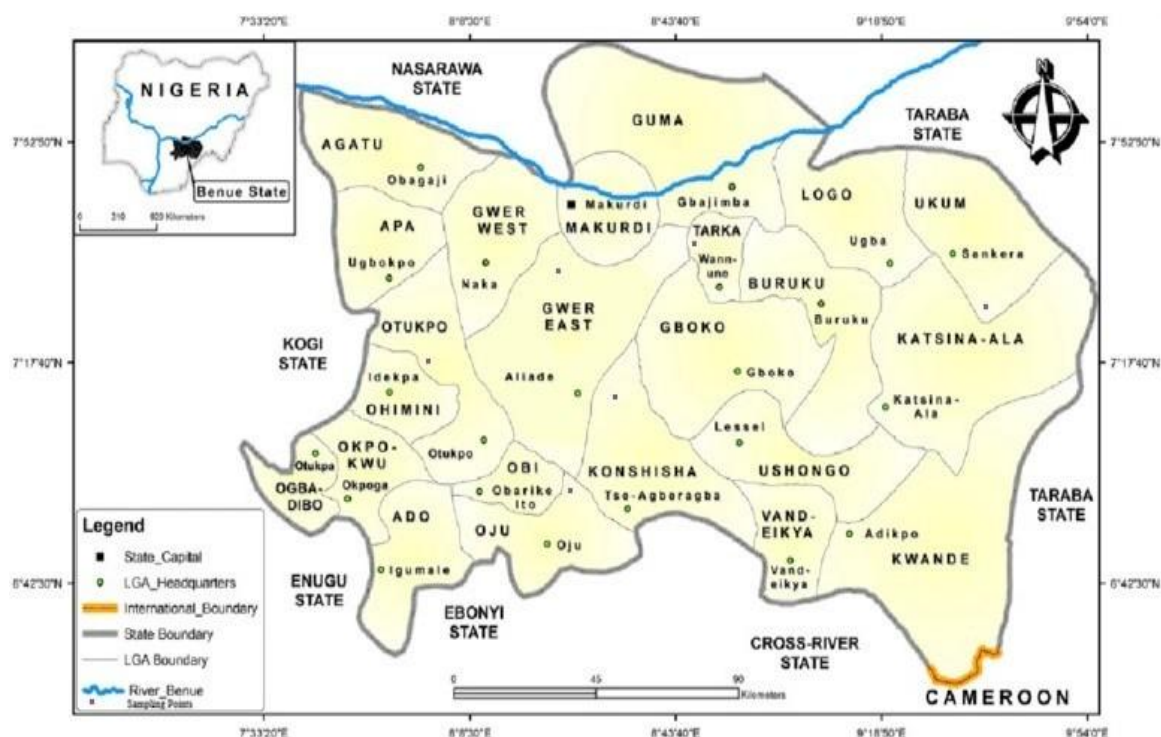


Figure 1: Map of the study area showing sampling locations in Benue State, Nigeria.

2.2 Soil Sampling and Preparation

Soil samples were collected using a random sampling technique from multiple farm sites within each location. Samples were obtained at two depths (0–20 cm and 20–40 cm) using a soil auger. Composite samples were prepared, air-dried, crushed, and sieved through a 2 mm mesh before analysis.

2.3 Physicochemical Analysis

2.3.1 Soil pH

Soil pH was determined in a 1:2.5 soil-to-water suspension. Ten (10) grams of air-dried soil were mixed with 25 mL of distilled water, stirred, and allowed to equilibrate for 30 min. The pH was measured using a calibrated digital pH meter (Thomas, 1996).

2.3.2 Organic Matter

Soil organic matter was determined by the Loss-on-Ignition (LOI) method. Approximately 5 g of soil was oven-dried at 105°C, then ignited at 550°C for 4 h in a muffle furnace. The percentage weight loss was used as an indicator of organic matter content (Nelson & Sommers, 1996).

$$\%OM = \frac{w_1 - w_2}{w_1} \times 100$$

Where:

- W_1 = oven-dry weight before ignition (g)
- W_2 = weight after ignition at 550°C (g)

2.3.3 Cation Exchange Capacity (CEC)

CEC was determined using the BaCl₂ saturation method. Soil samples (10 g) were saturated with 1 M BaCl₂, and excess salt was removed by washing. Adsorbed Ba²⁺ was displaced using MgSO₄, and the displaced cations were quantified using Atomic Absorption Spectrophotometry (AAS). CEC was calculated accordingly (Sumner & Miller, 1996).

$$CEC = \frac{C \times V \times 100}{W}$$

Where:

- C = concentration of displaced cations (cmol_c L⁻¹)
- V = volume of extract (L)
- W = weight of soil (g)

2.3.4 Particle Size Analysis

Particle size distribution was determined using the hydrometer method. Soil samples (50 g) were dispersed in sodium hexametaphosphate solution and mechanically shaken. Hydrometer readings were taken at standard intervals to determine sand, silt, and clay fractions (Gee & Or, 2002).

2.3.5 Base Saturation

Exchangeable bases (Ca²⁺, Mg²⁺, K⁺, Na⁺) were extracted using 1 M NH₄OAc (pH 7.0). The extracts were analyzed using AAS, and base saturation was calculated as the percentage of CEC occupied by exchangeable bases (Sumner & Miller, 1996).

2.3.6 Buffering Capacity

Soil buffering capacity was determined using the ΔpH method. Soil samples were treated with known concentrations of HCl and NaOH, equilibrated, and the resulting pH measured. Buffering capacity (pHBC) was calculated as the ratio of added acid or base to the corresponding change in pH (Sparks, 2003).

2.4 Simulated Acid Rain Experiment

Two grams (2 g) of each soil sample were weighed into separate plastic containers. Broken tile fragments of varying sizes were thoroughly washed, air-dried, and weighed before being placed into the respective containers. 50 mL of distilled water was then added to each container, and the mixtures were stirred continuously for 30 minutes to obtain a uniform soil–water suspension. The pH of each suspension was subsequently adjusted to 2.5, 3.0, 4.0, and 5.6 using 1.5 M H₂SO₄ to simulate different levels of acid rain exposure. The prepared systems were left undisturbed under laboratory conditions for one week. At the end of the exposure period, the tile fragments were carefully removed from the solutions, gently dried to constant weight, and reweighed. The difference between the initial and final weights of the tiles was used to determine the extent of material loss, which served as an indicator of the intensity of acid attack and erosion caused by the acidic soil solutions.

$$\%Material\ Loss = \frac{W_i - W_f}{W_i} \times 100$$

Where:

- W_i = initial weight of tile fragment (g)
- W_f = final weight after exposure (g)

2.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA), and significant differences were determined at $p \leq 0.05$. Correlation analysis was performed to evaluate relationships between soil properties and buffering capacity.

Table 1: Physicochemical Properties of Soils from Selected Farmlands in Benue State

Parameter	Gwer East	Otukpo	Konshisha	Ukum	Tarka	Oju
pH	6.85 ± 0.05	5.90 ± 0.08	6.40 ± 0.06	5.60 ± 0.07	5.20 ± 0.05	6.10 ± 0.04
Organic Matter(%)	4.68 ± 0.12	3.01 ± 0.10	3.89 ± 0.11	3.70 ± 0.09	2.60 ± 0.08	4.20 ± 0.10
CEC (cmol kg ⁻¹)	11.30 ± 0.35	5.60 ± 0.22	8.50 ± 0.28	7.20 ± 0.25	6.10 ± 0.20	9.00 ± 0.30
Sand (%)	60.0 ± 1.5	71.0 ± 2.0	67.0 ± 1.8	72.0 ± 2.1	80.0 ± 2.2	64.0 ± 1.6
Silt (%)	21.0 ± 0.8	21.0 ± 1.0	20.0 ± 0.9	16.0 ± 0.7	12.0 ± 0.6	19.0 ± 0.8
Clay (%)	19.0 ± 0.9	8.0 ± 0.5	13.0 ± 0.7	12.0 ± 0.6	8.0 ± 0.5	17.0 ± 0.8
Base Saturation (%)	52.21 ± 1.20	42.86 ± 1.10	48.24 ± 1.15	43.50 ± 1.05	38.00 ± 1.00	50.00 ± 1.18

Values are means ± standard deviation (n = 3).

Table 2: Variation in soil pH buffering capacity across study locations.

Location	Initial pH	Final pH	ΔpH	Buffering Capacity
Gwer East	7.70 ± 0.05	6.70 ± 0.10	1.00 ± 0.04	High
Otukpo	8.90 ± 0.03	4.80 ± 0.02	4.10 ± 0.03	Very Low
Konshisha	9.40 ± 0.03	4.90 ± 0.03	4.50 ± 0.04	Very Low
Ukum	8.10 ± 0.04	4.60 ± 0.05	3.50 ± 0.03	Low
Tarka	7.90 ± 0.06	3.70 ± 0.04	4.20 ± 0.05	Very Low
Oju	7.40 ± 0.05	5.20 ± 0.06	2.20 ± 0.04	Moderate

ΔpH ≤ 1.0 = High buffering; 1–3 = Moderate; 3–4 = Low; >4 = Very Low.

Table 3: Effect of simulated acid rain on soil material loss.

Location	pH	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Weight Loss (%)
Gwer East	2.5	9.66 ± 0.04	9.48 ± 0.05	0.18 ± 0.03	1.86 ± 0.12
	3.0	8.35 ± 0.03	8.25 ± 0.04	0.10 ± 0.02	1.20 ± 0.07
	4.0	9.19 ± 0.05	9.09 ± 0.04	0.10 ± 0.02	1.09 ± 0.06
	5.6	7.31 ± 0.03	7.27 ± 0.03	0.04 ± 0.01	0.55 ± 0.03
Otukpo	2.5	7.36 ± 0.03	7.30 ± 0.04	0.06 ± 0.02	0.82 ± 0.05
	3.0	6.59 ± 0.04	6.49 ± 0.05	0.10 ± 0.03	1.52 ± 0.09
	4.0	8.83 ± 0.05	8.78 ± 0.04	0.05 ± 0.02	0.57 ± 0.04
	5.6	6.39 ± 0.03	6.35 ± 0.03	0.04 ± 0.01	0.63 ± 0.03
Konshisha	2.5	7.12 ± 0.05	7.06 ± 0.05	0.06 ± 0.02	0.84 ± 0.06
	3.0	10.29 ± 0.06	10.12 ± 0.06	0.17 ± 0.04	1.65 ± 0.10
	4.0	9.39 ± 0.05	9.28 ± 0.05	0.11 ± 0.03	1.17 ± 0.07
	5.6	5.79 ± 0.03	5.77 ± 0.03	0.02 ± 0.01	0.35 ± 0.02
Ukum	2.5	8.10 ± 0.05	7.92 ± 0.06	0.18 ± 0.04	2.22 ± 0.13
	3.0	7.25 ± 0.04	7.12 ± 0.05	0.13 ± 0.03	1.79 ± 0.10
	4.0	9.05 ± 0.05	8.95 ± 0.05	0.10 ± 0.02	1.10 ± 0.06
	5.6	6.80 ± 0.03	6.76 ± 0.03	0.04 ± 0.01	0.59 ± 0.03
Tarka	2.5	6.90 ± 0.05	6.68 ± 0.06	0.22 ± 0.05	3.19 ± 0.15
	3.0	7.80 ± 0.05	7.58 ± 0.06	0.22 ± 0.05	2.82 ± 0.14
	4.0	8.40 ± 0.05	8.30 ± 0.05	0.10 ± 0.02	1.19 ± 0.06
	5.6	5.95 ± 0.03	5.92 ± 0.03	0.03 ± 0.01	0.50 ± 0.03
Oju	2.5	7.50 ± 0.04	7.32 ± 0.05	0.18 ± 0.04	2.40 ± 0.12
	3.0	6.85 ± 0.04	6.70 ± 0.05	0.15 ± 0.03	2.19 ± 0.11
	4.0	8.10 ± 0.05	8.01 ± 0.04	0.09 ± 0.02	1.11 ± 0.06
	5.6	6.20 ± 0.03	6.17 ± 0.03	0.03 ± 0.01	0.48 ± 0.03

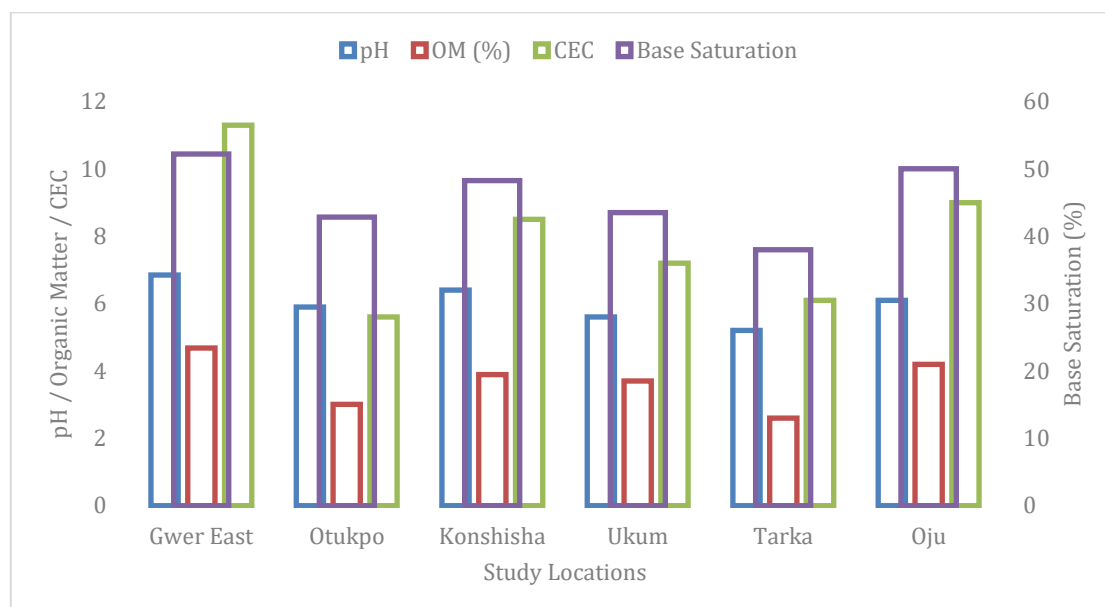


Figure 2: Comparison of soil physicochemical properties across selected study locations in Benue State.

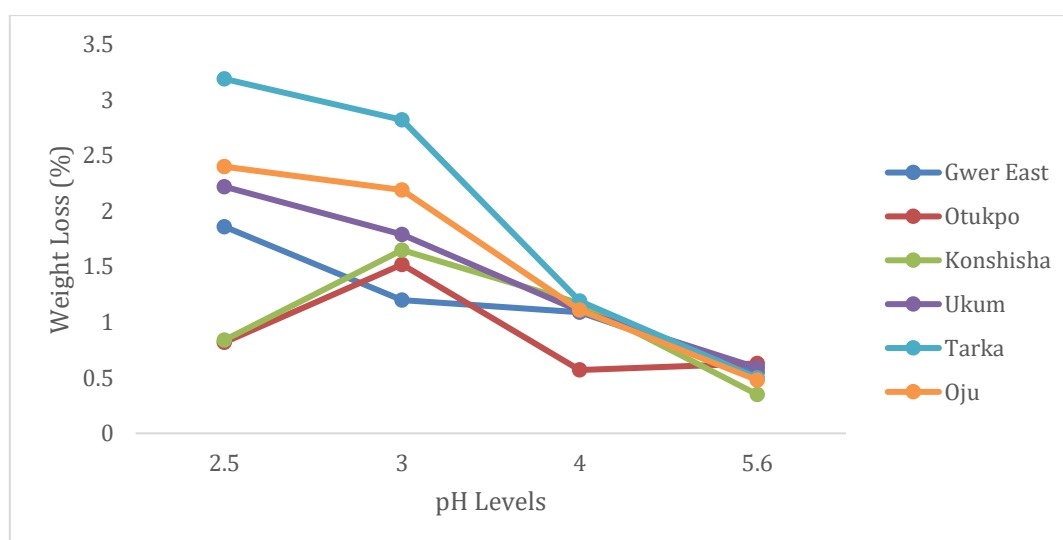


Figure 3: Effect of simulated acid rain on soil degradation (percentage weight loss) across different pH levels in selected farmlands of Benue State.

3. DISCUSSION

The soils examined were generally slightly acidic to moderately acidic, with pH values ranging from 5.20 in Tarka to 6.85 in Gwer East (Table 1). This pH range is consistent with typical soils of the Southern Guinea Savanna. Figure 2 further shows clear spatial variation in soil physicochemical properties across the study locations, with Gwer East and Oju exhibiting comparatively higher pH, organic matter, CEC, and base saturation values, while Tarka recorded the lowest values, indicating poorer soil fertility and weaker resistance to acidification. These findings support previous reports that cultivated tropical soils are prone to progressive acidification under intensive land use, fertilizer application, and high rainfall conditions (Brady & Weil, 2016). Under such conditions, continuous leaching of exchangeable base cations such as Ca^{2+} , Mg^{2+} , and K^{+} gradually lowers soil pH and reduces nutrient availability.

A clear relationship was observed between soil organic matter, cation exchange capacity (CEC), and buffering performance. Gwer East recorded the highest organic matter content (4.68%) and the highest CEC (11.30 cmol kg^{-1}), whereas Tarka showed the lowest organic matter (2.60%) and a relatively low CEC (6.10 cmol kg^{-1}). This trend is scientifically significant because soil buffering capacity is strongly controlled by the amount of negatively charged exchange sites supplied by clay minerals and soil organic matter. These colloidal components act as proton sinks, adsorbing H^{+} ions and thereby resisting sudden pH changes. The soil texture data further support this interpretation. Tarka had the highest sand content (80%) and one of the lowest clay fractions (8%), indicating a coarse-textured soil with limited surface area for ion exchange. Sandy soils are known to have lower nutrient retention and weaker resistance to acidification than clay-rich soils because they contain fewer negatively charged surfaces for

cation adsorption. By contrast, Gwer East and Oju, with relatively higher clay and organic matter contents, exhibited improved chemical stability and stronger buffering responses.

This relationship is strongly reflected in the buffering capacity results (Table 2). Gwer East showed the highest buffering capacity, with a ΔpH of 1.00, indicating strong resistance to pH change following acid addition. In contrast, Konshisha ($\Delta\text{pH} = 4.50$), Tarka ($\Delta\text{pH} = 4.20$), and Otukpo ($\Delta\text{pH} = 4.10$) exhibited very low buffering capacities. These results confirm that soils with reduced organic matter, lower CEC, and high sand fractions are less capable of neutralizing acidic inputs. Similar observations have been reported in previous soil chemistry studies where buffering capacity was positively correlated with organic matter and exchangeable bases.

The base saturation values further strengthen this interpretation. Gwer East recorded the highest base saturation (52.21%), followed by Oju (50.00%), whereas Tarka recorded the lowest (38.00%). Base saturation reflects the proportion of the exchange complex occupied by basic cations, and higher values indicate stronger reserve alkalinity and greater resistance to acidification. Soils with low base saturation possess fewer reserve cations available to neutralize incoming hydrogen ions, making them more vulnerable to rapid pH decline.

The simulated acid rain experiment (Table 3) provides strong experimental evidence for the importance of buffering capacity in mitigating acid-induced degradation. Across all locations, material loss increased as acidity intensified, with the highest losses consistently observed at pH 2.5 and the lowest at pH 5.6. Figure 3 shows that soil weight loss increased as acidity intensified (lower pH), with Tarka recording the highest degradation and Gwer East the lowest, indicating that stronger acidity promotes greater soil breakdown across all locations.

Among all locations, Tarka exhibited the highest percentage of material loss, reaching 3.19% at pH 2.5, followed by Oju (2.40%) and Ukum (2.22%). In contrast, Gwer East showed comparatively lower losses (1.86%) despite exposure to the same acidity level. This finding strongly suggests that soils with stronger buffering capacity offer greater protection against acid-induced erosion and mineral dissolution.

The progressive decrease in weight loss with increasing pH across all sites indicates that the severity of acid attack is directly related to proton concentration. At lower pH values, the abundance of H^+ ions accelerates dissolution reactions, destabilizes soil aggregates, and enhances the displacement of base cations from exchange sites. This leads to weakening of the soil matrix and increased structural degradation.

The strong correspondence between low buffering capacity and high material loss is particularly important for agricultural sustainability in Benue State. Tarka and Konshisha, which demonstrated poor buffering, are likely to experience faster nutrient depletion, greater leaching losses, and increased susceptibility to aluminum toxicity under prolonged acid deposition or unsustainable fertilizer use. Conversely, Gwer East and Oju possess comparatively greater resilience owing to their higher organic matter and exchange capacities.

The combined evidence from Tables 1–3 confirms that soil buffering capacity is fundamentally controlled by soil organic matter, clay fraction, CEC, and base saturation, and that these properties directly influence the soil's resistance to acidification and degradation. These findings emphasize the importance of maintaining soil organic matter through residue incorporation, compost application, and liming as practical strategies for mitigating soil acidity and sustaining long-term productivity in Benue farmlands.

CONCLUSION

The results indicate that soils in the study area vary considerably in their chemical and physical characteristics, with pH ranging from slightly to moderately acidic conditions. Soils with higher organic matter content and greater cation exchange capacity, particularly in Gwer East and Oju, showed stronger buffering ability and reduced susceptibility to acid-induced degradation, while Tarka and some other locations with low organic matter and high sand content exhibited weak buffering capacity and greater material loss under simulated acid rain. A consistent pattern emerged in which higher organic matter and CEC were associated with improved soil stability and lower weight loss, whereas sandy textures were linked to reduced nutrient retention and increased vulnerability to acid attack. These relationships confirm that soil resistance to acidification is largely dependent on organic matter content, clay fraction, and exchangeable base reserves. Thus, the findings demonstrate that maintaining soil organic matter and improving base saturation are critical for enhancing buffering capacity, reducing soil degradation, and sustaining agricultural productivity in the Benue State.

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