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Geochemical Characteristics of Gully Impacted Soils in Southeast Nigeria

Amarikwa, Ogechi Chukwuemeka; Ndokiari, Boisa; Obunwo, Charles Chuku; *Akinfolarin, Oladapo Mawoya

Department of Chemistry, Rivers State University, Port Harcourt, Nigeria.

(*) Corresponding author: oladapo.akinfolarin@ust.edu.ng Phone number: +2348064214910

Abstract

Gully erosion remains a critical environmental issue in Southeast Nigeria, threatening land productivity, infrastructure, and ecological balance. This study investigates the geochemical characteristics of gully-impacted soils in order to identify the underlying factors contributing to erosion susceptibility and to inform effective mitigation strategies. Soil samples were collected from three erosion-prone states—Imo, Abia, and Anambra—representing Southeast Nigeria, while control samples were obtained from the three senatorial districts of Rivers State, a relatively stable area. Heavy metal analysis revealed elevated concentrations of manganese (Mn) and nickel (Ni) in the gully-affected soils, with values reaching 46.05 mg/kg and 15.71 mg/kg, respectively—significantly higher than those found in the control. Conversely, the control soils exhibited higher levels of iron (Fe), lead (Pb), copper (Cu), and zinc (Zn), which are essential for plant growth, microbial activity, and soil structural integrity. Notably, cadmium (Cd) and arsenic (As) were present in all test samples, but undetected in the control, highlighting potential toxicity concerns. Mineralogical analysis using X-ray diffraction identified quartz, albite, orthoclase, and vermiculite as the dominant minerals. Quartz appeared in 10 samples (9.90–96.00%), albite in 9 samples (0.80–13.00%), orthoclase in 6 (0.30–23.00%), and vermiculite in 3 (0.07–5.00%). The control soils were characterized to be predominantly coarse, erosion-resistant minerals—such as quartz and orthoclase—which enhance structural resilience. The findings suggest that both heavy metal contamination and mineral composition significantly influence soil stability and erosion potential. It is recommended that policymakers and land managers adopt soil-specific management strategies, including integrated conservation practices, to mitigate erosion and promote sustainable land use in Southeast Nigeria.

Keywords: Gully erosion, Southeast Nigeria, Soil geochemistry, Heavy metals, Erosion susceptibility, Mineralogical composition

Introduction

Background to the Study

Soil erosion is a critical but often underestimated global environmental challenge, with extensive ecological and economic implications. It is estimated to cost the global economy over $10 trillion each year, largely due to decreased agricultural productivity and the degradation of ecosystem services [1]. These losses stem from both direct (on-site) and indirect (off-site) consequences [2]. On agricultural lands, the effects are most severe, while sedimentation caused by wind or water runoff causes downstream issues. In hilly or mountainous regions such as the Caribbean, soil erosion is particularly pronounced, exacerbated by deforestation and unsustainable farming, which leads to soil degradation and nutrient depletion [3]. Declines in soil fertility often result in increased fertilizer costs, reduced yields, food insecurity, and decreased land value.

In Southeast Nigeria, the situation mirrors these global trends. Extensive tracts of farmland have been lost to gully erosion, resulting in diminished agricultural output, damage to infrastructure, restricted mobility, and property loss. Figure 1 illustrates the economic impact of gully erosion in this region [4]. Ojukwu [5] documented various gully sites across Southeastern Nigeria, highlighting their distribution and severity.

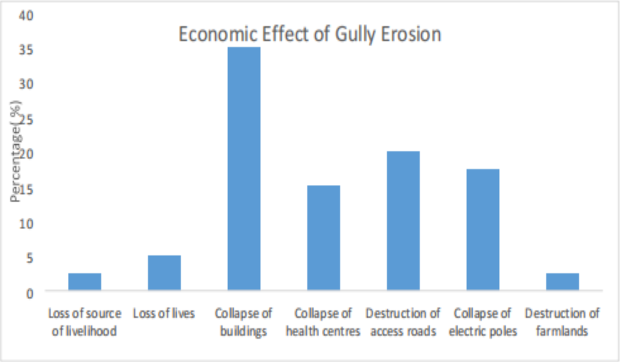

Figure 1: Economic Effect of Gully Erosion [4]

Table 1: Distribution of Gully Erosion Sites in Southeastern Nigeria

Site No.	State	No. of Gullies	State of the Gully Site	Control Measures
1	Abia	300	Mostly Active/Some Dormant	Not Successful
2	Anambra	700	Mostly Active	Not Successful Yet
3	Ebonyi	250	Mostly Minor Gully Sites	No Records
4	Enugu	600	Some Active/Some Dormant	None
5	Imo	450	Some Active/ Some Dormant	Not Successful Yet

Source: [5]

Table 1 provides a breakdown of gully occurrences in the region, with Anambra and Enugu recording the highest numbers. Gully expansion is alarmingly rapid, estimated between

20 to 50 meters annually [6]. Ojukwu [5] notes that over 2,800 active gullies have been identified, including more than 1,000 in Anambra alone. The World Igbo Environmental Foundation (WIFE) reports that some gullies—such as those in Amucha, Okwudor, and Urualla—reach depths of up to 150 meters, widths of 5.6 meters, and lengths exceeding 2.5 kilometers. These gullies often trace natural fractures and faults, with some now attracting tourist interest [4].

Surface runoff plays a key role in initiating and expanding gullies, and the limited success of both governmental and community-based control efforts suggests a complex interplay of external and internal driving factors [7][8]. Natural factors such as rainfall erosivity and anthropogenic influences like poor land use practices exacerbate the issue. Geophysical conditions—such as geological fractures, slopes, and rock structures—make much of Southeast Nigeria highly vulnerable to erosion [9][6].

Soil Geochemistry and Erosion Susceptibility

Soil erosion adversely affects fertility, water quality, and ecological resilience. Understanding soil geochemistry—including mineral content, elemental composition, and chemical behavior—is vital for predicting and managing erosion risks. Erosion-prone soils are typically low in organic matter, clay minerals, and oxides of iron and aluminum—key components for stable soil aggregates [10][11]. Factors such as low pH and poor cation exchange capacity (CEC) reduce nutrient retention and increase the risk of erosion [12].

Soils rich in minerals like quartz and feldspar are more vulnerable due to their poor resistance to weathering, while clay minerals such as kaolinite enhance cohesion [13][14]. High sand content also undermines water retention and structural integrity [15]. Erosive forces further deplete soil nutrients through leaching and the selective removal of fine particles [16][17].

Human interventions, including deforestation and excessive use of fertilizers, accelerate erosion by altering soil chemistry and structure [18][19]. Modern geochemical analysis tools—like XRD, ICP-MS, and soil spectroscopy—have improved our understanding of soil erosion dynamics and support the development of more effective conservation strategies [20][21].

This study seeks to address the urgent issue of gully erosion by exploring its underlying geophysical and geochemical causes, filling a research gap in current literature [22].

The aim is to offer data-driven recommendations for policy makers and environmental managers working to mitigate erosion in Southeast Nigeria.

Materials and Methods

Table 2: Definition of Soil Sample Labels

State	Senatorial District	Code
Anambra	Anambra South	AN1
Anambra	Anambra Central	AN2
Anambra	Anambra North	AN3
Imo	Imo West	IM1
Imo	Imo North	IM2
Imo	Imo East	IM3
Abia	Abia Central	AB1
Abia	Abia South	AB2
Abia	Abia North	AB3

The Southeastern region of Nigeria is one of the country's six geopolitical zones. Geographically, it lies between latitudes 5.9260°N and 7.6927°N and longitudes 6.6774°E to 8.7090°E, approximately. This region features a variety of landscapes, such as dense tropical rainforests, undulating hills, and expansive fertile plains. It is traversed by the Niger River and its numerous tributaries, which form a complex system of waterways. Prominent urban centers in the region include Enugu, Owerri, and Umuahia—each situated within distinct terrain types. As of January 2022, the region had an estimated population of about 40 million people inhabiting a land area of 29,792 square kilometers, although this figure is subject to change due to variables such as population growth, migration, and other demographic dynamics [23]. The economic activities in the area are varied, reflecting both urban and rural lifestyles. Major occupations include farming, trading, commercial services, artisanal craftsmanship, and various forms of manual labor.

Table 3 provides the geographic coordinates for the sampling sites within the study area, along with those from the control area.

Table 3: Geolocation of Sample Sites

S/No	Sample Type	Location	State	Longitude	Latitude	Date
1	Eroded	Umudum, Nnewi North	Anambra	6.91821	5.99479	24.02.2022
2	Uneroded	Off Ozubulu road	Anambra	6.92531	5.96844	24.02.2022
3	Eroded	Ihembosi	Anambra	6.85728	5.92326	24.02.2022
4	Uneroded	Ihembosi	Anambra	6.85524	5.92116	24.02.2022
5	Eroded	University Road Uli	Anambra	6.86444	5.78516	24.02.2022
6	Uneroded	Ojukwu University Road Uli	Anambra	6.85495	5.78529	24.02.2022
7	Uneroded	Owerri/Orlu Road, Njaba	Imo	7.01107	5.70281	25.02.2022
8	Eroded	Owerri/Orlu Road, Njaba	Imo	7.06507	5.58197	25.02.2022
9	Uneroded	Okigwe Road, Atta	Imo	7.13236	5.61851	25.02.2022
10	Eroded	Okigwe Road, Atta	Imo	7.14244	5.63854	25.02.2022
11	Ueroded	Umuagu, Okwelle	Imo	7.18849	5.69891	25.02.2022
12	Eroded	Unnamed Road, Amauzari	Imo	7.13623	5.65368	25.02.2022
13	Eroded	Isiala Ngwa, Aba Owerri Express,460120	Abia	7.28739	5.31003	25.02.2022
14	Uneroded	Aba Owerri Express Road, 451101	Abia	7.31152	5.28749	25.02.2022
15	Eroded	Umuchichi Road. Aba	Abia	7.36334	5.14529	26.02.2022
16	Eroded	Ukwa West Asa	Abia	7.24067	4.92851	26.02.2022
17	Uneroded	Umuelechi,Uzuaku Asa	Abia	7.17926	4.89925	26.02.2022
18	Uneroded	Port Harcourt/Aba Express Road	Abia	7.14586	4.88954	26.02.2022
19	Uneroded	Degema	Rivers	6.83121	4.81598	05.03.2022
20	Uneroded	Eleme	Rivers	7.09277	4.81576	05.03.2022
21	Uneroded	PHALGA	Rivers	6.97721	4.80438	05.03.2022

Sampling and Sample Treatment

Representative sampling was used. Three states of the Southeast Nigeria were used to represent the region. The states were Anambra, Imo and Abia. These states were chosen because they represent over 50% of the landmass of the region and for their proximity to the control state (Rivers State). Most importantly, about two-thirds of gullies in the region occur in Anambra, Imo and Abia. Samples were collected with the aid of the auger, from gully sites in each of the three senatorial districts of the states; a total of nine sites. For each site, samples were collected at two points representing the gully head and the gully tail. For each point, samples were collected at two depths; 0-15cm and 15-30cm representing the top soil and the subsoil respectively. These sum up to 36 samples. An additional 6 samples from the three senatorial districts of Rivers State taken at depths 0-15cm and 15-30cm served as control for the study. The collected soil was stored in airtight polyethylene bags and labeled appropriately.

Sample Treatment

Heavy Metals

About 30 g of soil was weighed (using a top loading balance) from each of the four samples taken per site to form a composite sample. The composites were air dried, crushed with a porcelain mortar and pestle and sieved with a 2 mm sieve.

The composite samples were digested in triplicates using the reverse aqua regia method.
The concentrations of the following heavy metals were also analyzed Co^{2+}, Zn^{2+}, Cr^{3+}, Mn^{2+}, Fe^{2+}, Cu^{2+}, Cd^{2+}, Ni^{2+}, As^{3+}, Pb^{2+} using Atomic Absorption Spectroscopy and the results were presented in milligrams per liter.

Mineralogy of the soil

The methodology employed to determine the mineralogical composition of soil samples using X-ray Diffraction (XRD) follows a systematic approach, including sample collection, preparation, instrumental analysis, and data interpretation to ensure accurate and reproducible results.

Collected samples were air-dried at room temperature for 48 hours to remove moisture. The dried samples were then sieved through a 2 mm mesh to remove coarse fragments and organic debris.

The sieved soil was ground to a fine powder using an agate mortar and pestle. For improved homogeneity and reduction of preferred orientation effects, the samples were further processed in a mechanical ball mill for 10 minutes until a particle size of <75 μm was achieved.

A back-loading technique was employed to prepare the soil samples for XRD analysis. This method minimizes preferred orientation effects by ensuring a randomly oriented powder surface. The fine powder was pressed onto a sample holder and smoothed to achieve a uniform surface for diffraction measurements.

X-ray diffraction analysis was performed using a standard X-ray diffractometer equipped with a Cu-Kα radiation source (λ = 1.5406 Å)

Instrument calibration was conducted using a standard silicon reference sample. Regular calibration checks ensured consistency and accuracy throughout the measurements. Additionally, an internal standard (corundum) was incorporated into selected samples to assess instrument stability and correct for potential peak shifts.

Each sample was scanned to ensure high-resolution diffraction patterns. The obtained diffraction patterns were recorded.

The acquired XRD patterns were analyzed and compared against standard reference databases to identify crystalline phases present in the samples.

To ensure the reliability of results, duplicate analyses were conducted on randomly selected samples. Additionally, standard reference materials were analyzed alongside the soil samples to validate the accuracy of phase identification and quantification [24, 25].

RESULTS

Table 4: Heavy Metals Concentration

METAL	AN1	AN2	AN3	IM1	IM2	IM3	AB1	AB2	AB3	CONTROL
Co	19.77	8.03	13.1	13.3	23.17	37.6	32.1	29.83	38.6	16.43
Cd	41.23	45.5	46.7	45.53	39.4	44.27	46.2	33.8	46.23	NA
As	25.6	22.6	34.53	65.93	28.03	51.33	64.63	41.27	32.17	NA
Cr	49.3	52	54.7	38.37	47.23	37.47	34.6	31.73	31.73	35.44
Cu	20.7	19.3	18.6	16.87	16.9	17.1	16.9	14.2	24.1	67.38
Fe	1279.8	1155.1	1209.5	1135.4	1080.1	987.5	936.17	894.77	898.77	3543.78
Mn	63.27	60.77	63.3	70.97	60	56.5	61.97	75.9	63.8	46.05
Ni	24.53	19.5	38.23	46.9	59.07	45.63	48.17	42.4	69.3	15.71
Pb	NOT DETECTED									1846.15
Zn	32.44	25.95	21.09	25.14	30.82	29.2	31.63	38.12	38.93	87.13

Table 5: X-Ray Diffraction of the Soil Mineralogy

		AB1	AB2	AB3	AN1	AN2	AN3	IM1	IM2	IM3
	Quartz	Quartz	Gibbsite	Quartz	Quartz	Quartz	Berlinite	Quartz	Quartz	Quartz
	81%	96%	80.2	87.7%	78%	76%	45	66%	86%	62%
	Albite	Berlinite	Quartz	Goethite	Albite	Albite	Quartz	Orthoclase	Anthophyllite	Anorthite
	13	4	9.9%	11.4	9	12	41%	23	7	30
	Orthoclase	Orthoclase	Albite	Albite	Nacrite	Clinochlore	Albite	Albite	Albite	Albite
	6	0.3	6.13	0.8	8	12	13	6	4	6
	Vermiculite	Chorite	Kaolinite	Illite	Vermiculite	Orthoclase	Orthoclase	Vermiculite	Columbite	Orthoclase
	0.07	0.1	3.83	0.1	5	0.4	1.0	5	3.4	2
Mineral Present	**CTRL**	**ABIA**			**ANAMBRA**				**IMO**	

Discussion

The geochemical parameters analyzed and discussed here are heavy metals and minerology of the soils.

Heavy Metals

Manganese:

Table 4 shows that the control soil has the least manganese concentration (46.05 mg/kg) compared to the test soils, which have values as high as 75.90 mg/kg. Manganese is a trace element that plays several roles in soil chemistry and biology. While it is not typically considered a major factor in soil stability and erosion resistance, its presence can indirectly influence these factors through various mechanisms [23]. High concentrations of manganese in soil can potentially impact soil stability and erosion resistance, although the exact effects will depend on various factors, including soil type, pH, and the specific plant and microbial communities present. While manganese is an essential nutrient for plants and microorganisms, excessive levels can lead to toxicity and adverse effects on soil health in the following ways:

a) Reduced Plant Growth: Excessive manganese can be toxic to plants, inhibiting root growth and overall plant health. This reduction in vegetation cover can decrease soil stability, as plant roots are crucial for binding soil particles together and preventing erosion [24].

b) Altered Microbial Activity: High manganese levels may also affect soil microbial communities. Some microbes such fungi, are sensitive to heavy metals like manganese and may be inhibited or killed off at elevated concentrations. This disruption in microbial activity can impact nutrient cycling and soil structure, potentially reducing soil stability [25].

c) Changes in Soil Structure: Manganese toxicity can interfere with soil aggregation, which is essential for creating stable soil structure. Without proper aggregation, soil is more susceptible to erosion by wind and water [26].

d) Increased Erosion Risk: Ultimately, the combination of reduced vegetation cover, altered microbial activity, and changes in soil structure can increase the risk of erosion in manganese-contaminated soils.

e) Plant Growth: Manganese is essential for plant growth and plays a key role in photosynthesis, enzyme activation, and nitrogen metabolism. Healthy plant growth can contribute to soil stability by promoting root development, which helps bind soil particles together and reduce erosion [27].

f) Microbial Activity: Manganese is also involved in the activity of certain soil microorganisms. These microbes play important roles in decomposing organic matter, cycling nutrients, and improving soil structure. A healthy microbial community can enhance soil stability by promoting aggregation and the formation of soil aggregates, which are less prone to erosion [28].

g) pH Regulation: Manganese availability in soil is strongly influenced by soil pH. In acidic soils, manganese can become more soluble and may reach toxic levels for plants, affecting their growth and ultimately reducing soil stability. Conversely, in alkaline soils, manganese may be less available to plants, potentially impacting their ability to establish and contribute to soil stability [29].

h) Oxidation State: Manganese exists in different oxidation states in soil, including Mn^{2+} and Mn^{4+}. The presence of these different forms can affect soil redox reactions, which in turn influence nutrient cycling and soil structure. Redox reactions involving manganese can contribute to the formation of stable soil aggregates [30].

i) Heavy Metal Toxicity: While manganese itself is not typically considered toxic to plants at normal levels, elevated concentrations can be detrimental. In some cases, excessive manganese can inhibit plant growth and contribute to soil degradation, reducing stability and increasing erosion risk [24].

Overall, while manganese may not directly determine soil stability and erosion resistance, its influence on plant growth, microbial activity, pH regulation, and redox reactions can indirectly impact these factors.

Nickel: Table 4 shows that the concentration of nickel in the control (15.71mg/kg) is least when compared to those of the test samples which have nickel concentration as high as 69.30mg/kg. High concentrations of nickel in soil can also have significant implications for soil stability and erosion resistance, similar to other heavy metals like manganese. While nickel is an essential micronutrient for some plants, excessive levels can be toxic and lead to adverse effects on soil health [31].

a) Plant Growth Inhibition: Elevated nickel levels can inhibit plant growth by interfering with various physiological processes such as photosynthesis, enzyme activities, and nutrient uptake. Reduced vegetation cover can lead to decreased root biomass, which in turn weakens soil structure and stability [30].

b) Microbial Activity Disruption: Soil microorganisms play critical roles in nutrient cycling, organic matter decomposition, and soil aggregation, all of which contribute to soil stability. High nickel concentrations can disrupt microbial communities, leading to decreased microbial diversity and activity. This disruption can impair soil structure and increase erosion susceptibility [32].

c) Soil Structure Degradation: Nickel toxicity can negatively impact soil aggregation, which is essential for maintaining soil structure and stability. Without proper aggregation, soil becomes more susceptible to erosion by wind and water [33].

Iron: in soil, iron exists in form of the oxides. Iron oxides, such as hematite and goethite, can enhance soil cohesion and reduce erosion susceptibility. These iron oxides play a crucial role in binding soil particles together, promoting the formation of aggregates [34].

The process involves the physical and chemical interactions of iron with other soil components. Expectedly, the concentration of iron in the control (3543.78mg/kg) far exceeds those of the samples which were as low as 894.77mg/kg.

Copper: As presented in Table 4, the concentration of copper in the control soil is at least more than double those of the test samples, which have copper concentration as low as 14.204 mg/kg. The concentration of copper in soil can influence soil resistance to erosion through various mechanisms. Copper can have both positive and negative effects on soil stability, depending on its concentration and other environmental factors. While high concentrations of copper can be toxic to plants and soil organisms, moderate levels of copper can contribute to soil stability through various mechanisms, including:

b) Plant Growth Promotion: Copper is an essential micronutrient for plants, playing a crucial role in enzyme activation and electron transport processes. Adequate copper levels in soil promote healthy plant growth, leading to the development of robust root systems. Stronger root systems help bind soil particles together, enhancing soil stability and reducing erosion risk [35].

c) Stimulation of Soil Microbial Activity: Copper can stimulate the activity of certain soil microorganisms, particularly those involved in organic matter decomposition and nutrient cycling. Increased microbial activity can improve soil structure by promoting the formation of stable soil aggregates, which are less prone to erosion. Soil microorganisms also play crucial roles in nutrient cycling, organic matter decomposition, and soil aggregation, all of which contribute to soil stability [36].

d) Impact on Plant Growth: Copper is necessary for various physiological processes in plants, including photosynthesis and enzyme activation. However, excessive copper levels can be toxic to plants, inhibiting growth and reducing vegetation cover. Reduced plant cover decreases soil stability by weakening root systems, which are essential for binding soil particles and preventing erosion [37].

e) Enhanced Organic Matter Decomposition: Copper availability in soil can influence the decomposition rate of organic matter. Moderate levels of copper can enhance the activity of soil microorganisms responsible for organic matter decomposition, leading to increased turnover of plant residues and litterfall. The breakdown of organic matter contributes to soil aggregation and stability [38].

f) Indirect Effects on Soil Structure: While copper itself does not directly bind soil particles, its influence on plant growth, microbial activity, and organic matter decomposition can indirectly affect soil structure and stability. Healthy vegetation, active microbial communities, and abundant organic matter contribute to the formation of stable soil aggregates, which reduce erosion susceptibility [39].

Zinc: Zinc is another essential micronutrient for plant growth and development. Adequate levels of zinc can contribute to healthy plant roots, indirectly promoting soil stability by enhancing vegetation cover [40] Zinc concentration as presented in Table 4 shows the control having the highest value of 87.13 mg/kg, compared with test samples having values as low as 21.09 mg/kg (AN3). Zinc can indirectly improve soil stability and resistance to erosion through its influence on plant growth and soil structure. While zinc itself does not directly bind soil particles or affect soil aggregation, it plays a crucial role in plant physiology, which in turn can enhance soil stability in the following ways:

a) **Growth Promotion:** Zinc is an essential micronutrient for plants, playing a key role in various physiological processes such as enzyme activation, hormone regulation, and photosynthesis. Adequate zinc levels in soil promote healthy plant growth, leading to the development of robust root systems. Stronger and more extensive root systems help bind soil particles together, preventing erosion by stabilizing the soil surface [40,41]

b) **Increased Organic Matter Accumulation:** Zinc availability in soil can influence plant productivity and biomass production. Enhanced plant growth resulting from sufficient zinc levels can lead to increased organic matter accumulation in the soil through root turnover, litterfall, and decomposition of plant residues. Organic matter contributes to soil stability by improving soil structure, increasing water infiltration rates, and reducing soil erosion susceptibility [42].

c) **Improved Soil Aggregation:** While zinc itself does not directly affect soil aggregation, its influence on plant growth and organic matter accumulation indirectly contributes to soil aggregation and stability. Organic matter serves as a binding agent, promoting the formation of soil aggregates. These aggregates help create a stable soil structure that is more resistant to erosion by wind and water [42, 43].

Cadmium: While cadmium was not detected in the control soil, values were as high as 46.70 mg/kg in the test soils. High concentrations of cadmium can negatively impact soil stability by interfering with soil structure and reducing aggregate stability [44]. Cadmium can contribute to increased erosion susceptibility as it may lead to decreased root development in plants, reducing their ability to bind soil particles [45].

Arsenic: The arsenic concentration in the test samples ranged between 22.60 mg/kg and 65.93 mg/kg, whereas arsenic was not detected in the control soil. Arsenic can affect soil stability by influencing microbial activity and organic matter decomposition. In certain forms, arsenic may lead to decreased soil aggregation, potentially increasing erosion risk [46,47].

Minerology

Results presented on Table 5 reveal that quartz, albite, orthoclase and vermiculite are present in the control soil. A closer study of the results so presented show that at least two of these minerals which are present in the control also occur in the test soils in varying percentage abundances. The order of particle size for the minerals identified in the soils from smallest to largest is typically as follows: Nacrite, Kaolinite, Illite, Quartz, Albite, Orthoclase, Anorthite, Anthophyllite, Berlinite, Columbite, Chlorite, Clinochlore, Vermiculite, Gibbsite, Goethite. According to [48]. The particle sizes of minerals in soil is one factor that could influence the soil's stability to erosion. Determining the exact order of susceptibility to erosion for minerals is a complex process and is influenced by various factors such as mineral composition, grain size, and environmental conditions. The minerals Kaolinite, Nacrite, and Gibbsite have high susceptibility to erosion minerals with low susceptibility to erosion. This could explain, in part, the control's stability to erosion.

1. Mineral Hardness and Erosion Susceptibility

Mineral hardness is measured using Mohs Hardness Scale, which ranges from 1 (softest, e.g., talc) to 10 (hardest, e.g., diamond). Harder minerals are generally more resistant to mechanical erosion, while softer minerals break down more easily.

Soft minerals (Mohs 1-4) (e.g., gypsum, calcite, feldspar) are more susceptible to abrasion and breakdown under mechanical stress such as wind and water transport [49].

Moderately hard minerals (Mohs 5-7) (e.g., quartz, amphiboles) show greater resistance to mechanical breakdown, but grain size plays a role in erosion. Quartz, despite its hardness, is commonly eroded as sand due to its abundance [50].

Very hard minerals (Mohs 8-10) (e.g., zircon, corundum) are highly resistant to physical erosion and tend to accumulate in sediments as heavy mineral grains [51].

2. Chemical Stability and Erosion Susceptibility

Chemical stability refers to how resistant a mineral is to chemical weathering processes such as hydrolysis, oxidation, and dissolution. The **Goldich Stability Series** [52] ranks minerals based on their resistance to chemical breakdown.

- **Least stable minerals** (e.g., olivine, pyroxenes, amphiboles) weather quickly due to their high reactivity with water and atmospheric gases. These minerals are rarely found in sediments because they break down into clays and oxides [53].
- **Moderately stable minerals** (e.g., feldspars, micas) chemically alter into clay minerals over time but may persist in some environments [49].
- **Most stable minerals** (e.g., quartz, zircon, rutile) resist chemical weathering and are commonly found in mature sediments and soils.

The minerals identified in the test soils and control have been discussed below based on their susceptibility to erosion.

1. **Nacrite ($Al_2Si_2O_5(OH)_4$)**: A polymorph of kaolinite, nacrite is a clay mineral with very fine particle size and relatively low hardness. Its chemical stability is moderate, making it susceptible to erosion [56, 57].
2. **Kaolinite ($Al_2Si_2O_5(OH)_4$)**: Another clay mineral with fine particles and low hardness. Kaolinite is more chemically stable than some other clay minerals but still susceptible to erosion due to its particle size [57, 58].
3. **Illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2\cdot nH_2O$**: A mica-like clay mineral with fine particle size and moderate hardness. Illite has moderate chemical stability but is prone to erosion because of its fine particles [56, 57].
4. **Vermiculite $(Mg,Fe,Al)_3(Al,Si)_4O_{10}(OH)_2\cdot 4H_2O$**: A clay mineral with fine particle size and low hardness. Vermiculite is less chemically stable, especially under acidic conditions, making it susceptible to erosion [57, 58].
5. **Chlorite $(Mg,Fe)_{5-6}(Al,Si)_4O_{10}(OH)_8$**: A group of phyllosilicate minerals with fine particle size and moderate hardness. Chlorite has moderate chemical stability but can be eroded due to its particle size [56, 58].
6. **Clinochlore $(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$**: A member of the chlorite group, clinochlore shares

similar properties with fine particle size and moderate hardness, leading to susceptibility to erosion [57, 59].

7. **Gibbsite ($Al(OH)_3$)**: A hydroxide mineral with fine particle size and low hardness. Gibbsite is relatively stable chemically but can be eroded due to its particle size [60].
8. **Goethite (FeO(OH))**: An iron oxyhydroxide mineral with fine particle size and moderate hardness. Goethite is chemically stable but can be subject to erosion because of its particle size [60, 61].
9. **Anthophyllite ($Mg_7Si_8O_{22}(OH)_2$)**: An amphibole mineral with coarser particle size and higher hardness. Anthophyllite is relatively stable chemically and less susceptible to erosion [59].
10. **Anorthite ($CaAl_2Si_2O_8$)**: A calcium-rich feldspar with coarser particle size and higher hardness. Anorthite has moderate chemical stability and is less prone to erosion [54, 62].
11. **Albite ($NaAlSi_3O_8$)**: A sodium-rich feldspar with coarser particle size and higher hardness. Albite is relatively stable chemically and less susceptible to erosion [62].
12. **Orthoclase ($KAlSi_3O_8$)**: A potassium-rich feldspar with coarser particle size and higher hardness. Orthoclase has good chemical stability and is less prone to erosion [54, 63].
13. **Berlinite ($AlPO_4$)**: An aluminum phosphate mineral with properties similar to quartz, including high hardness and chemical stability, making it resistant to erosion [64, 65].
14. **Columbite ($(Fe,Mn,Mg)(Nb,Ta)_2O_6$)**: A niobium-rich mineral with high hardness and chemical stability. Columbite is resistant to erosion due to these properties [64, 65].
15. **Quartz (SiO_2)**: A silica mineral with coarse particle size, high hardness, and excellent chemical stability, making it highly resistant to erosion [63, 66].

Conclusion

The comparative analysis of heavy metal concentrations and mineralogical composition reveals that the control soil exhibits greater stability than the gully-affected test soils. This enhanced resilience is primarily attributed to lower levels of toxic heavy metals—such as cadmium, arsenic, manganese, and nickel—which are known to impair plant growth, microbial activity, and soil aggregation. Conversely, the control soil contains higher concentrations of beneficial micronutrients, including iron, copper, and zinc, which support plant root development, microbial processes, and aggregate stability.

Mineralogical analysis further underscores the superior stability of the control soil, which is rich in erosion-resistant minerals like quartz, albite, and orthoclase. These minerals possess coarse grain sizes, high hardness, and strong chemical stability, making them less prone to physical disintegration and chemical weathering. In contrast, the test soils are dominated by finer, softer minerals such as kaolinite, nacrite, illite, and gibbsite—attributes that increase their vulnerability to erosion. The findings emphasize that mineral properties, especially grain size and hardness, play a crucial role in soil stability and erosion risk.

Recommendations

To mitigate erosion and improve soil health in Southeast Nigeria, we recommend the following:

1. **Regulate heavy metal levels**: Minimize cadmium, arsenic, manganese, and nickel concentrations through pH adjustment (e.g., liming), organic amendments, and chelating agents to immobilize toxic metals.
2. **Optimize micronutrient balance**: Maintain adequate levels of iron, copper, and zinc to support soil structure and biological activity.
3. **Evaluate soil mineralogy**: Identify erosion-prone minerals and target affected areas with appropriate interventions.

4.Adopt erosion control techniques: Implement mulching, terracing, revegetation, and conservation tillage to reduce surface runoff and soil loss.

5. Promote soil structure and health: Increase organic matter content and enhance microbial diversity to reinforce aggregation.

Stakeholders—including policymakers, farmers, and land managers—should adopt integrated soil management strategies tailored to specific soil types to ensure sustainable land use and erosion control.

References

1. World Economic Forum. *The $10 Trillion Cost of Degrading Nature*. 2022. Available at: https://www.weforum.org

2. University of Basel. *Global Soil Erosion and Its Socio-Economic Impacts*. 2020.

3. University of Massachusetts Amherst. *Soil Degradation in Caribbean Landscapes*. 2022.

4.Eni, D. D., Ujoh, F., & Eshett, E. T. Economic implications of gully erosion in Southeast Nigeria. *Environmental Monitoring and Assessment*, 2020;192:244.

5. Ojukwu, C. C. Mapping and analysis of gully erosion sites in southeastern Nigeria. *Journal of Environmental Geography*, 2018;11(1–2):35–45.

6.Nwankwo, C. N., & Nwankwoala, H. O. Gully erosion in southeastern Nigeria: Causes and management. *Hydrology for Disaster Management*, 2018b;3(2):102–112.

7.Nwankwo, C. N., Okoro, B. C., & Okezie, N. O. Hydrological response to gully erosion in southeastern Nigeria. *International Journal of Environmental Sciences*, 2015;4(6):78–89.

8. Egbueri, J. C., Unigwe, C. O., & Umeokeke, C. U. Community-based approaches to gully erosion control. *Geoscience Frontiers*, 2019;10(4):1501–1513.

9. Anikoh, I. I., & Egbai, J. C. Structural geology and its role in gully formation in southern Nigeria. *Journal of African Earth Sciences*, 2017;132:20–30.

10. Zhao, Y., Peth, S., Krümmelbein, J., Horn, R., Wang, Z., & Steffens, M. Soil structure stability and organic matter. *Soil and Tillage Research*, 2018;175:1–10.

11.Basile, A., Coppola, A., & de Mascellis, R. Soil chemical properties in eroded terrains. *Catena*, 2020;195:104801.

12. Liu, D., Wang, Z., & Zhang, L. Soil pH and cation exchange capacity under erosion stress. *Geoderma*, 2017;295:57–65.

13.Wang, B., Wu, P., Zhao, X., Gao, X., & Wang, J. Mineralogical control of soil erodibility. *Soil Use and Management*, 2019;35(1):1–9.

14. Sun, W., Zhao, H., & Qin, J. Role of clay minerals in soil aggregation. *Applied Clay Science*, 2020;185:105403.

15.Shi, X., Zhang, Y., & Tang, K. Influence of sand content on water retention. *Soil Science Society of America Journal*, 2016;80(3):632–640.

16.Chen, J., Li, Y., & Li, M. Nutrient loss through erosion in sloping farmland. *Environmental Earth Sciences*, 2015;74(7):5557–5567.

17. An, Y., Liu, S., Zhang, X., & Zhou, W. Particle-selective erosion and nutrient depletion. *Soil and Tillage Research*, 2018;178:10–17.

18. Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., et al. An assessment of soil erosion rates in Europe. *Nature Sustainability*, 2017;1(11):425–433.

19. Lal, R. Accelerated soil erosion: A global threat to soil productivity. *Earth's Future*, 2020;8(11):e2020EF001552.

20. Tian, Y., Liu, Z., Chen, Y., & Wang, L. Advancements in soil spectroscopy for erosion studies. *Sensors*, 2019;19(14):3135.

21. Chacha, R. *Geochemical Methods for Soil and Sediment Analysis*. Nairobi: Earth Science Publications; 2020.

22. ASTM International. *Standard Practice for X-ray Diffraction Analysis of Soil and Rock by the*

Rietveld Method (ASTM D7348-22). West Conshohocken, PA: ASTM International; 2022.

23. Huang, J., Wang, L., Zhao, Z., Zhang, L., & Yu, Q. (2021). Soil manganese dynamics and its impact on soil microbial activity. *Environmental Pollution*, 270, 116064.

24. Bashir, F., Murtaza, G., Ghafoor, A., & Mahmood, T. (2018). Impact of manganese toxicity on plant growth and soil health. *Journal of Environmental Management*, 210, 200–208.

25. Li, H., Zhang, Y., Wang, L., & Luo, J. (2020). Heavy metals and soil microbial communities: Responses, interactions, and mechanisms. *Applied Soil Ecology*, 154, 103636.

26. Gupta, S. K., Vollmer, M. K., & Krebs, R. (2018). Soil aggregation and the effect of heavy metal contamination on soil structure. *Ecotoxicology and Environmental Safety*, 150, 85–91.

27. Sun, Y., Xu, Y., Wu, L., & Zhao, Y. (2021). Manganese in soils: A key micronutrient for plant and microbial health. *Agronomy*, 11(4), 738.

28. Chaudhary, D. R., Kim, J., Kang, H., & Kim, C. (2017). Effects of manganese contamination on soil microbial activity and structure. *Science of the Total Environment*, 605–606, 894–900.

29. Wei, C., Wang, Y., Wang, Z., & Zhao, Y. (2019). Influence of pH on manganese mobility and toxicity in soil–plant systems. *Environmental Earth Sciences*, 78(17), 511.

30. Zhang, R., Liu, C., & Zheng, Y. (2020). Redox dynamics of manganese in soils and its impact on soil structure. *Soil Science Society of America Journal*, 84(6), 1850–1862.

31. Reis, A. R., Azevedo, R. A., & Santos, M. A. (2017). Nickel in plants and soil: Roles, toxicity, and tolerance mechanisms. *Environmental Science and Pollution Research*, 24(23), 19547–19560.

32. Mohanty, M., Kumar, A., & Dhal, B. (2019). Microbial stress under nickel pollution in soils: A review. *Ecotoxicology and Environmental Safety*, 170, 739–750.

33. Qin, X., Zhao, X., & Wu, Y. (2021). The impact of nickel contamination on soil structure and erosion potential. *Journal of Hazardous Materials*, 412, 125281.

34. Parfitt, R. L., Giltrap, D. J., & Whitton, J. S. (2018). Contribution of iron oxides to soil aggregation and stability. *Soil Science Society of America Journal*, 82(4), 1012–1020.

35. Bennett, L. E., Burkhead, J. L., Hale, K. L., Terry, N., & Pilon-Smits, E. A. H. (2017). Copper transport and tolerance in plants. *Physiologia Plantarum*, 132(3), 449–460.

36. Smith, K. A., Ball, T., & Conen, F. (2017). Soil microbiology and the interaction with copper

concentrations. *Soil Biology and Biochemistry*, 110, 99–109.

37. Alloway, B. J. (2019). *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability* (4th ed.). Springer.

38. Feng, N., Yu, J., & Zhao, H. (2019). Copper effects on microbial community composition and organic matter turnover in soil. *Environmental Pollution*, 250, 298–306.

39. Jiang, Y., Li, S., & Zhang, J. (2020). Effect of copper on soil microbial dynamics and structure. *Environmental Research*, 186, 109524.

40. Alloway, B. J. (2008). Zinc in soils and crop nutrition. *International Zinc Association*, 2nd ed.

41. Broadley, M. R., White, P. J., Hammond, J. P., Zelko, I., & Lux, A. (2007). Zinc in plants. *New Phytologist*, 173(4), 677–702.

42. Rengel, Z. (2015). Availability of zinc and other micronutrients in relation to soil pH. *Plant and Soil*, 361(1–2), 189–204.

43. Bronick, C. J., & Lal, R. (2005). Soil structure and management: A review. *Geoderma*, 124(1–2), 3–22.

44. McLaughlin, M. J., Parker, D. R., & Clarke, J. M. (1999). Cadmium in agricultural soils and crops: Overview. *Risk Assessment of Cadmium in the Human Food Chain*, 31–62.

45. Nagajyoti, P. C., Lee, K. D., & Sreekanth, T. V. M. (2010). Heavy metals, occurrence and toxicity for plants: A review. *Environmental Chemistry Letters*, 8(3), 199–216.

46. Wang, S., & Mulligan, C. N. (2006). Occurrence of arsenic contamination in Canada and the treatment options. *Science of the Total Environment*, 366(2–3), 701–721.

47. Smith, E., Naidu, R., & Alston, A. M. (2002). Chemistry of arsenic in soils: II. Effect of phosphorus, sodium, and calcium on arsenic sorption. *Journal of Environmental Quality*, 31(2), 557–563.

48. Zhang, L., Liu, C., Zhang, Y., & Li, D. (2018). The effect of soil mineral grain size on susceptibility to erosion. *Catena*, 169, 191–200.

49. Pettijohn, F. J. (1975). *Sedimentary Rocks* (3rd ed.). Harper & Row.

50. Bagnold, R. A. (1941). *The Physics of Blown Sand and Desert Dunes*. Methuen.

51. Morton, A. C. (1985). Heavy minerals in provenance studies. *Geological Society, London, Special Publications*, 18(1), 7–12.

52. Goldich, S. S. (1938). A study in rock-weathering. *The Journal of Geology*, 46(1), 17–58.

53. Nesbitt, H. W., & Young, G. M. (1982). Early Proterozoic climates and plate motions inferred

from major element chemistry of lutites. *Nature*, 299, 715–717.

54. Nesbitt, H. W., & Young, G. M. (1984). Prediction of some weathering trends of plutonic and volcanic rocks based on thermodynamic and kinetic considerations. *Geochimica et Cosmochimica Acta*, 48(7), 1523–1534.

55. Tucker, M. E., & Slingerland, R. (1997). *Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks*. Wiley-Blackwell.

56. Grim, R. E. (1968). *Clay Mineralogy* (2nd ed.). McGraw-Hill.

57. Velde, B. (1995). *Origin and Mineralogy of Clays: Clays and the Environment*. Springer-Verlag.

58. Chamley, H. (1989). *Clay Sedimentology*. Springer-Verlag.

59. Deer, W. A., Howie, R. A., & Zussman, J. (2013). *An Introduction to the Rock-forming Minerals* (3rd ed.). Mineralogical Society.

60. Sposito, G. (1989). *The Chemistry of Soils*. Oxford University Press.

61. Cornell, R. M., & Schwertmann, U. (2003). *The Iron Oxides: Structure, Properties, Reactions, Occurrences and Uses*. Wiley-VCH.

62. Berner, R. A., & Holdren, G. R. (1977). Mechanism of feldspar weathering—I. Experimental studies. *Geochimica et Cosmochimica Acta*, 41(1), 11–25.

63. Blatt, H., Middleton, G. V., & Murray, R. (2006). *Origin of Sedimentary Rocks* (2nd ed.). Prentice Hall.

64. Anthony, J. W., Bideaux, R. A., Bladh, K. W., & Nichols, M. C. (1995). *Handbook of Mineralogy*. Mineralogical Society of America.

65. Gaines, R. V., Skinner, H. C. W., Foord, E. E., Mason, B., & Rosenzweig, A. (1997). *Dana's New Mineralogy* (8th ed.). Wiley.

66. Siever, R. (1962). Silica solubility, 0°–200°C, and the diagenesis of siliceous sediments. *Journal of Geology*, 70(2), 127–150.