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Physicochemical Characteristics of Gully Impacted Soils in Southeast Nigeria

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Abstract

Gully erosion is a critical environmental concern in Southeast Nigeria, causing extensive land degradation, loss of arable soil, and disruption of socio-economic activities. This study investigates the physicochemical characteristics of gully-impacted soils across three states—Imo, Abia, and Anambra—representing the Southeast geopolitical zone, with soils from Rivers State serving as a control. The research aimed to identify key soil properties that influence erosion susceptibility and to inform effective mitigation strategies. Soil samples were analyzed for pH, bulk density, porosity, moisture content, organic carbon, organic matter, cation exchange capacity (CEC), and exchangeable bases. Results reveal that most gully-affected soils were acidic (pH 0.62–6.08), compared to the near-neutral control (pH 7.15), indicating a potential role of acidity in soil structure breakdown. Bulk densities of affected soils (0.853–1.479 g/cm^3) were lower than the control (1.624 g/cm^3), while porosity values (44.32–67.82%) were significantly higher, suggesting increased pore space that may weaken soil cohesion and promote erosion. Organic carbon (0.09–3.02%) and organic matter (0.10–5.21%) levels were variable, with several samples falling below control levels, potentially limiting structural stability. Moisture content ranged widely (0.22–11.26%), indicating inconsistent water retention capacity. Exchangeable calcium and magnesium were generally lower in the affected soils, while sodium was higher—conditions unfavorable to aggregate stability. Most samples also exhibited reduced CEC compared to the control (29.78 meq/100g), indicating lower nutrient-holding capacity. Texturally, soils were predominantly sandy and loamy sand, with minimal clay content, further exacerbating erodibility. The study concludes that the interplay of low pH, high porosity, low nutrient retention, and poor structural integrity contribute significantly to gully formation. Therefore, integrated soil management practice is recommended, such as liming, organic amendments, and targeted fertilization—to enhance soil stability and combat erosion in the region.

Keywords: Gully erosion, Southeast Nigeria, organic matter, porosity, cation exchange capacity, soil conservation

Introduction

Soil erosion, along with its wide-ranging impacts, stands as one of today's most significant environmental issues, though it often remains under recognized. The financial burden of this phenomenon is immense, with soil degradation estimated to cost the global economy more than $10 trillion annually, primarily through its impact on agricultural productivity and ecosystem services [1]. These costs arise from both on-site and off-site effects of erosion [2]. On-site effects are particularly severe on agricultural land, while off-site problems typically result from downstream or wind-driven sedimentation. In steep, mountainous regions, such as parts of the Caribbean, soil erosion is especially prominent due to deforestation and unsustainable agricultural practices, leading to land degradation and loss of fertility [3]. This degradation manifests in soil loss, reduced soil structure, and decreased levels of nutrients and organic matter. As soil fertility declines, it leads to increased costs for fertilizers, reduced agricultural productivity, threats to food security, and a significant drop in land values.

In Nigeria and the Southeast in particular, the case is not different. A lot of arable land has been lost to gully erosion resulting in loss of farm lands and properties, reduced income, transportation difficulty and destruction of amenities.

Figure 1 shows the economic impact of gully erosion in parts of Southeast Nigeria.

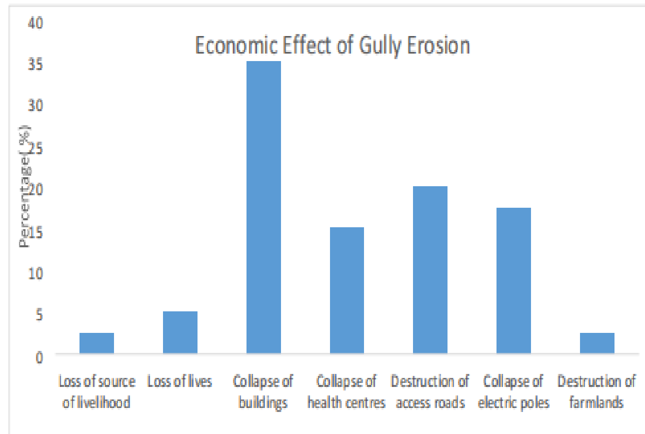

Figure 1: Economic Effect of Gully Erosion [4]

Ojukwu, documented numerous gully sites and their development stages in Southeast Nigeria (Table 2) [5].

Table 1: Distribution of Gully Erosion 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]

The rate of gully expansion in Southeastern Nigeria is estimated to be between 20 and 50 meters per year [6]. According to Ojukwu [5], there are over 2,800 active erosion sites, including over 1,000 in Anambra, 300 in Imo, and 500 each in Abia, Enugu, and Ebonyi states as reported by the World Igbo Environmental Foundation (WIFE). Some of these gullies, such as those in Amucha, Okwudor, Umuagor, Urualla, and Isu Njaba, have depths ranging from 22 to 150 meters, widths from 0.4 to 5.6 meters, and lengths between 0.7 and 2.5 kilometers. Many of these gullies follow linear zones of weakness and have become tourist attractions [4].

Gully formation is driven by increased surface runoff, which acts as an erosive force. The significant depths of these gullies and the ineffectiveness of most control measures suggest that their development is likely due to a combination of external and internal forces [7]. As indicated in Table 1.2, government efforts to control major gullies have largely been unsuccessful, with limited and insufficient attempts made in Anambra and Imo States. Local communities have also attempted various temporary control measures, but these have not been effective in mitigating the severe impacts [8]

Erosivity and erodibility are key factors in soil erosion and gully formation. Erosivity, determined by rainfall intensity, is a natural phenomenon beyond human control.

Erodibility, on the other hand, depends on soil properties, topography, and land management. Proper land management is crucial in Southeast Nigeria, where the region's geotectonic, geologic, and geohydrologic characteristics make many areas prone to gully erosion. Features such as cuestas, fractures, and joints are common in these gully-prone areas and have been identified as significant contributors to gully erosion and landslides [9,10].

Gully erosion presents a major environmental challenge in Southeast Nigeria, highlighting the need for thorough geophysical and geochemical investigations to understand its root causes and develop effective mitigation strategies. The rapid spread of gullies in the area has resulted in severe soil degradation, the loss of farmland, and negative effects on local communities.

This study tackles the urgent issue of gully erosion by examining its physicochemical characteristics that contribute to gully formation [11]

Understanding the physicochemical dynamics of gully erosion is crucial for sustainable land management and the creation of effective conservation strategies. This research aims to bridge the current knowledge gap and offer valuable insights for policy makers, land-use planners, and environmentalists working to reduce the harmful effects of gully erosion in Southeast Nigeria.

Materials and Methods

Materials and equipment

The materials and equipment utilized in this research study included a variety of glassware, reagents, and other essential tools. The glassware comprised test tubes, beakers, pipettes, conical flasks, burettes, and volumetric flasks, all of which were fundamental for conducting the experiments. Reagents employed, included hydrochloric acid (HCl), nitric acid (HNO_3), ammonium acetate (NH_4OAc), potassium cyanide (KCN), hydroxylamine (NH_2OH), potassium ferrocyanide (K_4Fe), potassium chloride (KCl), and EDTA, which were carefully selected to facilitate the chemical analyses. Materials and equipment necessary for sampling and analysis included an auger, a shovel, and sampling bottles for fieldwork. A porcelain mortar was used for grinding, while a pH meter was employed for pH measurements. Personal protective equipment such as nose masks, synthetic hand gloves, and safety goggles ensured safety during experimental procedures. An analytical balance was used for precise weighing, and a 2-mm sieve aided in sample preparation. Cylindrical aluminum drums and filter paper were also utilized in the study for storage and filtration purposes respectively.

Methodology

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	AB
Abia	Abia North	AB3

Southeast Nigeria is one of the six geopolitical zones in Nigeria. It is located on 5.9260 ^{0}N to 7.6927^{0}N and longitude 6.6774^{0}E to 8.7090^{0}E (approximately) (Figure 3.1) The region is characterized by diverse landscape, including lush tropical rainforest, rolling hill and fertile plains. The region is home to the Niger River and its tributaries, contributing to a network of water ways. Cities such as Enugu, Owerri and Umuahia are situated in this region, each with its unique topography. An approximate 40 million people inhabit the 29,792 square kilometers land mass as at January, 2022, though figures vary over time due to factors such as birthrate, migration and other demographic factors [12]. The main occupations of people in the region are diverse reflecting a mix of urban and rural livelihoods. Key occupations include agriculture, trade and commerce, craftsmanship and artisanal work, etc.

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Study Area

The location and coordinates of sample sites from the study area as well as those of the control area are presented on Table 3

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.

i. Sampling

Eroded and uneroded soil samples were collected from nine gully sites across three senatorial districts per state using an auger. Each site had samples from the gully head and tail at 0-15cm and 15-30cm depths, totaling 36 samples. Six control samples from Rivers State were included. Undisturbed swampy soil samples were taken using cylindrical metal drums. Each state provided four uneroded samples (three per district, one control), plus one extra from Rivers State

ii. Sample Treatment

About 30g 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 2mm sieve.

Data obtained were strictly for laboratory analysis of the various soil physicochemical parameters that were considered. The physicochemical parameters examined include: pH, bulk density, porosity, total organic carbon, moisture content, organic matter, exchangeable Ca, exchangeable Mg, exchangeable Na and exchangeable K, cation exchange capacity (CEC).

Determination of Physicochemical Parameters

Table 4: Summary of Methodology

Soil Test	Method	Reference
Soil moisture content	Gravimetry	[13] [14]
Exchangeable Cations (Ca, Mg, Na, and K) and Cation exchange capacity	EDTA complexometric titration / Summation	[15] [16]
Soil Ph	Water, using a glass electrode	[17] [18]
Bulk Density	Core	[19] [20]

Soil Test	Method	Reference
Soil organic matter	Loss on ignition	[17][21]
Total Organic Carbon	Wet combustion	[17] [18]
Total Porosity	Core	[13] [22]

Results

The results of physicochemical analysis is presented in Table 5.

Table 5: Physicochemical Analysis of the Soil Samples

Sample Code	pH	Bulk Density g/mg	Porosity %	Organic carbon %	Moisture content %	Organic matter %	Exchangeable Cations (mol/kg) Ca	Mg	Na	K	Texture (%) Sand	Silt	Clay	Texture	CEC meq/100g	
CTRL	7.15	1.624	38.73	0.77	6.24	1.32	26.524	1.991	1.06	0.040	93.6	3.00	3.40	Sand	29.78	0.245
AN1	6.62	0.913	65.55	0.38	1.27	0.66	6.010	0.271	1.561	0.045	83.6	3.87	12.53	loamy sand	8.02	0.041
AN2	6.27	1.108	58.18	0.74	8.00	1.28	8.148	0.346	1.841	0.034	87.67	1.33	11.00	loamy sand	10.4	0.186
AN3	6.49	1.310	58.68	0.27	11.26	0.80	17.572	3.087	1.783	0.088	85.93	3.60	9.73	loamy sand	22.1	0.073
IM1	6.08	0.853	67.82	0.04	0.22	0.097	2.753	0.171	1.407	0.051	95	1.33	3.67	Sand	4.429	0.033
IM2	7.37	1.083	48.39	3.02	8.38	5.21	11.491	3.173	1.419	0.073	91.33	3.00	6.67	Sand	16.436	0.033
IM3	6.47	1.261	52.52	0.73	8.62	1.27	33.247	7.020	3.576	0.319	68.4	11.47	20.13	sandy loam	44.138	0.057
AB1	6.42	1.479	44.32	0.27	1.23	0.47	1.396	0.314	0.875	0.028	95	0.70	4.33	Sand	2.876	0.057
AB2	7.85	1.119	57.79	0.93	1.23	1.59	21.077	0.365	1.381	0.046	56.6	20.23	23.70	loam	23.08	0.077
AB3	6.58	1.302	50.68	0.35	2.24	0.64	6.131	0.407	1.385	0.065	92.73	2.23	5.03	Sand	8.237	0.09

Discussion

Physicochemical Parameters

pH: Most sample soils (AN1, AN2, AN3, IM1, IM3, AB1, AB3) are slightly acidic (pH < 6.6), while AB2 (7.85) and IM2 (7.35) are slightly alkaline. Soil pH influences aggregation, microbial activity, and erosion susceptibility. Acidic soils reduce aggregation, making them prone to erosion, while high pH affects nutrient availability and soil stability. The control soil (pH 7.15) shows better erosion resistance due to balanced microbial activity and nutrient supply [23,24].

ii. Bulk Density: Sample soils have bulk densities slightly above 1.0 g/cm³, while the control is more compact at 1.64 g/cm³. Higher bulk density reduces erosion by increasing soil strength but also lowers infiltration, leading to runoff that can worsen erosion [25,26].

iii. Porosity: Sample soils have high porosity (44.32%–67.82%) compared to the control (28.72%). High porosity enhances water retention but may increase erosion risk through excessive drainage and internal erosion [27]. The control soil's lower porosity likely contributes to its erosion resistance.

iv. Soil Moisture: Soil moisture levels varied, with Abia having the lowest (1.23%–2.24%) and Anambra the highest (11.26%). The control soil had 6.24%. Moisture enhances cohesion, reducing erosion risk, while insufficient moisture can cause compaction and cracking, decreasing stability [28].

v. Soil Organic Carbon (SOC): SOC values varied, with IM2 having the highest (3.023%) and IM1 the lowest (0.04%). Five samples had SOC below the control (0.767%). SOC improves soil stability by enhancing aggregation, water retention, nutrient availability, and microbial activity. It also aids carbon sequestration and pH buffering. However, excessive SOC may cause compaction and increase erosion risk [29,30].

i. Soil Organic Matter (SOM) follows the same trend as SOC, with samples AN1, AN3, IM1, AB1, and AB3 having higher SOM than the control (1.303%). SOM plays a crucial role in soil stability by enhancing porosity, aggregation, and nutrient retention [31,32]. It consists of decomposed organic materials that improve soil structure and function [33,34]. Key contributions of SOM to soil stability include: a) Aggregation – Acts as a binding agent, forming stable soil aggregates [30]. b) Water Retention – Enhances moisture availability, preventing excessive loss [33]. c) Cation Exchange Capacity (CEC) – Improves nutrient retention and soil fertility [35]. d) Microbial Activity – Supports microbes that release stabilizing compounds [36,37]. e) Carbon Sequestration – Stores carbon, aiding in soil structure and climate mitigation [38,39].

ii. Exchangeable Calcium influences soil stability, with the control having the highest value (26.524%), except for IM3 (33.247%). Calcium enhances stability by: a) Aggregation – Promotes flocculation of clay particles [40,41]. b) CEC – Retains essential nutrients, improving fertility [35]. c) pH Buffering – Neutralizes soil acidity. d) Reducing Dispersion – Prevents structural degradation [42].

iii. Exchangeable Magnesium, higher in AN3, IM2, and IM3, impacts soil stability differently. While it aids aggregation, excessive amounts cause clay dispersion and structure breakdown [26,43]. Exchangeable magnesium impacts soil in the following ways: a. Cation Exchange Capacity: Magnesium is one of the cations involved in CEC. While it contributes to CEC, excessive levels can imbalance soil cation ratios, affecting structure and nutrient availability [44]. b. pH Effects: High levels of magnesium can have a slight acidifying effect on pH, which may influence microbial activity, nutrient availability, and soil structure [45]. c. Impacts on Root Growth: Excessive magnesium can hinder root development, reducing soil stability [46].

ix. Exchangeable Sodium: Exchangeable sodium in soil can significantly impact its stability and resistance to erosion, particularly in sodic soils [47]. Except for AB1 (0.875 mol/kg), the control has the least sodium. Sodium impacts stability through: a) Dispersion of Clay Particles [48]. b) Reduced Infiltration [49]. c) Surface Crusting [41]. d) Soil Structure Degradation [50]. e) Alkalinity [51].

x. Cation Exchange Capacity (CEC): CEC measures the soil's ability to retain and supply nutrients. Soils with adequate CEC have better structure and are less prone to erosion [51]. The control's high CEC (29.78 mol/kg) may explain its erosion resistance. Mechanisms include: a. Soil Structure and Aggregation [52]. b. Nutrient Retention and Availability [53]. c. Water Holding Capacity [54]. d. pH Buffering Capacity [55].

xi. Percent Clay: The control has the least percent clay. Clay influences erosion through: a. Soil Structure [56]. b. Water Retention [57]. c. Soil Cohesion [58]. d. Surface Sealing [59]. e. Slope Stability [60].

xii. Soil Texture: The control's clay to silt ratio is 1:1; samples range from 2:1 to 11:1. High clay to silt ratio may increase erodibility. Soil texture enhances erosion resistance through: a. Soil Aggregation [61]. b. Cohesion [62]. c. Surface Crusting [25]. d. Low Permeability [23]. e. Vegetative Cover [27].

Conclusion

This study identifies key physicochemical factors—pH, bulk density, porosity, moisture content, and soil organic carbon (SOC)—that influence the susceptibility of soils in Southeast Nigeria to gully erosion. Slightly acidic soils (pH < 6.6) were common, potentially reducing soil aggregation and increasing erodibility. However, erosion was also observed in soils with alkaline pH, indicating other contributing factors such as vegetation cover and soil type.

Bulk density values above 1.0 g/cm^3 suggest reduced compaction, which can enhance strength but limit infiltration, increasing runoff. High porosity (44.32%–67.82%) compared to the control (28.72%) may also weaken soil cohesion and increase erosion risk. Moisture content varied widely, with lower levels potentially leading to compaction and cracking, while adequate moisture supports soil integrity. SOC levels below the control (0.767%) in several samples indicate reduced structural and nutrient benefits, increasing erosion risk. Higher soil organic matter (SOM) in some samples highlights its importance in improving structure and fertility. Exchangeable calcium was highest in the control sample, enhancing aggregation, while high sodium levels in others promoted dispersion and erodibility. The control soil's higher cation exchange capacity (CEC) and balanced clay-to-silt ratio also contribute to greater stability.

Overall, the interplay of soil properties significantly affects erosion processes. Addressing these through targeted conservation strategies is essential for restoring and maintaining soil health in the region.

Recommendations

To mitigate gully erosion, the following strategies are recommended: **Enrich Organic Matter** – Add compost or green manure to boost SOC, improving structure and water retention.**Implement Cover Crops** – Protect soil from rainfall impact and enhance moisture retention and cohesion.

Manage Soil pH – Apply lime to acidic soils to enhance aggregation and microbial activity.

Control Grazing & Vegetation – Prevent overgrazing and maintain ground cover to reduce compaction and runoff.

Promote Community Engagement – Educate local communities on sustainable land use to reduce erosion-inducing activities.

These integrated practices can significantly reduce gully erosion and support sustainable land management in Southeast Nigeria.

References

1. World Economic Forum (2022). Global Risks Report. Geneva: WEF
2. University of Basel (2020) Soil erosion – invisible threat to our environment. Basel: UNIBAS.
3. University of Massachusetts Amherst (2022). Soil degradation in mountainous Caribbean areas. Massachusetts: UMass.

4. Eni DI, Esu IE, Eja EI. (2020) The Economic Cost of Gully Erosion in Southeastern Nigeria. Geojournal.; 85(3):621-35.

5. Ojukwu CP. (2018). Gully Erosion in Southeast Nigeria: Distribution and Control. Nigerian J Environ Sci.; 6(2):45–52.

6. Nwankwo CI, Nwankwoala HO. (2018). The rate of gully erosion in Southeastern Nigeria. Int J Environ Sci.;9(1):33–42.

7. Nwankwo CI, (2015). Analysis of gully erosion triggers. Soil Use Manage.; 31(2):245–52.

8. Egbueri JC, (2019). Community Efforts and Gully Control. J Afr Environ Manage.; 13(1):87–95.

9. Anikoh SO, Egbai JC. (2017). Geological Structures and Gully Erosion. J Geosci Environ Earth Sci.;4(4):124–30.

10. Nwankwoala HO, Nwankwo CI. (2018). Influence of geology on erosion processes. Int J Phys Geogr.; 6(3):12–20.

11. Opara, A. I., Egboka, B. C. E., & Nwankwoala, H. O. (2014). Physicochemical characteristics of soils in gully erosion sites in Southeastern Nigeria. *Journal of Soil Science and Environmental Management*, 5(10), 284–290.

12. Merem EC, Wesley J, Twumasi Y. (2019). Analyzing population and land use in Nigeria's southeast. J Environ Health.; 81(10):120–34.

13. Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S., & Lu, X. (2000). The gravimetric method of soil moisture determination: Part I. A study of sampling devices. *Journal of Hydrology*, *229*(1–2), 113–123.

14. JOVE (2022). Science Education Database. Determination of moisture content in soil.

15.Jones, J. B., Wolf, B., & Mills, H. A (2014). Laboratory Guide for Conducting Soil Tests. Boca Raton: CRC Press.

16. Rayment GE, Lyons DJ. (2018). Soil Chemical Methods – Australasia. Melbourne: CSIRO Publishing.

17. Nelson DW, Sommers LE. Total Carbon, Organic Carbon, and Organic Matter. In: Methods of Soil Analysis. Part 3. Madison: ASA; 2018.

18. Rowell DL. (2014). Soil Science: Methods and Applications. London: Routledge;

19. Blake GR, Hartge KH. (2014). Bulk Density. In: Methods of Soil Analysis. Part 1. Madison: ASA;

20. Grossman RB, Reinsch TG. (2018). Bulk Density and Porosity. In: Dane JH, Topp GC, editors. Methods of Soil Analysis: Part 4. SSSA Book Series No. 5. Madison: ASA;

21. Schulte EE. (2014). Loss-on-Ignition Method for Soil Organic Matter Estimation. Commun Soil Sci Plant Anal.; 35(9–10):1311–29.

22. Flint AL, Flint LE. (2014). Porosity and Water Content by Volumetric Analysis. In: Dane JH, Topp GC, editors. Methods of Soil Analysis. Part 4. Madison: ASA;

23. Brady N, Weil R. (2016). The nature and properties of soils. 15th ed. Upper Saddle River: Pearson Prentice Hall

24. Huang Y, Li Z, Wu J. (2010). Soil pH and its effects on soil erosion: A review of the mechanisms and influencing factors. Geoderma.;157(1–2):1-10.

25. Lal R. (2001). Soil degradation and erosion. In: Lal R, editor. Encyclopedia of soil science. 2nd ed. New York: CRC Press; p. 1492-1497.

26. Hillel D. (2004). Environmental soil physics: Fundamentals, applications, and environmental considerations. San Diego: Academic Press;

27. Morgan RPC. (2005). Soil erosion and conservation. 3rd ed. Chichester: Wiley-Blackwell;

28. Le Bissonnais Y. (1996). Aggregate stability and assessment of soil degradation. In: Baver LD, editor. Soil and water conservation. New York: Academic Press; p. 99-130.

29. Six J, Conant RT, Paul EA. (2004). Stabilization mechanisms of soil organic matter: Implications for the global carbon cycle. In: Lal R, editor. Soil carbon sequestration and the greenhouse effect. 2nd ed. Madison: ASA; p. 231-249.30.Lal R. (2004). Soil organic matter and climate change. CRC Press;

31. Balesdent J, Mariotti A, Guillet B. (2018). The turnover of soil organic matter and carbon in the Cretaceous. In: Lal R, editor. Soil carbon sequestration. Boca Raton: CRC Press; p. 201-225.

32.Kumar S, Kahlon M, Singh R. (2019). Organic matter and soil microbial biomass in reclaimed soils. Soil Biol Biochem.;135:256-263.

33. Lehmann J, Kleber M. (2015). The role of organic matter in soil aggregation. Soil Biol Biochem. ;88: 127-145.

34. Kögel-Knabner I, Amelung W, Celi L. (2020). Organomineral interactions and their impact on soil organic matter. In: Singh B, editor. Soil chemistry and fertility. Amsterdam: Elsevier; p. 343-367.

35. Havlin JL, Tisdale SL, Nelson WL. (2014). Soil fertility and fertilizers: An introduction to nutrient management. 7th ed. Upper Saddle River: Pearson;

36. Rillig MC, Mummey DL, Allen MF. (2017). Soil aggregation and microbial communities. In: Rillig MC, editor. Soil ecology and

management. Amsterdam: Elsevier; p. 315-337.

37. Zhang L, Zeng Q, Shen Z. (2019). Effects of organic matter and microbial activity on soil aggregation and stability. Soil Biol Biochem.;132: 48-57.

38. Lal R. Soil (2018). carbon sequestration to mitigate climate change. Geoderma. ;145(1-2): 56-64.

39. Stockmann U, Adams MA, Crawford JW. (2019). The knowns, known unknowns and unknown unknowns of sequestration of soil organic carbon. Agric Ecosyst Environ. ;176:3-16.

40. Rowley JL, Lawley D, Donaldson LA. (2018). The role of exchangeable calcium in soil aggregate stability. Soil Sci Soc Am J. ;82(2):345-354.

41. Zhao J, Qiao Y, Yang Y. (2021). Effects of calcium on soil aggregation and stability in a forest ecosystem. Soil Sci Soc Am J. ;85(6):1234-1243.

42. Schulze D, Hoorfar J, van der Meer W. (2017). Degradation of soil structure by exchangeable calcium: A review of the effects on soil aggregation. Geoderma. ;280:1-11.

43. Hillel D. (2017). Soil structure and dispersion. In: Hillel D, editor. Handbook of soil science. 2nd ed. Boca Raton: CRC Press; p. 110-132.

44. Jiang H, Wu H, Zhang Y. (2015). Impact of magnesium and calcium cations on the cation exchange capacity of soil. Soil Sci Soc Am J.;79(1):221-230.

45. Feng S, Yu Q, Gao Y. (2016). Effects of exchangeable magnesium and calcium on soil pH and stability. Geoderma. ;265:76-82.

46. Mohammad D, Ryan J, Madramootoo CA. (2017). Magnesium toxicity and its effects on soil and plant growth. Soil Sci. ;182(4):151-159.

47. Rengasamy P, Olsson K. (2015). Soil sodicity: A review. Soil Res. ;53(1):1-15.

48. Babu MS, Zhan Z, Lin F. (2020). Influence of sodium on soil dispersion and structural stability. Soil Sci. ;185(3):130-139.

49. Rengasamy P, McGowan J, Rayar A. (2020). Effects of exchangeable sodium on soil permeability and erosion. Soil Sci Soc Am J. ; 84(6):1313-1321.

50. Schulze D, Kuzyakov Y, Breulmann G. (2020). Exchangeable sodium and its effect on soil erosion and structure. Soil Sci Soc Am J. ;84(4):1120-1130.

51. Olk DC, Kaspar TC, Cook N. (2016). Cation exchange capacity and soil structure in relation to nutrient retention. Geoderma; 278:24-34.

52. FAO. (2016).Cation exchange capacity in soil fertility management. FAO Soil Bulletin No. 82. Rome: FAO.

53. Gao X, Chang Y, Zhang X. (2018). The role of CEC in soil water holding capacity and erosion resistance. Soil Sci Soc Am J. ;83(3):505-515.

54. Zhou L, Cheng Z, Zhang X. (2016). Soil buffering capacity and pH resistance as related to CEC. Geoderma. ;280:50-60.

55. Liu G, Zhang Y, Wang T. (2019). Influence of clay on soil aggregation and erosion. Soil Tillage Res. ;189:38-45.

56. Rattan L, Pandey S, Bhagat R. (2015). Effect of clay on water retention and its role in soil erosion. Soil Sci. ;180(5):307-316.

57. Gupta R, Kar A (2022). Soil cohesion in relation to clay content. Soil Sci Soc Am J. ;86(2):130-138.

58. Selby MJ. (2015). Soil erosion and slope stability. Soil Sci. ;180(1):123-130.

59. Thornes J, Stokes M. (2016). Impact of clay content on soil permeability and erosion. Catena. ;139:68-77.

60. Zhao Y, Zhang L, Liu X. (2019). Clay and silt content in soils and their impact on erosion. Soil Tillage Res. ;196:130-138.

61. Tian Q, Yang M, Zhang Y. (2016). Role of clay in promoting soil cohesion and reducing erosion. Geoderma.; 279:92-101