JJEES
Jordan Journal of Earth and Environmental Sciences

JJEES (2026) 17 (1): 56-62
ISSN 1995-6681

"Soil Evolution Response Using Geochemical Weathering Indicators in Different Climates" (a Scientific review)

Omar Alsalam[1*], Abdul Baqi D.S. Almaamouri[1], Mahmood Ahmed L. Al-Bayati[2]

[1] Department of Soil Sciences and Water Resources, College of Agricultural Engineering Sciences, University of Baghdad, Baghdad, Iraq.
[2] Department of Soil Sciences and Water Resources, College of Agriculture, University of Tikrit, Tikrit, Iraq.

Received on 30 December 2024; Accepted on 16 August 2025

Abstract

Rates of weathering and renewable soil production are significantly influenced by climate. To assess the level of soil development, geochemical weathering indices are frequentlyutilized. Infinite varieties of soils with different characteristics could be created by accounting for the climatic variability of the variables and processes. The impacts of weathering are reflected in the concentrations of elements in soils. Yet, the effects of pedogenic losses, transformations, gains, and translocations, as well as chemical weathering are prominently reflected in the mineralogical and chemical composition of more mature soils. The impact of climatic contrast on soil properties has been demonstrated by studies in humid regions with declining temperatures and rising rainfall. Generally speaking, tropical climates produce deeply weathered soils made up of stable secondary minerals. The soils, on the other hand, are typically weakly to moderately developed in areas with drier climates, such as arid or semi-arid environments. Climate is accountable for the emergence of weakly to moderately developed soils. To predict how climate will affect weathering rates, soil- formating processes, and soil evolutionary stages, research on the diversity of soils grown under opposing climate conditions might be useful in this regard.

Keywords: *Climate, Indices weathering, Soil development, Soil formation, Geochemical weathering, Soil pedogenesis.*

1. Introduction

Information on the factors that influence weathering rates due to climatic change can be found in the evolution of soil. Thus, weathering rates are regarded as a function of climate, and there are variable climatic factors like evapotranspiration, weathering, precipitation amount, and water percolation, among other properties that change with climate (Moshtaha et al., 2025; Al Shamary et al., 2022; Al-Shamare and Essa, 2020). Climate is a significant soil-forming factor that affects the genesis, characteristics, and classification of soils. One crucial element that regulates chemical weathering processes is the availability of water (Merkli et al., 2009; Lybrand et al., 2011; Moazallahi and Farpoor, 2012; Fayyadh and Ismail, 2021; Saleh et al., 2023; Jimoh et al., 2023). Precipitation driven by climate change might influence the dynamics of soil water availability. The rates and types of biological, chemical, and physical processes are influenced by temperature and precipitation, which have a special impact on soil properties. The effect of climatic variations on plant groups and soil types has been previously studied. The primary mechanisms guiding soil development might alter when pedogenesis processes alter the geochemical characteristics of the soil.

Through changing the rate and type of chemical processes and the consequent chemical characteristics, climate change could have a considerable effect on geochemical weathering. Changes in soil organic matter, acidity, clay content, and exchangeable ions were prevalent trends in previous investigations of how climate affects weathering and soil (Egli et al., 2006; Lawrence et al., 2015; Fattah and Karim, 2021; Razvanchy and Fayyadh, 2023; Ilevbare and Adeleye, 2023). The process by which weathering modifies the constituents of the parent deposit by removing more mobile (i.e., soluble) elements and simultaneously enriching less mobile elements, as well as by altering and forming new secondary minerals and accumulating organic matter, is known as pedogenesis. The lithology of the parent material, climatic conditions, topography, time, existence of organisms within the strata, vegetation, and time all have a significant impact on the rate of pedogenesis. In both non-crystalline and crystalline phases, geochemical weathering begins with the loss of non-hydrolyzing cations (such as magnesium, calcium, and sodium) and the concomitant enrichment of aluminum, silicon, and iron ions. Geochemical weathering indices, based on the chemistry of surface soils, are frequently used to quantify and compare the relative intensity and extent of soil pedogenesis. As a result, the climate regime has a significant influence on the link between chemical weathering and the extent of the response to soil evolution. Although their respective roles are still hotly contested, climate variability has been considered the principal controlling influence on weathering up to this point. Gathering as various chemical weathering indicators as possible while knowing how to use and apply them to the evolution of soil profiles and their properties which were examined across various ecosystems is the primary goal of this work.

* Corresponding author e-mail: omar.t@coagri.uobaghdad.edu.iq

2. References Review

2.1. Chemical weathering indices

The most significant geochemical proxies frequently employed to show soil weathering processes are chemical weathering indices (Zhou et al., 2015). (Lybrand etal., 2011; Moazallahi and Farpoor, 2012; Egli etal., 2003; Osat et al., 2016) They could be utilized to illustrate how climate affects soil weathering. The primary function of chemical weathering indices is to predict the sources of mobile nutrients and changes in metal concentrations, evaluate soil fertility, determine the amount of yield of mobile components throughout weathering, and improve kinetic element mobility in weathering (Dönmez, 2023). The mechanisms and intensity of chemical weathering are described by chemical indices derived from soil chemical investigations. Mineral breakdown causes element breakdown and redistribution during weathering. Since various weathering processes have varying effects on particular elements, element redistribution can follow contrasting patterns (Alsalam et al., 2025). A common method for estimating the extent of weathering and the behavior of elements throughout weathering is the redistribution and mobility of elements within the secondary environment (Beyala et al., 2009; El-Hafez et al., 2019; Issa, 2022). As they are freed from host minerals and leached from the parent rock, the more geochemically mobile total elements (MgO, Na_2O, CaO, and K_2O) will generally decrease with weathering grade. There will be fewer immobile and mobile oxides, including SiO_2, P_2O_5, Al_2O_3, Fe_2O_3, MnO, and TiO_2 (Baumann et al., 2014). Four crucial factors must be considered for the effective use of chemical weathering indices (Haskins, 2006):

1. It is best to use just those elements that exhibit consistent geochemical behavior throughout weathering.
2. The indices ought to be unaffected by the weathered material's level of oxidation.
3. It is best to use just those chemical elements that are frequently reported in studies.
4. Chemical indices have to be rather simple to use and apply.

The type and redistribution of weathered products cause the behavior of many chemical elements to be complex, and it was determined that chemical weathering indices must be chosen based on site-specific behavior (Haskins, 2006).

2.2. Calculation of weathering indices

Weathering indices is a technique for digitizing weathering. Conventionally, many formulas based on the molecular ratios of major-element oxides are used to calculate weathering indices. The index values show the chiometric variation of the key element oxides throughout weathering. The weight percentages of the individual oxides make it simple to determine the molecular ratios of each oxide (Al-Momani and Alqudah, 2020). For the purpose of describing weathering in soils, numerous indices were proposed (Harnois, 1988; Nesbit and Young, 1989). All indices share a common general premise:the calculation of various ratios between basic cations (Mg, Ca, Na, and K) and cations such as Si and Al. Some of the most popular indices are shown in the examples below.

Chemical weathering index	Formula	References
Weathering potential index (WPI)	$WPI = \frac{(K_2O+Na_2O+CaO-H_2O)*100}{SiO_2+AL_2O_3+Fe_2O_3+FeO+TiO_2+CaO+MgO+K_2O+Na_2O}$	Ruxton, 1968
Product index (PI)	$PI = \frac{(SiO_2)*100}{SiO_2+AL_2O_3+Fe_2O_3+FeO+TiO_2}$	Ruxton, 1968
Ruxton ratio (R)	$R= \frac{SiO_2}{AL_2O_3}$	Ruxton, 1968
Parker index (P)	$P =\left[\left(\frac{2Na_2O}{0.35}\right)+\left(\frac{MgO}{0.9}\right)+\left(\frac{2K_2O}{0.25}\right)+\left(\frac{CaO}{0.7}\right)\right]X100$	Parker, 1970
Vogt ratio (V)	$V = \frac{(K_2O+AL_2O_3)*100}{CaO+MgO+Na_2O}$	Vogt, 1927; Roaldest, 1972
Modified weathering potential index (MWPI)	$MWPI = \frac{(K_2O+Na_2O+CaO+MgO)*100}{SiO_2+AL_2O_3+Fe_2O_3+CaO+MgO+K_2O+Na_2O}$	Vogel, 1973
Lixiviation index (ß)	$ß = \frac{\left(\frac{K_2O+Na_2O}{AL_2O_3}\right) Weathered}{\left(\frac{K_2O+Na_2O}{AL_2O_3}\right) Fresh+\left(\frac{CaO}{MgO}\right)}$	Rocha-Filho et al., 1985
Loss on ignition (LOI)	LOI = H_2O^+ content (in weight) of specimen heated to 900-1000ºC	Sueoka et al., 1985
Alumina to potassium-sodium oxide ratio (ALK)	$ALK = \left(\frac{K_2O}{K_2O+Na_2O}\right)X100$	Harnois & Moore, 1988

Alumina to calcium-sodium oxide ratio (ACN)	CAN = $(\frac{AL_2O_3}{AL_2O_3+CaO+Na_2O})X100$	Harnois, 1988
Chemical index alteration (CIA)	CIA = $\frac{AL_2O_3}{AL_2O_3+CaO+K_2O+Na_2O}X100$	Nesbitt & Young, 1982
Chemical index of weathering (CIW)	CIW = $\frac{AL_2O_3+K_2O}{AL_2O_3+CaO+Na_2O}X100$	Harnios, 1988
Plagioclase index of alteration (PIA)	PIA = $\frac{AL_2O_3-K_2O}{AL_2O_3+CaO+Na_2O-K_2O}X100$	Fedo *etal*., 1995
Silica-Titania index (STI)	STI = $\frac{\left(\frac{SiO_2}{TiO_2}\right)}{\left(\frac{SiO_2}{TiO_2}+\frac{SiO_2}{AL_2O_3}\right)+\left(\frac{AL_2O_3}{TiO_2}\right)} X\ 100$	De Jayawardena & Lzawa, 1994
Index of compositional variability (ICV)	ICV = $\frac{Fe_2O_3+TiO_2+CaO+MgO+K_2O+Na_2O+MnO}{AL_2O_3}$	Cox et al., 1995
Mobiles index (I_{mob})	I_{mob} = $\frac{(CaO+Na_2O+K_2O)fresh-(CaO+Na_2O+K_2O)\ weathered}{(CaO+Na_2O+K_2O)\ fresh}$	Irfan, 1996
Sesquioxide content (SOC)	SOC = $AL_2O_3+Fe_2O_3$	Irfan, 1996
Mineralogical index of alteration (MIA)	MIA = 2*(CIA-50)	Voicu *etal*., 1996
Weathering index on carbonate-rich sediments (FENG)	FENG = $\frac{AL_2O_3+Fe_2O_3}{P_2O_5+CaO+MgO+K_2O+Na_2O}$	Feng, 1997
S/SAF	$\frac{SiO_2}{SiO_2+AL_2\,O_3+Fe_2O_3}$	Hill *etal*., 2000
Chemical proxy of alteration (CPA)	CPA = $\frac{AL_2O_3}{AL_2O_3+Na_2O}X100$	Buggle et al., 2011

The majority of mobile cations are among the elements removed during soil weathering, as measured by the weathering potential index (WPI). This index could be more dependable compared to a simple index that only depends on one or two chemical components, because it incorporates a large number of them—the intensity regarding leaching and weathering increases with decreasing measured WPI value. Stated differently, a declining Product Index (PI) indicates a declining silica content, which happens with the commencement of weathering, and a falling WIP index declines with greater weathering intensity as well as soil development (Ng et al., 2001). Ruxton (1968) developed the Silica-Alumina Ratio, which measures total element loss as a ratio of alumina content (assuming silica loss to be equivalent to total element loss). He believed that the SiO2/Al2O3 ratio could be used to determine the extent of weathering in humid climates on freely draining acidic rocks with an acidic weathering environment. The proportions of the main alkaline metals and their strength of binding with oxygen serve as weighting factors for the Parker Index (p), developed by Parker (1970). According to Gupta and Rao (2001), this index can be used for basic, intermediate, and acidic rocks, in which hydrolysis is the primary silicate weathering process. Vogt Ratio (V), developed by Vogt (1927) and promoted by Roaldset (1972), assumed that potassium remained stable within the soil weathering system while attempting to ascertain the ratio of immobile to mobile cations. In his evaluation of the weathering regarding acid metavolcanics, Vogel (1973) modified Ruxton's WPI by removing the H_2O^+ and iron oxidation state from the original WPI equation to create the Modified Weathering Potential Index (MWPI). Loss on ignition (LOI) has been suggested by Sueoka et al. (1985) as a reliable measure of the extent of chemical weathering. Just H_2O^+-content (in weight) of a specimen heated to 900 °C–1000 °C is referred to here as LOI, and it rises as weathering progresses due to hydration and clay formation. This signal, which is the sum of H_2O^- and H_2O^+, will be referenced frequently in the following.

Given that feldspars are the most prevalent reactive minerals in the earth's upper crust, Nesbitt and Young (1982) discovered that aggressive soil solutions typically remove sodium, calcium, and potassium from the feldspars during weathering. They suggested that the aluminaratio-toalkalis ratio might normally increase in the weathered product as weathering progressed and that the Chemical Index of Alteration (CIA) may provide a reliable indicator of the extent of weathering. Although they were leached throughout weathering, Harnois, (1988) proposed that potassium cations could be adsorbed onto other clays in the weathered profile through ion exchange, potentially disrupting $K+$ geochemical trends. As an alternative to WPI, p,V, MWPI, and CIA, he suggested the Chemical Index of Weathering (CIW), which excludes K2O, as a more accurate indicator of weathering. Since plagioclase is common in silicate rocks and dissolves rather quickly, PIA could be used as an alternative to the CIW index in cases where just plagioclase weathering needs to be studied (Fedo et al., 1995). As soil changes and weathering intensity increase, so do the indicators. Since potassium has a high exchange capacity and can be adsorbed onto other clays in the weathering profile, obscuring its mobility, Harnois, (1988) argued that using K2O as a mobile component in WPI, CIA, and MWPI restricts their application to soils where potassium has leached. In contrast to evidence that potassium is frequently leached, the Vogt Ratio treats K2O as an immobile component.

CaO should be limited to that obtained from silicate minerals (CaO*) in such indices. The carbonates Ca have been subtracted from total Ca to estimate CaO*. Depending on the supposition that feldspar and mica are the most prevalent minerals in the soil, CIW, CIA, and PIA are regarded as indicators of the degree of feldspar and mica conversion to clay (Baumann et al., 2014; Osat et al., 2016). All such authors agree that knowledge of the geochemical composition, processes, and trends of specific material of interest is necessary for the successful application of any weathering index for chemical weathering indices to be effective. Through their investigations of metamorphic rocks in Sri Lanka, De Jayawardena and Izawa (1994) suggested the silica-titania index for chemical weathering and concluded that there may be correlations between SiO2, Al2O3, and TiO2. There has long been disagreement over whether the different weathering indices apply to other materials and weathering conditions. It is possible to ascertain the mineralogy (primary or secondary minerals) of soils by their chemical composition. The degree of chemical weathering is estimated by the index of compositional variability (Cox et al. 1995). The ratio of major cations to Al2O3 is higher in primary minerals than in pedogenic clay minerals. As a result, primary minerals have a higher ICV. ICV values greater than one are therefore indicative of young, immature soils that contain a significant proportion of primary silicate minerals. Conversely, ICV values below 1 should be observed in highly weathered soils that contain primarily secondary clay minerals formed under intense weathering (Cox et al. 1995).

The degree of decomposition regarding rocks containing feldspar is indicated by the mobiles index (Imob) (Aristizabal et al., 2005). Since it incorporates information from both the weathering products and their fresh parent materials, the index provides useful insights and evaluates the variation in the concentrations of mobile cations (Na2O, K2O, and CaO). Thus, it shows how soil composition varies as a result of weathering. The more intense the weathering, the greater the difference in the number of mobile cations in fresh and weathered soils (Ng et al., 2001). The insoluble oxides Al2O3 and Fe2O3 are represented by the sesquioxide content (SOC) of a sample. According to Ng et al. (2001), a higher SOC suggests either a intensity of leaching or oxidation driven by the enrichment of ferric iron from the oxidation of ferrous iron. The degree of mineralogical weathering is assessed using the mineralogical index of alteration (MIA). Incipient (0–20%), moderate (40–60%), weak (20–40%), and intense to extreme (60–100%) weathering are all indicated by the MIA value. A value of 100% indicates complete weathering of parent rock as well as the formation of a primary mineral into its corresponding weathered product. To overcome the carbonate biases mentioned above, Feng (1997) factored out Ca and added Mg and P as crucial factors. Throughout the weathering and soil development processes, this index rises. Since Al and Na are the best elements to reflect weathering intensity, CPA seeks to avoid the biases of carbonate Ca and K-fixation that have been previously addressed (Buggle et al., 2011). Because K phases, like the K-feldspar and clay minerals, have a higher susceptibility to weathering, the overall K release is less than the Na release. This analysis suggests that K has a negligible impact in cold climates, which makes this WI a useful substitute for our study.

2.3. Soil development response using chemical weathering

The stages of soil development are associated with characteristic soil features, namely typical geochemical properties, which were researched in the South China Sea, including Hainan Island, which experiences a tropical monsoon climate. The study found that whereas Mg, Ca, Na, K, and Si all significantly vanished throughout rock weathering and soil formation, Al and Fe were comparatively enriched. The degree of sequential weathering over successive time periods was not adequately reflected in indicators based on soil microelements, such as the silicon-aluminum ratio of the alteration, the chemical index of alteration (CIA), and the chemical index of weathering (CIW). As a measure of soil formation, the weathering index (WI) shows a strong correlation with soil formation stages (Zhang et al., 2007). The concept of geochemical weathering indices is introduced in Southeast and Eastern Europe. It stands for the records of Late and Middle Pleistocene climate shifts in the area. The best index for silicate weathering is the Chemical Proxy of Alteration (CPA). The CIA, CIW, and PIA were examined under regularly used climatic conditions. At the same time, biases brought on by K-fixation or uncertainties in distinguishing carbonate-Ca from silicate-Ca might affect (PIA, CIA, CIW). Against such impacts, the CPA is insensitive. It also offers the same advantages as other Na-type indices (Buggle et al., 2011). Understanding the relationships between climate, chemical weathering, and pedogenic processes in a variety of semi-arid ecosystems in southern Arizona. The data show that climate and chemical weathering have a significant interactive effect on soil development rates (Lybrand et al., 2011). The intensity of chemical weathering in certain weathering profiles is assessed using Parker's WIP and CIA. To anticipate chemical weathering in China, which is affected by the humid subtropical climate, the concentrations of key oxides were investigated and gathered. The steady rise in CIA, the decline in WIP values, and the drop in altitude all point to an increase in weathering intensity. In China, the main determinants of chemical weathering are surface runoff and precipitation. This work illustrates that suitable geochemical proxies can be used to quantify the carefully applied concentration of integrated chemical weathering (Shao et al., 2012). The main soils formed on igneous rocks in the semi-arid northwest of Iran were evaluated for weathering intensity. The soil profiles formed on volcanic rocks are more weathered than those on plutonic igneous rocks, according to the research area's weathering indicator data (Yousefifard et al., 2012). Pedogenic oxide ratios (POR) and Weathering indexes (WI) were employed in China to characterize patterns of soil development and climate weathering intensity, especially during the climatic period along gradients of elevation that are most impacted by the varied influences of the Asia-India Monsoon. Although specific soil moisture (SM) conditions result from certain climatic factors, topography and climate are always linked to them. They discovered that WI might vividly show weathering tendencies under climatic variations. The most suitable is the CIA (Baumann et al., 2014). Surface soil samples have been -collected from a range of profiles (2000–3600 m) in a humid zone in northwest Ethiopia. The chemical weathering of the soils was investigated. Principal component analysis (PCA) was used to determine the mineral alteration assemblage and the formation throughout pedogenesis, and several chemical weathering indices were used to assess the degree of change in CIA and CIW. CIW and CIA could be more readily identified when comparing weathering indices computed in this work, and they could provide information regarding the formation of the initial rock composition. Furthermore, the degree of pedogenesis is known to be influenced by weathering factors, such as precipitation, which are linked to the CIA index. Information from traditional chemical weathering indices can be supported by the CIA index, which could help us better understand the processes that occur throughout weathering (Le Blond et al., 2015). To demonstrate the relationship between soil development indices and soil taxonomic classes, this work was carried out in a hilly area of northern Iran. To assess soil development, geochemical weathering indices are commonly used. Those indices indicated reduced weathering intensity in more developed soils, even though there were substantial relationships between mostgeochemical weathering indices and the Soil Taxonomic Classes; the Vogt index had the greatest coefficient of correlation. The reason for these connections was that low-gradient slopes, where weathering products from upper slopes accumulate and their parent materials are carbonatic, tended to have better-developed soils (Osat et al., 2016). Assess the sequential effects of climate on soil pedogenesis and weathering rates. Geochemical signals were directly linked to notable variations in the soils' morphological, chemical, and physical characteristics. Higher soil development in moist places was to be a significant factor in defining the soil properties in the study area, notwithstanding the influence of climate on weathering. Over successive climates, the intensity of weathering transformations has changed dramatically. The soil profiles in the moist region had the highest weathering densities (Silva et al., 2016). The reliability of various mineralogical and geochemical weathering proxies as climatic indicators is tested, and the relationships between provenance and climatic controls on soil composition are examined using complementary geochemical datasets on soil collected along the Atlantic margin of subequatorial southwestern Africa. These proxies are more accurate climate estimators in the geological context of SW Africa than traditional weathering indices, such as WIP or CIA (Dinis et al., 2017). Used geochemical data, specifically the CIA, CIW, Base/R2O3 Ratio, WIP, and PIA, to assess the extent of soil weathering in semi-arid and arid climatic zones in Turkey. The findings unequivocally demonstrated that gradual progressive weathering is the cause of soil development at the Altınova State Farm in Konya, Turkey's Central Anatolia region. The primary signs in this instance are weak structural development and secondary calcium carbonate illuviation, with a weathering ratio of silicon to aluminum larger than two in every profile (Tunçay et al., 2019). This investigation was carried out in Turkey's mountainous, humid regions. Four representative profiles were dug at various heights for this purpose. Four soils were transected between elevations of 1139 and 1809 meters, and soil samples were collected for geochemical analysis from each horizon. Pedogenic processes for climate across various elevations are compared using the Mineral Alteration Index (MIA), WIP, PIA, and CIA. Soil Taxonomic Classes were strongly impacted by climosequene characteristics. The findings indicate that as elevation increases, the rate of chemical weathering of the CIA, PIA, CIW, and MIA indicators decreases. On the other hand, the WIP value increased at higher altitudes. Thus, the region's elevation-dependent climatic factors were sufficiently effective to affect soil formation, and the elevation difference between the profiles has increased precipitation, leading to intense weathering and leaching. The main factors influencing weathering intensity are the availability and flux of water through the soil, which are also decisive factors and sufficient to distinguish the profiles. According to this research, climatic conditions had a considerable impact on soil qualities and processes (Alsalam et al., 2020).

3. Conclusions

This study has shown how different types of chemical weathering indices can be used to evaluate soil evolution as a function of climate according to their degree of weathering. Previous studies clearly indicate that climatic conditions are an essential factor in weathering since climate determines the weathering products of soil horizons. Water availability is a critical factor that controls chemical weathering processes. The speed of chemical reactions increases with increasing water availability. In other words, increased precipitation is linked to leaching processes and thus affects chemical weathering indicators.

According to previous results, the rate of chemical weathering of CIA, CIW, PIA, CPA and MIA indicators went up with ncreased rainfall leaching, leading to the formation of more developed soils. In contrast, WIP value increased in climates with less leaching and therefore less developed soils formed. The availability and flux of water through the soil are the prime factors in chemical weathering intensity, and they have a decisive role in profile differentiation and the formation of different types of soils. This study indicated that soil properties and processes were strongly related to water availability, which determines the leaching regime and chemical weathering rates. This shift in climate produced appreciable changes in different types of soils.

References

AlMomani, T., & Alqudah, M. (2020). Mineralogical and geochemical characterization of Jarash kaolinitic clay, northern Jordan. Jordan Journal of Earth & Environmental Sciences, 11(4), 272–281.

Al Shamary, S. H. K., Al Maamouri, D. S., Hassan, A. B., & Dwenee, S. J. (2022). Effects of climatic variation on weathering intensity for the mineral composition in some Iraqi soils. Caspian Journal of Environmental Sciences, 5, 991–1001.

AlShamare, A. H. D., & Essa, S. K. (2020). The effect of sedimentation sources on the exchange properties of the clay particles of some soils in Wasit and Maysan governorates. Plant Archives, 20(2), 566–573.

Alsalam, O., Isa, H. A., Al-Bayati, M. A. L. and Alserae, H. (2025). Topographic effect on the total oxides distribution of calcareous soils in northern Iraq. PJOAR 38: 162-74. doi:10.17582/journal.pjar/2025/38.2.162.174.

Alsalam, O., Şeker, C., & Dedeoğlu, M. (2020). Quantifying the role of chemical weathering rates on soil developed along an altitudinal transect in mountainous environments, Turkey. Eurasian Journal of Soil Science, 2, 140–150.

Aristizabal, E., Roser, B., & Yokota, S. (2005). Tropical chemical weathering of hillslope deposits and bedrock source in the Aburrá Valley, northern Colombian Andes. Engineering Geology, 81, 389–406.

Baumann, F., Schmidt, K., Dörfer, C., He, J.S., Scholten, T., & Kühn, P. (2014). Pedogenesis, permafrost, substrate and topography: Plot and landscape scale interrelations of weathering processes on the centraleastern Tibetan Plateau. Geoderma, 226, 300–316. https://doi.org/10.1016/j.geoderma.2014.02.016

Beyala, V. K. K., Onana, V. L., Priso, E. N. E., Parisot, J. C., & Ekodeck, G. E. (2009). Behaviour of rare earth elements and mass balance calculations in a lateritic profile over chlorite schist in South Cameroon. Chemie der Erde, 69, 61–73.

Buggle, B., Glaser, B., Hambach, U., Gerasimenko, N., & Marković, S. (2011). An evaluation of geochemical weathering indices in loess–paleosol studies. Quaternary International, 2, 12–21.

Cox, R., Lowe, D. R., & Cullers, R. L. (1995). The influence of sediment recycling and basement composition on evolution of mudrock chemistry in the southwestern United States. Geochimica et Cosmochimica Acta, 59, 2919–2940. https://doi.org/10.1016/00167037(95)001694

De Jayawardena, U., & Izawa, E. D. S. (1994). Application of present indices of chemical weathering for Precambrian metamorphic rocks in Sri Lanka. Bulletin of the International Association of Engineering Geology, 49, 55–61.

Dinis, P., Garzanti, E., Vermeesch, P., & Huvi, J. (2017). Climatic zonation and weathering control on sediment composition (Angola). Chemical Geology, 7, 110–121.

Dönmez, H. (2023). Applications of soil geochemistry in mineral exploration. ISERDAR, 1(1), 12–18. https://doi.org/10.5281/zenodo.10436738

Egli, M., Mirabella, A., Sartori, G., & Fitze, P. (2003). Weathering rates as a function of climate: results from a climosequence of the Val Genova (Trentino, Italian Alps). Geoderma, 111, 99–121.

Egli, M., Mirabella, A., Sartori, G., Zanelli, R., & Bischof, S. (2006). Effect of north and south exposure on weathering rates and clay mineral formation in Alpine soils. Catena, 67, 155–174.

ElHafez, N. A., Mousa, A., ElHariri, T., ElMoghny, M. A., & Sharaka, H. (2019). Mineralogical and geochemical studies on some early Miocene sediments of southwestern Sinai, Egypt. Jordan Journal of Earth & Environmental Sciences, 10(2), 64–74.

Fattah, M. A., & Karim, K. H. (2021). Performance of linear models in predicting cation exchange capacity of calcareous soils. Iraqi Journal of Agricultural Sciences, 52(6), 1489–1497.

Fayyadh, M. A., & Ismail, H. K. (2021). Genesis, development, and classification for some selected soils at Kurdistan region, north of Iraq. Iraqi Journal of Agricultural Sciences, 52(6), 1498–1507.

Fedo, C. M., Nesbitt, H. W., & Young, G. M. (1995). Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology, 23, 921–924. https://doi.org/10.1130/00917613(1995)023<0921:UTEOKM>2.3.CO;2

Gupta, A. S., & Rao, K. S. (2001). Weathering indices and their applicability for crystalline rocks. Bulletin of Engineering Geology and the Environment, 60, 201–221. https://doi.org/10.1007/s100640100100

Harnois, L. (1988). The CIW index: A new chemical index of weathering. Sedimentary Geology, 55, 319–322.

Harnois, L., & Moore, J. M. (1988). Geochemistry and origin of ore chemistry formation, a transported paleoregolith in the Grenville Province of southern Ontario, Canada. Chemical Geology, 69, 267–289.

Haskins, D. A. V. I. D. (2006). Chemical and mineralogical weathering indices as applied to a granite saprolite in South Africa. In The 10th IAEG International Congress, Nottingham, United Kingdom: Cosmogenic Nuclides, Geology, 7, 597–600.

Hill, I., Worden, R., & Meighan, I. (2000). Yttrium: The immobilitymobility transition during basaltic weathering. Geology, 28, 923–926.

Ilevbare, M., & Adeleye, R. A. (2023). Geochemical discriminant for provenance, source area weathering and paleoredox of some shale deposits in Edo State, Nigeria. Jordan Journal of Earth & Environmental Sciences, 14(4), 258–267.

Irfan, T. (1996). Mineralogy, fabric properties and classification of weathered granites in Hong Kong. Quarterly Journal of Engineering Geology and Hydrogeology, 1, 5–35.

Issa, S. K. (2022). Soil minerals. Ministry of Higher Education and Scientific Research, University House for Printing and Publishing.

Jimoh, R. O., Olatunji, A. S., Ajadi, J., & Afolabi, A. O. (2023). Mineralogy and geochemistry of berylbearing pegmatite dykes from Gbayo, southwestern Nigeria. Jordan Journal of Earth & Environmental Sciences, 14(2), 91–102.

Lawrence, C. R., Harden, J. W., Xu, X., Schulz, M. S., & Trumbore, S. E. (2015). Longterm controls on soil organic carbon with depth and time: a case study from the Cowlitz River Chronosequence, WA, USA. Geoderma, 247–248, 73–87. https://doi.org/10.1016/j.geoderma.2015.02.005 U.S. Geological Survey

Le Blond, J. S., Cuadros, J., Molla, Y. B., Berhanu, T., Umer, M., Baxter, P. J., & Davey, G. (2015). Weathering of the Ethiopian volcanic province: A new weathering index to characterize and compare soils. American Mineralogist, 100(11–12), 2518–2532. ResearchGate

Lybrand, R., Rasmussen, C., Jardine, A., Troch, P., & Chorover, J. (2011). The effects of climate and landscape position on chemical denudation and mineral transformation in the Santa Catalina Mountain Critical Zone Observatory. Applied Geochemistry, 26(Supplement), S80–S84. https://doi.org/10.1016/j.apgeochem.2011.03.036

Merkli, C., Sartori, G., Mirabella, A., Egli, M., Mancabell, A., & Plotze, M. (2009). The soils in the Brenta region: Chemical and mineralogical characteristics and their relation to landscape evolution. Studi Trentini di Scienze Naturali, 85, 7–22.

Moazallahi, M., & Farpoor, M. H. (2012). Soil genesis and clay mineralogy along the xericaridic climotoposequence in southcentral Iran. Journal of Agricultural Science & Technology, 14, 683–696. SDIOPR

Moshtaha, R., Romer, R. L., & Jarrar, G. H. (2025). Age, geochemistry, and petrogenetic constraints on Ediacaran granitoids, southwest Jordan. Jordan Journal of Earth & Environmental Sciences, 16(2), 117–135. Jordan Journal+1

Nesbitt, H. W., & Young, G. (1982). Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature, 299(5885), 715–717. Eurasian Journal of Soil Science

Nesbitt, H. W., & Young, G. M. (1989). Formation and diagenesis of weathering profiles. Journal of Geology, 97(2), 129–147. Eurasian Journal of Soil Science

Ng, C. W. W., Guan, P., & Shang, Y. J. (2001). Weathering mechanisms and indices of igneous rocks of Hong Kong. Quarterly Journal of Engineering Geology and Hydrogeology, 34(2), 133–151. Eurasian Journal of Soil Science

Osat, M., Heidari, A., Eghbal, M. K., & Mahmoodi, S. (2016). Impacts of topographic attributes on soil taxonomic classes and weathering indices in a hilly landscape in northern Iran. Geoderma, 281, 90–101.

Parker, A. (1970). An index of weathering for silicate rocks. Geological Magazine, 107(6), 501–504.

Razvanchy, H. A. S., & Fayyadh, M. A. (2023). Study of development and classification in Erbil province, Kurdistan, Iraq using mathematical indices. Iraqi Journal of Agricultural Sciences, 54(6), 1802–1813.

Roaldset, E. (1972). Mineralogy and geochemistry of Quaternary clays in the Numedal area, southern Norway. Norsk Geologisk Tidsskrift, 52, 335–369.

RochaFilho, P., Antunes, F. S., & Falco, M. F. G. (1985). Quantitative influence of the degree of weathering upon the mechanical properties of a young gneiss residual soil. In Proceedings of the First International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasília, 1, 281–294.

Ruxton, B. P. (1968). Measures of the degree of chemical weathering of rocks. Journal of Geology, 76, 518–527.

Saleh, A. M., Khudhair, M. F., & Ahmed, F. W. (2023). Identification of top soils with discriminant analysis in AlMaimouna project, Maysan, Iraq. International Journal of Agricultural and Statistical Sciences, 19(2), 657–668.

Shao, J., Yang, S., & Li, C. (2012). Chemical indices (CIA and WIP) as proxies for integrated chemical weathering in China: Inferences from analysis of fluvial sediments. Sedimentary Geology, 265, 110–120.

Silva, Y. J. A. B., Do Nascimento, C. W. A., Biondi, C. M., Van Straaten, P., de Souza Jr, V. S., & Ferreira, T. O. (2016). Weathering rates and carbon storage along a climosequence of soils developed from contrasting granites in northeast Brazil. Geoderma, 284, 1–12.

Sueoka, T., Lee, I. K., Huramatsu, M., & Imamura, S. (1985). Geomechanical properties and engineering classification for decomposed granite soils in Kaduna district, Nigeria. In First International Conference of Geomechanics in Tropical Lateritic and Saprolitic Soils, Brasília, 1, 175–186.

Tunçay, T., Dengiz, O., Bayramin, I., Kilic, S., & Baskan, O. (2019). Chemical weathering indices applied to soils developed on old lake sediments in a semiarid region of Turkey. Eurasian Journal of Soil Science, 1, 60–72.

Vogel, D. E. (1973). Precambrian weathering in acid metavolcanic rocks from the Superior Province, Villebon Township, southcentral Quebec. Canadian Journal of Earth Sciences, 12, 2080–2085.

Vogt, T. (1927). Sulitjelmefeltets geologi og petrografi. Norges Geologiske Undersøkelse, 121, 1–560.

Voicu, G., Bardoux, M., Jébrak, M., & Voicu, D. (1996). Normative mineralogical calculations for tropical weathering profiles. Winnipeg' '96, GAC/MAC Annual Meeting, Winnipeg, Canada, 27 May.

Yousefifard, M., Ayoubi, S., & Jalalian, A. (2012). Mass balance of major elements in relation to weathering in soils developed on igneous rocks in a semi-arid region, northwestern Iran. Agricultural Science, 9, 41–58.

Zhang, G. L., Pan, J. H., Huang, C. M., & Gong, Z. T. (2007). Geochemical features of a soil chronosequence developed on basalt in Hainan Island, China. Revista Mexicana de Ciencias Geológicas, 24(2), 261–269.

Zhou, X., Li, A., Jiang, F., & Lu, J. (2015). Effects of grain size distribution on mineralogical and chemical compositions: A case study from sizefractional sediments of the Huanghe (Yellow River) and Changjiang (Yangtze River). Geological Journal, 50(4), 414–433.