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Innovations in Soil Fertilization and the Role of Remineralizers

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Inovações na Fertilização do Solo e o Papel dos Remineralizadores.

RESUMO

Objetivo – Revisar o papel dos remineralizadores de solo (REM) na fertilidade de solos tropicais, com foco na CTC, no carbono orgânico e no potencial de mitigação ambiental.

Metodologia – Revisão bibliográfica em bases científicas (Web of Science e Google Acadêmico), com seleção de estudos sobre REM, CTC e dinâmica do carbono.

Originalidade/relevância – O estudo aborda lacunas sobre a geração de cargas e a estabilidade do carbono em solos tropicais com REM, destacando sua relevância para a agricultura sustentável.

Resultados – Os REM aumentam a CTC, melhoram a disponibilidade de nutrientes e contribuem para a estabilização do carbono no solo.

Contribuições teóricas/metodológicas – Avanço na compreensão dos processos de biointemperismo e da interação entre minerais e matéria orgânica no solo.

Contribuições sociais e ambientais – Redução da dependência de insumos químicos, incentivo à rochagem e mitigação de impactos ambientais.

PALAVRAS-CHAVE: Sustentabilidade agrícola. Manejo de Solos. Pó-de-rocha

Innovations in Soil Fertilization and the Role of Remineralizers.

ABSTRACT

Objective – To review the role of soil remineralizers (REM) in tropical soil fertility, focusing on CEC, organic carbon, and environmental mitigation potential.

Methodology – Literature review using scientific databases (Web of Science and Google Scholar), selecting studies on REM, CEC, and carbon dynamics.

Originality/relevance – The study addresses gaps in understanding charge generation and carbon stability in tropical soils amended with REM, highlighting its relevance for sustainable agriculture.

Results – REM increase CEC, improve nutrient availability, and contribute to carbon stabilization in soils.

Theoretical/methodological contributions – Advances in the understanding of bioweathering and mineral–organic matter interactions in soils.

Social and environmental contributions – Reduction in dependence on chemical inputs, promotion of rock-based agriculture, and mitigation of environmental impacts.

KEYWORDS: Agricultural sustainability. Soil management. Rock powder

Innovaciones en la fertilización del suelo y el papel de los remineralizantes.

RESUMEN

Objetivo – Revisar el papel de los remineralizadores del suelo (REM) en la fertilidad de suelos tropicales, con énfasis en la CTC, el carbono orgánico y el potencial de mitigación ambiental.

Metodología – Revisión bibliográfica en bases científicas (Web of Science y Google Académico), seleccionando estudios sobre REM, CTC y dinámica del carbono.

Originalidad/relevancia – El estudio aborda vacíos sobre la generación de cargas y la estabilidad del carbono en suelos tropicales con REM, destacando su relevancia para la agricultura sostenible.

Resultados – Los REM aumentan la CTC, mejoran la disponibilidad de nutrientes y contribuyen a la estabilización del carbono en el suelo.

Contribuciones teóricas/metodológicas – Avances en la comprensión del bioweathering y de la interacción entre minerales y materia orgánica en el suelo.

Contribuciones sociales y ambientales – Reducción de la dependencia de insumos químicos, fomento de la remineralización y mitigación de impactos ambientales.

PALABRAS-CLAVE: Sostenibilidad agrícola. Manejo de suelos. Polvo de roca

1 INTRODUCTION

1.1 TRADITIONALIST AGRICULTURAL PRACTICES AND THEIR ENVIRONMENTAL AND ECONOMIC IMPACTS

Agriculture has played a central role in the development of civilization, adapting over time to meet growing population demands. Initially, soil fertilization techniques involved organic materials such as ash and animal bones, reflecting an ecological understanding of nutrient recycling in a sustainable manner (Ciceri, 2015). However, the Green Revolution brought a profound transformation with the introduction of synthetic fertilizers, driven by the synthesis of ammonia by the Haber-Bosch process, significantly increasing agricultural productivity, especially after the Second World War and from the 1950s onwards (Heffer & Prudd'homme, 2013).

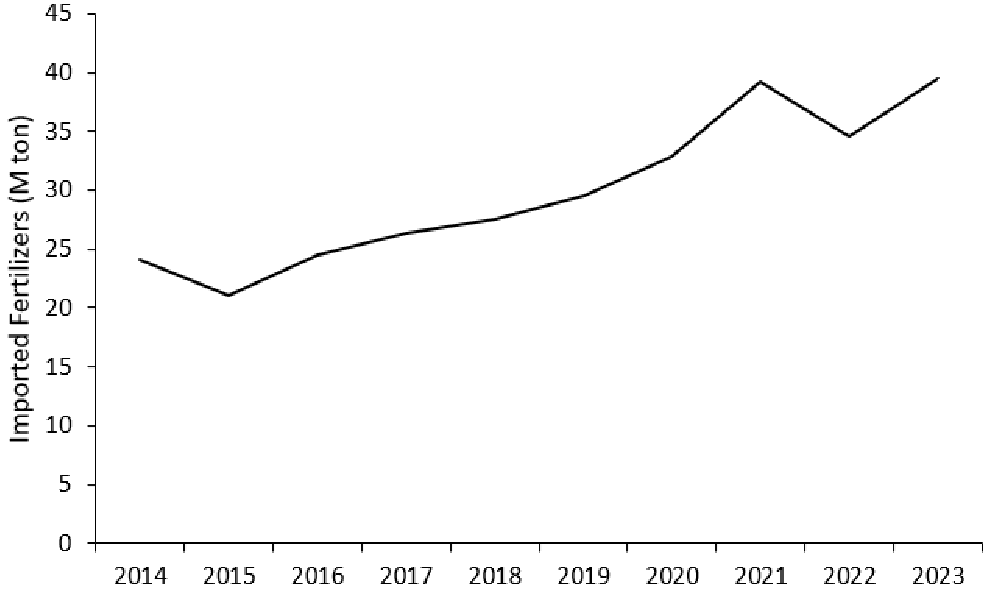
Although the intensive application of synthetic fertilizers has resulted in significant productivity gains, their unrestricted adoption has brought significant environmental and economic challenges. Figure 1 shows the evolution of soluble fertilizer imports in Brazil. The dependence on these inputs led to the import of approximately 85% of the fertilizers consumed in the country in 2023, totaling almost 40 million tons (ANDA, 2024). In addition, the excessive use of soluble fertilizers, conventional agriculture and extensive livestock farming contributed to the degradation of soil organic matter, acidification, nutrient leaching, and greenhouse gas emissions (Buss et al., 2024; Glorieux & Delmelle, 2022; Lopes et al.,2013). Intensive monoculture, largely sustained using these fertilizers, has also resulted in soil compaction and a reduction in microbial biodiversity, impacting soil fertility and resilience in the medium and long term (Derpsch, et al., 2024).

In this scenario, soil remineralization emerges as a promising alternative to reduce dependence on imported inputs and mitigate the environmental impacts of conventional agriculture. **Soil remineralizers (REM)** are mineral inputs derived from silicate rocks that have undergone only mechanical crushing and grinding processes, without significant chemical or thermal changes, and whose application aims to improve the chemical, physical, and biological properties of the soil (Martins et al., 2023). Unlike synthetic fertilizers, which provide nutrients immediately and in a highly soluble form, REM release nutrients gradually, favoring efficient absorption by plants and reducing losses due to leaching.

In addition to direct agronomic benefits, REMs play a fundamental role in stabilizing soil organic matter and increasing cation exchange capacity (CEC), positively impacting water retention and the availability of nutrients essential for plant development (Crusciol et al., 2022). Studies indicate that the application of these inputs can contribute to the formation of new mineral phases with high surface charge, promoting greater interaction between the mineral fraction and organic matter, which enhances carbon fixation in the soil (Santos et al., 2021). Thus, the strategic use of remineralizers not only improves soil fertility but also acts as a carbon sequestration mechanism, contributing to the mitigation of climate change.

Dependence on synthetic fertilizers represents one of the greatest challenges for Brazilian agricultural sovereignty, since inputs such as potassium chloride (KCl) and phosphates are largely imported from countries such as Russia, Canada and Morocco (Al Rawashdeh, 2020). International market volatility and geopolitical risks make this dependence a factor of economic vulnerability, directly impacting agricultural production costs.

Figure 1 - Evolution of imports of industrial fertilizers (in megatons) in Brazil in the decade 2014-2023



Source: (ANDA, 2024).

In this context, the use of **local and regional inputs** for soil fertility management emerges as a viable and sustainable alternative. Brazil has a vast geological diversity that allows the use of silicate rocks as regional sources of essential nutrients. Unlike conventional fertilizers, which are highly soluble and subject to losses through leaching, remineralizers present a gradual dissolution, allowing a continuous supply of elements such as calcium (Ca), magnesium (Mg), potassium (K) and silicon (Si), which are essential for plant growth and the improvement of the soil's physical and chemical properties (Martins et al., 2023).

Regional inputs include a variety of geological materials with agricultural potential, such as basalts, biotite syenites, biotite schists, and phonolites, which have significant levels of nutrients and high chemical and biological reactivity. Studies indicate that the minerals present in these remineralizers interact with soil biota, favoring biological weathering processes and stimulating the gradual release of nutrients over time (Swoboda et al., 2022). In addition, the use of these inputs reduces the carbon footprint associated with the transportation of imported fertilizers, strengthening local production chains and promoting the circular economy in agriculture.

The adoption of REM in tropical soils, such as highly weathered Latossolos, represents a unique opportunity to improve soil fertility in a sustainable manner. Studies show that the application of remineralizers can modify the proportion of variable and permanent loads in the soil, increasing CEC and providing greater efficiency in nutrient retention (Santos et al., 2021). In addition, the interaction between fresh minerals and the rhizosphere of plants stimulates beneficial microbial activity, creating a virtuous cycle of improving soil quality and increasing agricultural productivity (Bhattacharyya & Furtak, 2022).

The transition to a soil fertility management model incorporates remineralizers, a reassessment of harmful agricultural practices, and the adoption of more integrated and regional approaches. The process begins with bioweathering, in which primary minerals (originally from the rock) are transformed by biological action into new minerals (Krahl et al., 2022). These minerals, often in transition phases, have characteristics such as hydration, amorphous structure, and nature, requiring a higher CEC and specific surface area (SSE) compared to primary minerals. Thus, in addition to gradually providing essential nutrients, remineralizers stimulate weathering and bioweathering processes, favoring the formation of new mineral phases with high surface charge and improving soil CEC (Santos et al., 2021). Rapid leaching reduces their efficiency and contributes to negative environmental impacts (Martins et al., 2023). Therefore, for better results in the chemical attributes of soils treated with REM, biological activity is essential (Martins et al., 2023). The action of remineralizers goes beyond the gradual supply of nutrients, being directly linked to edaphoclimatic conditions and soil microbiota. Microorganisms, such as fungi and bacteria, intensify bioweathering, promoting the release of essential elements and favoring the retention of cations, chemical buffering, and mitigation of acidification and excessive leaching (Uroz et al., 2009). In addition, silicate-rich remineralizers can stabilize organic carbon by forming organo-mineral associations, contributing to carbon sequestration and improving soil structure (Zinn et al., 2005). Therefore, their use should not be seen only as an alternative to soluble fertilizers, but as an integrated strategy for agricultural sustainability, promoting soil biodiversity and synergy between minerals and microorganisms. Combined with practices such as crop rotation and the addition of organic matter, REM can strengthen more resilient agricultural systems (Ramos et al., 2022).

The implementation of these inputs must be guided by solid scientific criteria, considering the chemical and mineralogical composition of the remineralizers, as well as their granulometry and reactivity. Studies indicate that ground silicate rocks, such as basalts, biotite syenites and phonolites, can increase the availability of potassium and other essential nutrients without the adverse effects associated with synthetic fertilizers (Crusciol et al., 2022; Luchese et al. 2023). In addition, the use of these inputs has shown potential to stabilize soil organic carbon, helping to mitigate CO_2 emissions and build agricultural systems that are more resilient to climate change (Swoboda et al., 2022).

The adoption of REMs should be integrated with other sustainable practices, such as crop rotation, no-till systems, and the use of organic fertilizers, favoring the synergy between minerals, organic matter, and soil microbiota. The interaction between REMs and soil biota plays a fundamental role in the availability of nutrients, since the bioweathering process promoted by the rhizosphere accelerates the dissolution of minerals and the release of essential elements to plants (Krahl et al., 2022). Thus, efficient management must consider not only the chemical composition of the inputs, but also the biological and physical conditions of the soil, ensuring its full functionality over time.

In addition to the agronomic and environmental benefits, the valorization of regional inputs contributes to reducing dependence on imported fertilizers, strengthening the autonomy of producers and promoting an agricultural model that is less vulnerable to fluctuations in the international market (Manning & Theodoro, 2020). With the regulation of REM by the Ministry of Agriculture and Livestock (Brazil, 2016) and the growing acceptance of these inputs among farmers, Brazil is positioning itself as a global reference in the implementation of agricultural practices based on soil remineralization (Martins et al., 2024).

Thus, the strategic use of REM can represent a new paradigm in Brazilian agriculture, promoting greater efficiency in the use of regional resources and ensuring the sustainability of agricultural production in the long term. By integrating geochemical, mineralogical and biological knowledge on soil remineralization, this article seeks to contribute to the understanding of the mechanisms of action of these inputs and their practical application in the construction of more productive and resilient agricultural systems.

1.2 OBJECTIVES

This article aims to investigate, through a literature review, the importance of using soil remineralizers (SRM) in agriculture, their impacts on sustainable production and the capacity of these materials to promote regenerative agriculture. The study aims to connect information on fertility, cation exchange capacity (CEC) and organic carbon stabilization in soils treated with SRM, in addition to the potential to mitigate greenhouse gas emissions, especially in the context of tropical agriculture.

2. METHODOLOGY

To achieve the proposed objectives, a comprehensive literature review was carried out, consulting the Web of Science and Google Scholar databases. Studies that address the relationship between soil minerals and cation exchange capacity (CEC) were selected, as well as the influence of REM on this process. The focus of the analysis included changes in soil CEC because of REM, which affects the retention of essential nutrients such as calcium, magnesium, and potassium in the exchange complex (Santos et al., 2021; Krahl et al., 2022; Medeiros et al., 2023). In addition, studies that discuss the stabilization of soil organic carbon and the role of REM in mitigating greenhouse gas emissions were included in the review. To assess soil organic carbon (SOC) and its stabilization, articles that investigated the dynamics of SOC in relation to low-crystalline minerals and iron and aluminum oxides, in addition to the interaction between organic matter and soil minerals, were analyzed. The selection criteria included the methodology for adsorption and desorption of dissolved organic carbon (DOC) and field experiments that addressed COS stabilization under different management conditions and soil types. The selection of studies considered the depth of analysis, the suitability of experimental techniques and the relevance of the conclusions to understand the impacts of remineralizers on COS stabilization. The analysis will also include a discussion on how these practices can transform tropical soil management, providing more resilient agriculture adapted to global climate change (Bottoni et al. 2024).

3. RESULTS

3.1 CATION EXCHANGE CAPACITY

CEC is a fundamental measurement that indicates the soil's ability to retain and exchange cations, which are ions, such as potassium, or positively charged molecules, such as ammonium, and are essential for plant nutrition. Soils with a high CEC can retain a greater amount of cationic nutrients and are therefore more fertile and better able to support plant growth. CEC is influenced by the amount and type of clay and organic matter present, as well as soil pH (Sposito, 2008).

The charges in the soil, which form the CEC, can be divided into two main categories: permanent charges and variable charges. Permanent charges are generally associated with the crystal structure of clay minerals, where isomorphic substitutions and broken edges occur in the minerals that result in an imbalance of electrical charges. On the other hand, variable charges arise due to the adsorption or release of H^+ and OH^- ions on the surfaces of clay minerals and organic matter and are highly dependent on the pH of the medium (Parks & Bruyn, 1962; Sposito, 1984).

The formation of electrical charges in soils, therefore, results mainly from two distinct mechanisms, which involve a combination of chemical and physical factors of the mineral surfaces. First, there is the isomorphic substitution of high-valence ions for lower-valence ions in the structural layers of secondary minerals. For example, the substitution of Si4+ for Al3+ in siloxane groups generates structural (permanent) electrical charges, known as σp (Bollan et al., 1999; Fontes et al., 2001; Sposito, 2008). This process gives the surfaces a net negative charge, which facilitates the electrostatic attraction of metal cations. In addition, the variation in the pH of the environment promotes the formation of variable electrical charges through the protonation or deprotonation of hydroxyl groups (OH-) on the mineral surfaces. Metal oxides and crystallite edges of phyllosilicates are frequently involved in this type of charge, known as σH. As pH decreases, the protonation of functional groups presents on the surface of minerals and in soil organic matter, such as hydroxyls in iron and aluminum oxides, and carboxylic and phenolic groups in organic matter, increases the net positive charge of the system. This process favors the retention of anions, such as phosphates, sulfates and organic acids, through electrostatic interactions and specific bonds (Sposito, 2008; Mikutta et al., 2007). In addition, these charges influence the adsorption and stabilization of organic molecules, modulating their mobility in the soil profile and impacting processes such as carbon retention and the availability of essential nutrients for plants.

Organomineral adsorption mechanisms, influenced by mineral surface chemistry, can be grouped into different categories according to the charge present on mineral surfaces. Surfaces with variable charges, such as iron and aluminum oxides, can interact with organic matter through both positive and negative charges, depending on the pH and composition of the soil solution (Schneider et al., 2010). For example, in acidic soils, amorphous aluminum hydroxides present a positive charge, favoring the adsorption of anionic organic products, such as carboxylic and phenolic acids, through electrostatic interactions and ligand exchange bonds (Mikutta et al., 2007). In addition, mineral surfaces can certainly stabilize organic matter by reducing its microbial destruction, making organic compounds less accessible to degradative enzymes (Newcomb et al., 2017). On the other hand, negatively charged mineral surfaces, such as those of phyllosilicates, also play a fundamental role in the stabilization of organic matter. Studies indicate that negative charges can promote the retention of organic molecules through cationic interactions and protective bridges, in addition to specific interactions between functional groups of organic matter and reactive sites on the mineral surface (Newcomb et al., 2017). These mechanisms reinforce the idea that the stabilization of organic matter does not occur exclusively through adsorption to negative charges, but results from a complex balance between different types of chemical and physical interactions at the organomineral interface.

The presence of isomorphic substitution in many phyllosilicates generates surfaces with permanent negative charges, while the absence of this substitution in other minerals, such as some 2:1 phyllosilicates and minerals from the kaolinite group, results in electrostatically neutral surfaces. 2:1 phyllosilicates, such as smectites, vermiculites and illites, have a crystal structure composed of two tetrahedral layers of silicon intercalated by an octahedral layer of aluminum or magnesium, giving them high cation exchange capacity and variable expandability (Theng, 2018), in addition to isomorphic substitution in the octahedral and tetrahedral layer, which generates permanent charges in the soil. On the other hand, minerals from the kaolinite group, such as kaolinite and halloysite, have a 1:1 crystal structure, characterized by the repetition of a single tetrahedral layer of silicon combined with an octahedral layer of aluminum. This structural configuration results in a lower incidence of isomorphic substitutions, which, in turn, reduces the presence of permanent charges on the surface of these minerals (Souza Junior et al., 2007; Pereira et al., 2021). Therefore, kaolin group minerals have electrically neutral surfaces and low cation exchange capacity, becoming less reactive for the adsorption of ions and organic molecules when compared to 2:1 type phyllosilicates.

Although negative charges are traditionally associated with the stabilization of soil organic matter, studies show that positive charges also play a crucial role in this process. In acidic soils, minerals such as iron oxides (goethite, hematite) and aluminum (gibbsite) have positive charges due to the protonation of their hydroxyl groups, favoring electrostatic interactions with negatively charged organic compounds, such as carboxylic and phenolic acids (Schneider et al., 2010). Furthermore, the stabilization of organic matter occurs through mechanisms other than electrostatic interactions, including the formation of covalent complexes between organic functional groups and mineral surfaces. The binding of phosphates, for example, can directly compete with the adsorption of organic matter, influencing its stabilization and availability in the soil (Spohn et al., 2021).

The interaction between phosphorus and soil minerals has fundamental implications for the dynamics of fertility and stability of organic matter. Phosphorus can form strong covalent bonds with iron and aluminum oxides, reducing its availability to plants, while also influencing the adsorption and release of dissolved organic matter. Studies show that the addition of phosphate to soil can cause the destabilization of previously adsorbed organic matter, increase the concentration of dissolved organic carbon and enhance its mineralization. This phenomenon is particularly relevant in highly weathered soils, such as Latossolos, where competition between phosphorus and organic compounds for adsorption sites on minerals can significantly alter soil carbon sequestration processes (Spohn et al., 2021).

Furthermore, understanding these interactions is crucial to assess the dynamics of minerals in remineralizers and their effects on soil surface charge and CEC, which are determining factors for the reactivity and stability of organic compounds. Studies show that the permanent charge of primary minerals, such as feldspars, varies according to their composition and crystal structure (Kleber et al., 2021). Secondary minerals, such as 2:1 expansive clay, have a higher CEC due to the presence of permanent negative charges associated with isomorphic substitutions. Vermiculite and montmorillonite, for example, have a high permanent charge, while kaolinite, with a low CEC, has only variable charges (Churchman & Lowe, 2012). Iron and aluminum oxides, such as goethite and gibbsite, have a low CEC, but form strong bonds with organic matter and phosphorus, modulating the availability of these elements in the soil (Table 1).

The potential of remineralizers such as Syenite and others can contribute to the generation of new charges in the mineral fraction of the soil, increasing its cation retention capacity and mitigating these losses (Martins et al, 2023).

Table 1 - Cation Exchange Capacity (CEC) and Specific Surface Area (SSA) Parameters of Clay Minerals

Minerals	Type	σp (mmol$_c$ kg^{-1})	σH (mmol$_c$ kg^{-1})	CTC (mmol$_c$ kg^{-1})	SSA (m^2 g^{-1})
Caulinita	1:1	-	20 (1)	0 a 80 (2)	7 a 80 (1)
Gibbsita	1:1	-	20 (1)	pH dependent (2)	1 a 100 (1)
Goethita	1:1	-	0 a 150 (1)	pH dependent (2)	40 a 90 (1)
Vermiculita	2:1	140 (4)	180 a 220 (4)	1200 a 1500 (2)	600 a 800 (2)
Montmorilonita	2:1	700 (3)	110 (3)	800 a 1200 (2)	650 a 800 (2)
Illita	2:1	105 (3)	40 a 120 (3)	100 a 400 (2)	20 a 200 (1)
Alofana	amorphous	-	0 a 1000 (1)	pH dependent (2)	700 a 900 (1)

(1) Kleber et al., (2021); (2) Churchman and Lowe (2012); (3) Anderson and Sposito (1991); (4) Barshad (1948); (-) undefined

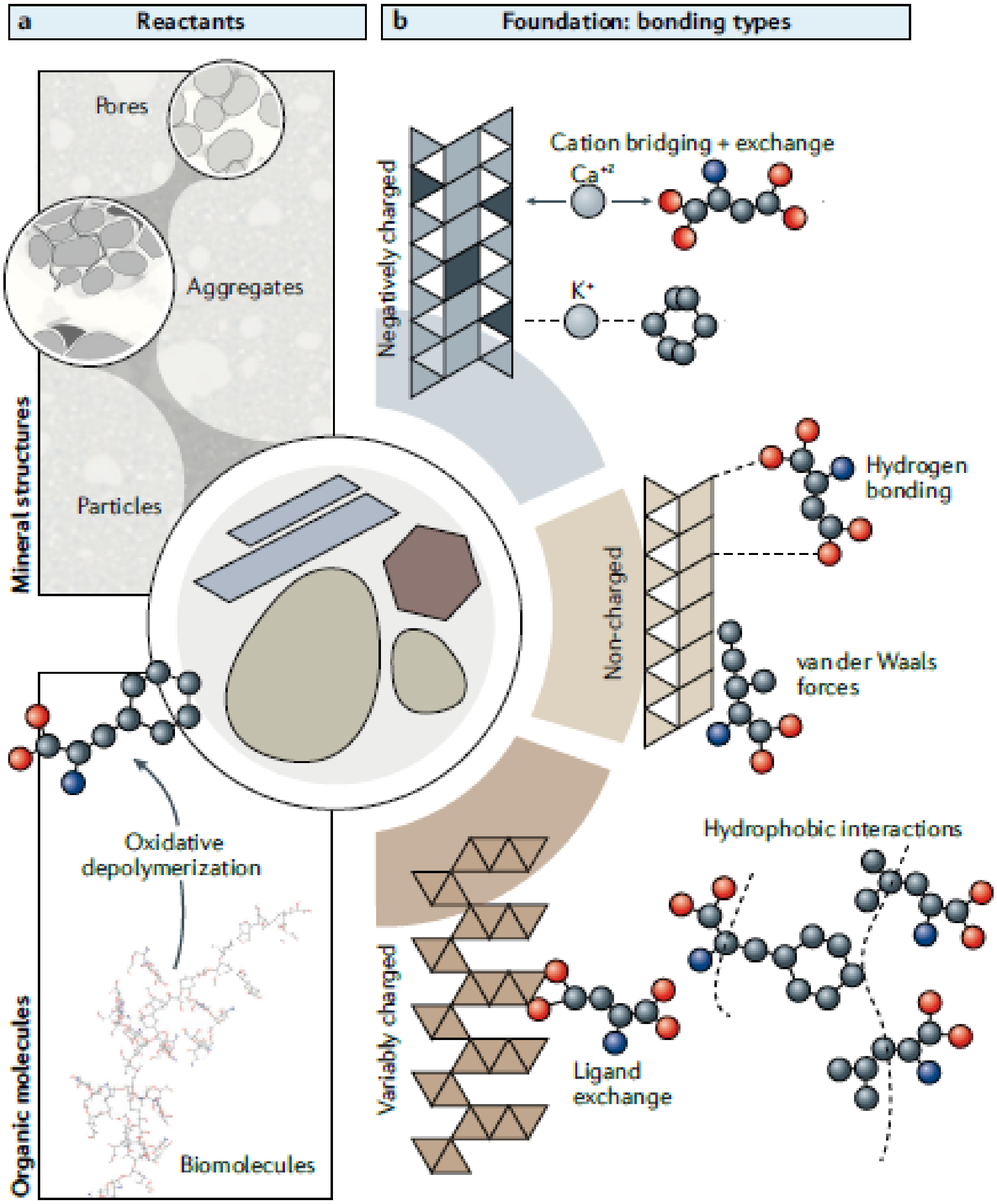
Furthermore, cesium (Cs^+) adsorption has been used as a method to quantify permanent charges in soils, allowing the estimation of mineral reactivity under different soil and climate conditions. Studies report permanent charge values ranging from 5.0 to 65.6 mmol$_c$ kg^{-1} in

Latossolos and Argisolos, evidencing mineralogical heterogeneity and its implications for soil fertility (Weber et al., 2005; Busato et al., 2012; Cunha et al., 2014).

In this context, the loss of nutrients by leaching to deeper layers of the soil that occurs is because highly weathered soils, such as Latossolos, are due to the fact that they have low base saturation due to the predominance of variable charges from aluminum and iron oxides, which favors the mobility of essential nutrients, such as calcium, magnesium and potassium, especially under conditions of high variations (Weber 2005; Santos et al., 2018).

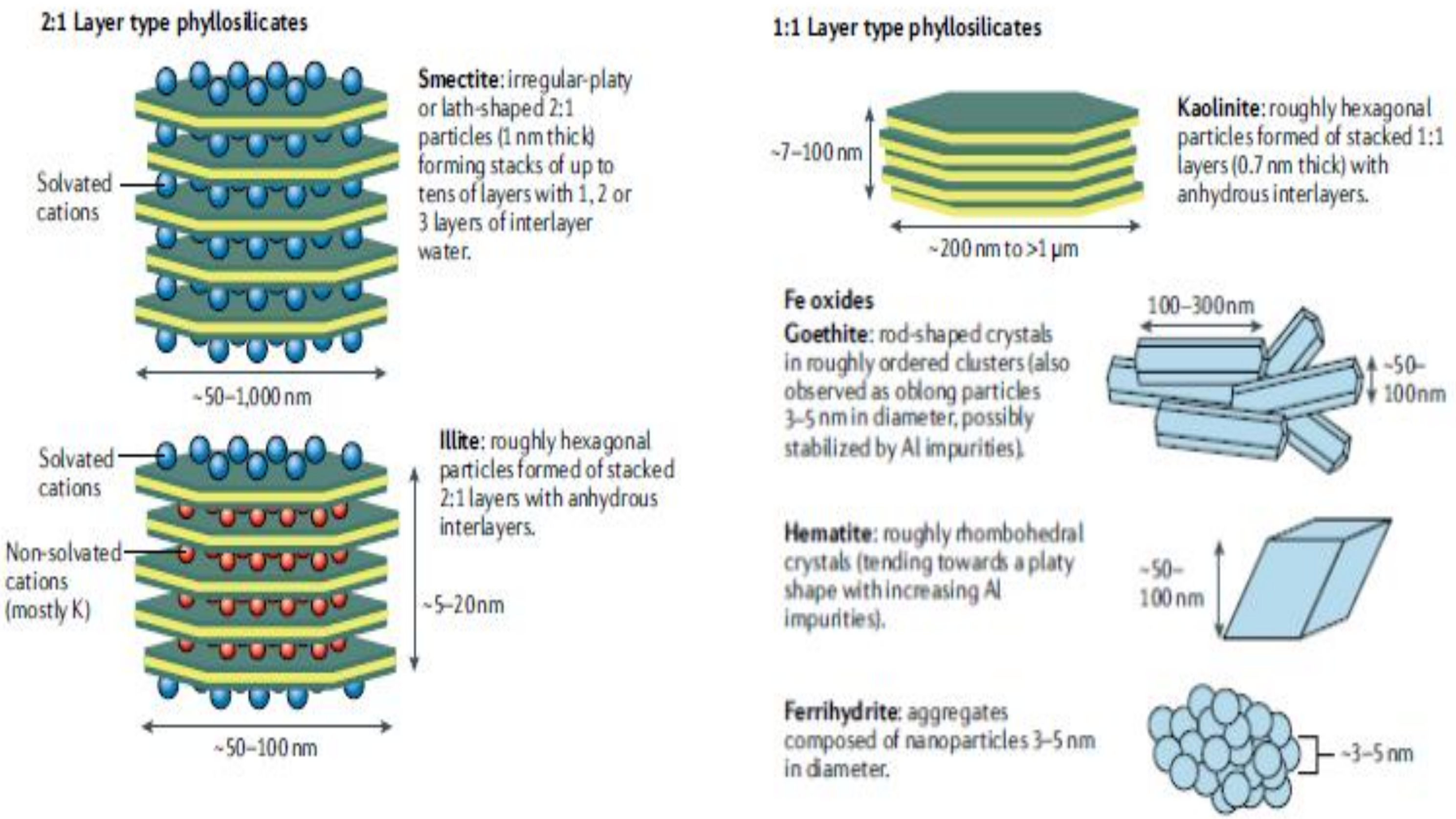
The Latossolos of the Cerrado biome are known for their low natural fertility, limited cation exchange capacity (CEC) and high acidity. These characteristics are mainly due to the mineralogy of the soils, with emphasis on the 1:1 layer minerals, such as goethite, hematite and gibbsite , iron and aluminum oxides formed by intense chemical weathering in tropical conditions (Fontes et al., 2001; Alleoni et al., 2009). These minerals have few available cation exchange sites, resulting in a reduced CEC. The high contribution of organic matter, favored by the high temperatures and humidity of the Cerrado, contributes to the reduction of its contribution to the CEC (Sposito, 2008). Studies such as that of Tan and Dowling (1984), who removed organic matter using hydrogen peroxide, demonstrated that this removal caused a significant reduction in CEC, evidencing the importance of charges associated with organic active groups in cation retention (Figures 2 and 3). The residual CEC after removal of organic matter was mainly associated with permanent charges of mineral clays, such as kaolinite and iron and aluminum oxides, confirming the limited nutrient retention capacity of these soils. In this context, the mineralogy of Latossolos, particularly the 1:1 layer minerals, plays a crucial role in determining fertility and the absorption capacity of nutrients such as phosphorus (Essington, 2003; Uehara and Gillman, 1980). Management strategies, such as the application of limestone and the preservation of organic matter, are essential to improve fertility and increase the productivity of these soils (Reatto and Martins, 2005; Wilcke and Lilienfein, 2005).

Figure 2: Organic ligands at mineral interfaces.



a) Mineral interfaces arise at a variety of spatial and topographic scales in soils and sediments, where low molecular weight amphiphilic organic ligands can reach the solid-solution interface. b) Once in proximity, ligands can adhere to mineral surfaces through one or several complexation mechanisms, based on permanent and variable surface charge distribution and structural reactivity (Kleber et al., 2021)

Figura 3 - Estrutura geométricas de argilominerais encontrados nos solo



Fonte: Kleber et al.,2021.

The application of finely ground biotite syenite in a Cerrado Latossolo resulted in increased levels of available phosphorus and potential phosphorus, in addition to increased permanent charges, favoring corn nutrition (Santos et al., 2021). Permanent charges, in turn, are intrinsic to the mineral structure and do not vary with environmental conditions (Cunha et al., 2014), while pH-dependent charges directly influence the cation exchange capacity (CEC), affecting nutrient retention according to pH, clay content, and soil organic matter (Bortoluzzi et al., 2005). Thus, the interaction between mineralogy, organic matter, and management practices, such as calculation and remineralization, is essential to optimize the fertility of Cerrado Latossolos.

3.2 REMINERALIZERS AND THE RELATIONSHIP WITH CTC

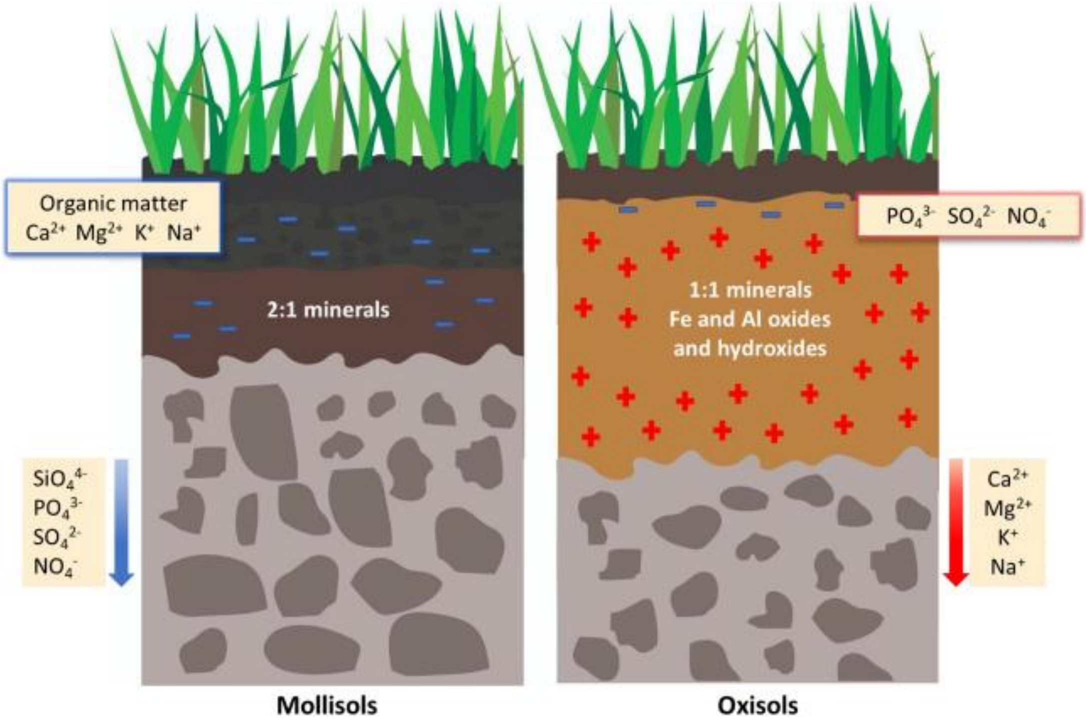
Soil remineralizers (REM), as defined by Brazilian legislation (Law No. 12,890, 2013), are mechanically ground mineral materials that have great potential to improve the cation exchange capacity (CEC) of soils, promoting greater nutrient retention and making agriculture more sustainable by reducing dependence on soluble fertilizers (Hinsinger et al., 2001; Bakken et al., 2000; Duarte et al., 2013). The effectiveness of REM on soil fertility is directly related to its mineralogy and the formation of new mineral phases over time. The rock grinding process reduces particle size, exposing new reactive surfaces and increasing the specific surface area (SSA). This expansion favors the interaction between minerals and the soil solution, intensifying chemical weathering reactions and promoting the gradual release of essential nutrients.

The rhizosphere plays a fundamental role in this process, since the exudation of organic compounds by the roots and microbial activity alter the chemical dynamics around the REM particles. Organic acids, such as citric acid and oxalic acid, are released by the roots and act to dissolve primary minerals, complexing cations and mobilizing nutrients such as potassium, calcium and magnesium (Taiz and Zeiger, 2013). In addition, the preservation of organic matter in the soil generates CO_2, which, when reacting with soil water, forms carbonic acid, promoting the weathering of the REM minerals and facilitating the progressive release of essential elements. As weathering progresses, the primary minerals of the REM undergo structural and chemical transformations, leading to the neoformation of secondary minerals, such as vermiculite and hydrobiotite. These minerals have permanent charges and are directly related to the increase in the soil CEC. Furthermore, the formation of amorphous and low-crystalline minerals confers greater chemical reactivity to the system, improving cation retention and providing improvements in the soil's physical-chemical attributes (Krahl et al., 2022).

The mineralogy of Latossolos, characterized predominantly by 1:1 layer minerals, plays a crucial role in the nutrient retention capacity (Figure 4). Due to the predominance of kaolinite and iron and aluminum oxides, these soils have a naturally low CEC and high susceptibility to leaching of essential cations. Management strategies, such as the application of limestone and the preservation of organic matter, are essential to improve their fertility and productivity (Essington, 2003; Uehara and Gillman, 1980; Reatto and Martins, 2005; Wilcke and Lilienfein, 2005).

In this context, the use of REM can complement these strategies by providing essential minerals that replenish nutrient stocks depleted over time. By gradually releasing cations such as potassium, calcium, and magnesium, remineralizers increase the availability of these elements in the soil, reducing leaching losses and favoring the maintenance of nutrients in the mineral fraction. This effect is particularly relevant in highly weathered tropical soils, where low CEC and rapid cation removal pose a challenge to soil fertility (Manning & Theodoro, 2020; Krahl et al., 2022; Martins et al., 2023). Thus, the application of remineralizers can contribute to more efficient soil fertility management by providing a gradual supply of nutrients and promoting the chemical stability of the agricultural system over time.

Figure 4 - Main characteristics of agricultural soils in temperate (Mollisols - Chernossolos) and tropical (Latossolos) climates.



Source: Krahl et al., 2022.

The influence of different rates of biotite-syenite in a Red-Yellow Latossolo in a greenhouse was verified and it was found that, without the addition of remineralizer, variable loads predominated, composing 20 $mmol_c\ kg^{-1}$ of soil while permanent loads were 5 $mmol_c\ kg^{-1}$ of soil (Santos et al., 2021). These surface load values are like those found in other studies that also used the Cs^+ adsorption method to quantify these loads in Latossolos (Busato et al., 2012; Weber et al., 2005). The addition of remineralizer significantly increased permanent loads at the highest rate used (2.4 ton ha^{-1}), remaining high after the first corn cultivation cycle, without altering variable loads (Santos et al., 2021). This increase can be explained by the grinding of the rock, which increases the surface area of the minerals, and by the biochemical action of the rhizosphere, which releases ions and forms new minerals with permanent charges (equation 1). Although the dissolution of the remineralizer is slow and does not significantly alter the total contents of $Fe^{2+}/^{3+}$ and Al^{3+} in the soil, the soluble fractions of these elements may increase when verified by chemical extractors. This mobilization may depend on the availability of nutrients and the formation of new compounds in the soil. In addition, the presence of 2:1 and 1:1 clay minerals may increase negative charges, contributing to the retention of cations and detrimental to leaching losses. However, due to the low rates applied, the mineral transformations promoted by remineralizers may occur in situations below the detection and determination limit of direct instrumental techniques, such as X-ray diffractometry (XRD), which generally detects only mineral phases present above 1% by mass (König et al., 2002). Thus, the characterization of the influence of remineralizers on soil requires indirect approaches, such as the determination of cation exchange capacity (CEC), the evaluation of soil pH, the analysis of the mineralogy of the surface horizon and the monitoring of the dynamics of nutrients, such as phosphorus and potential. These methodologies allow a more detailed understanding of the effects of the application of remineralizers in the long term, even when the mineral transformations are subtle and not directly detectable by conventional techniques.

However, a greenhouse experiment with successive corn cycles and different rates of remineralizers mixed with sand investigated the release of elements and the formation of new minerals by bioweathering in the rhizosphere, using basaltic rocks, biotite schist and biotite syenite. The results showed that the ground rocks provide nutrients to plants, with elements such as K, Ca, Mg and others present in the dry matter. XRD analysis indicated that basalt maintained its mineralogy, while the weathering of biotite resulted in the formation of hydrobiotite, being more pronounced in biotite schist, which also showed greater dry matter production and nutrient accumulation. The CEC increased significantly in biotite schist, which is particularly relevant for tropical soils with low cation retention. According to equation 1, weathering of biotite can lead to the formation of vermiculite, a mineral with high CEC and ASE (Acker & Bricker 1991; Holgersson et al., 2024; Krahl et al., 2022).

$$2KMg_3FeAlSi_3O_{10}(OH)_2(s)\ (\text{biotita}) + 8H_2O(aq) \rightarrow Mg_3Fe_2Al_2Si_2O_{10}(OH)_2^{2-}\ (\text{vermiculite})\ (s) + 2K^+(aq) + 4H_4SiO_4(aq) + 3Mg(OH)_2(aq)$$

Equation 1 - Biotite to vermiculite transformation reaction in the presence of water: This equation describes the chemical reaction where biotite (a silicate mineral) reacts with water to form vermiculite, potassium ions, silicic acid and magnesium hydroxide.

These results reinforce the potential of REM, especially those rich in biotite, in improving the fertility of tropical soils, as demonstrated by increased CEC and higher biomass production. The formation of new minerals, such as hydrobiotite, indicates that plant-induced bioweathering not only releases essential nutrients but also promotes changes in soil physicochemical properties (Krahl et al., 2022; Martins et al., 2023).

Thus, the continuous use of REM can act as a complementary strategy in agricultural management, contributing to improving nutrient availability over time. Although they do not completely replace soluble fertilizers, these materials can reduce the need for frequent applications, promoting more balanced nutrition for crops and favoring more sustainable agricultural practices. This advance is particularly relevant in regions with highly weathered soils, where low nutrient retention represents a constant challenge.

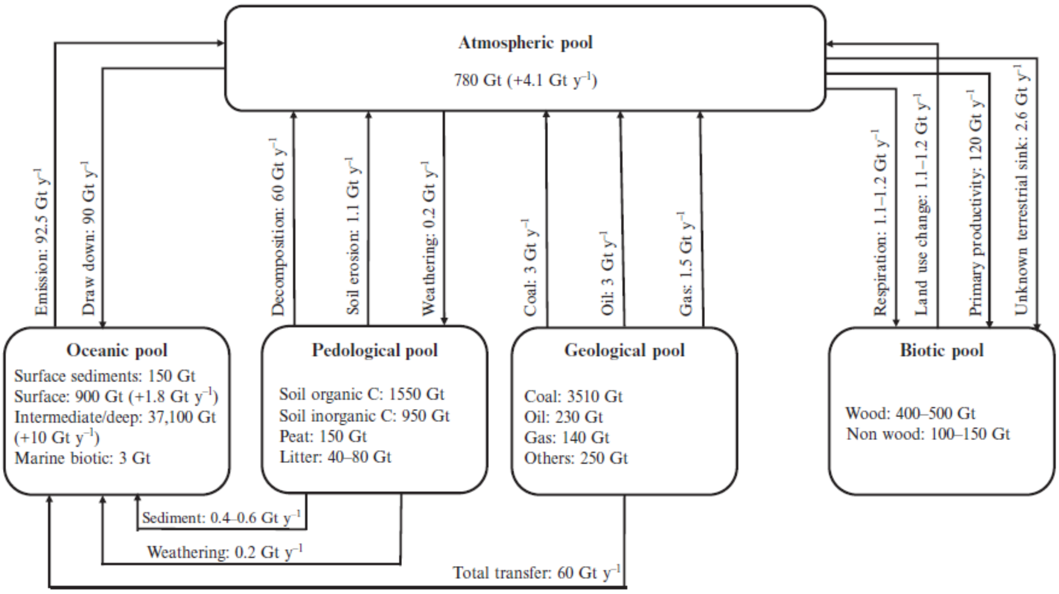
3.3 SOIL ORGANIC CARBON AND ITS STABILIZATION

Soil carbon (SC) is present in organic and inorganic forms. Soil inorganic carbon (SIC) is composed of alkali cation carbonates (Bronick & Lal, 2005; Wang et al., 2013). Globally, soils contain approximately 2,500 Gigatonnes (Gt) of carbon, of which 1,550 Gt is SOC and 950 Gt is SIC up to 1 m depth (Figure 5; Lal, 2008). Small variations in SIC content can have large impacts on the global carbon cycle and climate, given that the amount of carbon stored in soil is three times greater than that in terrestrial vegetation and the atmosphere (Schlesinger & Andrews, 2000). SOC is essential for soil health and agricultural sustainability, and its stabilization is fundamental for carbon sequestration and climate change mitigation (Lehmann & Kleber, 2015; Six et al., 2002). The interaction between low-crystalline minerals, such as amorphous minerals and iron and aluminum oxides, facilitates the stabilization of soil organic matter (SOM) through the adsorption of organic compounds, especially in tropical soils, where these minerals are predominant. These organomineral associations increase carbon retention in the soil, decreasing its mineralization and prolonging its residence time, being essential for mitigating greenhouse gas emissions and promoting ecosystem sustainability (Carvalho et al., 2023). Furthermore, there is a direct relationship between soil organic matter management and the global carbon cycle, which impacts the dynamics of SOM use. The alteration of soil mineralogy promoted by these inputs can influence the formation and stability of organomineral associations, contributing to a negative balance in CO_2 emissions and favoring the mitigation of climate change (Buss et al., 2024; Kottegoda et al., 2023; Guo et al., 2023; Carvalho et al., 2023).

Interactions between organic matter and minerals occur only through adsorption, which physically binds organic matter to the mineral surface, and occlusion, which encapsulates organic matter in aggregates or micropores, protecting it from microbial degradation and abiotic processes (Kleber et al., 2015b). In addition, the formation of organomineral complexes contributes significantly to the sequestration and stabilization of carbon in the soil, influencing the global carbon cycle and soil fertility (Kleber et al., 2021). Amorphous minerals play an essential role in carbon retention, as they have high chemical reactivity and a large surface area, facilitating the adsorption of organic compounds and their mineralization. In addition, these minerals may depend on the availability of nutrients by interacting with essential cations and anions, forming complexes with phosphorus, sulfur, and micronutrient metals, which can reduce leaching losses and increase the efficiency of nutrient use by plants (Chi et al., 2022). Minerals such as phyllosilicates, smectites, and iron and aluminum oxides also influence the stabilization of soil organic carbon (SOC), with soils rich in smectites presenting greater stabilization due to their high specific surface area and cation exchange capacity (CEC), favoring the retention of organic matter and essential nutrients (Jobbágy & Jackson, 2000; Wang et al., 2020).

Stabilization of COS, which is essential for carbon sequestration and climate change mitigation, can be physical, chemical or biological. Physical protection involves the segregation of organic matter within soil aggregates, hindering decomposition (Schmidt et al., 2011). Chemical stabilization occurs through interactions with minerals such as phyllosilicates and iron and aluminum oxides, while biological stabilization results from the incomplete decomposition of organic matter by microorganisms, forming stable organic compounds (Kleber et al., 2015a; Dungait et al., 2012).

Figure 5 – Major global C reservoirs and fluxes between them



Source: adapted from Lal, 2008.

Clay mineralogy is a crucial factor in soil organic carbon (SOC) stabilization, with minerals such as kaolinite, illite, and montmorillonite exhibiting different carbon buffering capabilities (Guo et al., 2024). Smectite-dominated soils tend to stabilize SOC better than kaolinite-dominated soils due to the higher CEC and SSA of smectite (Cotrufo et al., 2015). Furthermore, soil minerals affect carbon lability, influencing the ease with which it can be decomposed and released as CO_2 (Lehmann & Kleber, 2015). Allophanic and chloritic soils, for example, show lower SOC lability than kaolinitic and smectitic soils, contradicting the idea that smectites are more effective in stabilizing carbon (Kleber et al., 2015a). The interaction between organic matter and soil minerals occurs through mechanisms such as ligand exchange, cationic bridges, electrostatic attraction and van der Waals forces (Wang et al., 2013), which determines the stability of soil organic matter (SOM) and its resistance to decomposition (Dungait et al., 2012).

In addition to silicates, secondary minerals such as iron and aluminum oxides play an important role in stabilizing SOC, forming complexes with SOM that increase its stability (Torn et al., 1997). Studying dissolved organic carbon (DOC) sources, Benke et al. (1999) demonstrated that goethite has a high affinity for DOC, while Bednik et al. (2023) showed the influence of biochar on carbon dynamics in silty loam soils. Nguyen and Marschner (2014) observed that DOC sorption was lower in soils with higher total organic carbon (TOC) content and lower iron and aluminum concentrations, illustrating the complexity of interactions between DOC and soil minerals.

Studies of DOC adsorption and desorption in different soils reveal significant variations according to the type of mineral, including iron oxides, and the influence of DOC loss due to the priming effect (Kuzyakov & Domanski, 2000). Field experiments indicate that clay addition increases soil organic carbon through carbon incorporation into macroaggregates, especially with plant growth, suggesting effective strategies for short-term carbon sequestration (Churchman et al., 2020).

Adopting sustainable agricultural practices, such as crop rotation, use of cover crops, and application of organic composts, can improve COS stabilization. Enhanced rock weathering and the use of REM emerge as promising strategies to increase soil carbon sequestration capacity, with future studies needed to better understand the interactions between remineralizers and COS stabilization (Cotrufo et al., 2015). The impact of REM on soil mineralogy and nutrient release combined with organic matter and mineral-solubilizing microorganisms is a growing area of research, especially relevant for climate change mitigation strategies and a sustainable option in developing countries (Basak et al., 2022).

4. CONCLUSIONS

The results obtained suggest that soil remineralizers (REM) can influence the cation exchange capacity (CEC) and contribute to the stabilization of soil organic carbon (SOC). The interaction between minerals derived from remineralizers, organic matter, and iron and aluminum oxides has been identified as a relevant factor in the retention of charges and in the modification of the physicochemical properties of the soil (Santos et al., 2021). Thus, the addition of these inputs can favor the formation of new mineral phases with high surface charge, increasing the soil's potential to store nutrients and stabilize carbon. However, the magnitude of these effects can vary according to the mineralogical composition of the REM, the granulometry, and the management conditions, indicating the need for additional studies to quantify these interactions in different agricultural systems.

Furthermore, the influence of REM on COS stabilization should be considered in the context of weathering and bioweathering dynamics. As demonstrated in previous studies, the gradual release of nutrients and the interaction between fresh minerals and soil biota can stimulate processes that increase carbon retention and improve soil structure (Swoboda et al., 2022). However, more long-term experiments are still needed to assess how these interactions develop under different soil and climate conditions and land use. Thus, this study contributes to expanding the understanding of the mechanisms by which REM can act as agents promoting soil fertility and carbon stability, reinforcing the importance of integrated approaches for more sustainable management of tropical soil fertility.

However, it is important to emphasize that, despite the benefits, more field studies are still needed to evaluate the long-term effects and economic viability of using REM in different soil and climate conditions. As new research advances, it is expected that the use of REM will become consolidated as an essential practice for sustainable agriculture, contributing to greater resilience of agricultural systems and the preservation of natural resources, especially in tropical regions.

The literature analyzed provided information on the role of REM in the stability of organic matter and its contribution to more sustainable agriculture, with less dependence on external inputs and greater efficiency in preserving ecosystems and maintaining biogeochemical cycles (Buss et al., 2024; Glorieux & Delmelle, 2022).

5. REFERENCES

ALLEONI, L. R. F.; MELLO, J. W. V.; ROCHA, W. S. D. **Eletroquímica, adsorção e troca iônica no solo**. In: ALLEONI, L. R. F.; MELO, V. F. (Eds.). Química e Mineralogia do Solo – parte II. Viçosa-MG: Sociedade Brasileira de Ciência do Solo, 2009. p. 69-130.

AL RAWASHDEH, Rami. World peak potash: An analytical study. **Resources Policy**, v. 69, p. 101834, 2020. DOI: https://doi.org/10.1016/j.resourpol.2020.101834

ANDERSON, S. J.; SPOSITO, G. Cesium adsorption methods for measuring accessible structural surface charge. Soil **Science Society of America Journal**, v. 55, p. 1569-1576, 1991. doi: https://doi.org/10.2136/sssaj1991.03615995005500060011x.

ANDA. **Principais indicadores do Setor de Fertilizantes**. Disponível em: https://anda.org.br/pesquisa_setorial/. Acesso em: 09 jun. 2024.

ACKER, James G.; BRICKER, Owen P. The influence of pH on biotite dissolution and alteration kinetics at low temperature. **Geochimica et Cosmochimica Acta**, v. 56, n. 8, p. 3073-3092, 1992. DOI: https://doi.org/10.1016/0016-7037(92)90290-Y

BAKKEN, A. K.; GAUTNEB, H.; SVEISTRUP, T.; MYHR, K. Crushed rocks and mine tailings applied as K fertilizers on grassland. **Nutrient Cycling in Agroecosystems**, v. 56, p. 53–57, 2000.

BARSHAD, I. Vermiculite and its relation to biotite as revealed by base exchange reactions, x-ray analyses, differential thermal curves, and water content. **American Mineralogist: Journal of Earth and Planetary Materials**, v. 33, n. 11-12, p. 655-678, 1948.

BASAK, B. B. et al. Potassium supply in agriculture through biological potassium fertilizer: A promising and sustainable option for developing countries. **Archives of Agronomy and Soil Science**, v. 68, n. 1, p. 101-114, 2022. DOI: https://doi.org/10.1080/03650340.2020.1821191

BEDNIK, M.; MEDYŃSKA-JURASZEK, A.; ĆWIELĄG-PIASECKA, I.; DUDEK, M. Enzyme activity and dissolved organic carbon content in soils amended with different types of biochar and exogenous organic matter. **Sustainability**, v. 15, n. 21, p. 15396, 2023. DOI: doi.org/10.3390/su152115396.

BENKE, M. B.; MERMUT, A. R.; SHARIATMADARI, H. Retention of dissolved organic carbon from vinasse by a tropical soil, kaolinite, and Fe-oxides. **Geoderma**, v. 91, n. 1-2, p. 47-63, 1999.

BHATTACHARYYA, Siddhartha Shankar; FURTAK, Karolina. Soil–Plant–Microbe interactions determine soil biological fertility by altering rhizospheric nutrient cycling and biocrust formation. **Sustainability**, v. 15, n. 1, p. 625, 2022. DOI: https://doi.org/10.3390/su15010625

BOLLAN, N. S.; NAIDU, R.; SYERS, J. K.; TILLMAN, R. Surface charge and solute interaction in soils. In: **Advances in Agronomy**, v. 67, p. 87-140, 1999. doi: https://doi.org/10.1016/S0065-2113(08)60514-3.

BORTOLUZZI, E. C.; TESSIER, D.; RHEINHEIMER, D. S.; JULIEN, J. L. The cation exchange capacity of a sandy soil in southern Brazil: An estimation of permanent and pH-dependent charges. **European Journal of Soil Science**, v. 57, n. 3, p. 356-364, 2006. DOI: https://doi.org/10.1111/j.1365-2389.2005.00746.x.

BOTTONI, I. J.; NORMANHA, B. A.; SUGAHARA, C.R.; FERREIRA, D.H.L.; SILVA , M.P. Mudanças climáticas e plano de ação de mitigação das emissões de CO_2 no município de Campinas/SP. **Periódico Eletrônico Fórum Ambiental da Alta Paulista**, [S. l.], v. 21, n. 1, 2025. DOI:10.17271/1980082721120255597.

BRONICK, C. J.; LAL, R. Soil structure and management: a review. **Geoderma**, v. 124, p. 3–22, 2005. DOI: doi.org/10.1016/j.geoderma.2004.03.005.

BUSS, W.; HASSEMER, H.; FERGUSON, S.; BOREVITZ, J. Stabilisation of soil organic matter with rock dust partially counteracted by plants. **Global Change Biology**, v. 30, n. 1, e17052, 2024. doi: https://doi.org/10.1111/gcb.17052.

BUSATO, J. G.; LEÃO, T. P.; BALDOTTO, M. A.; CANELLAS, L. P. Organic matter quality and dynamics in tropical soils amended with sugar industry residue. **Revista Brasileira de Ciência do Solo**, v. 36, p. 1179-1188, 2012. doi: https://doi.org/10.1590/S0100-06832012000400012.

CARVALHO, Martha Lustosa et al. Stabilization of organic matter in soils: drivers, mechanisms, and analytical tools–a literature review. **Revista Brasileira de Ciência do Solo**, v. 47, p. e0230130, 2023. DOI: https://doi.org/10.36783/18069657rbcs20220130

CHI, J.; FAN, Y.; WANG, L.; PUTNIS, C. V.; ZHANG, W. Retention of soil organic matter by occlusion within soil minerals. **Reviews in Environmental Science and Bio/Technology**, v. 21, n. 3, p. 727-746, 2022. DOI: doi.org/10.1007/s11157-022-09628-x.

CHURCHMAN, G. J.; LOWE, D. J. **Alteration, formation, and occurrence of minerals in soils**. In: HUANG, P. M.; LI, Y.; SUMNER, M. E. (Eds.). Handbook of Soil Sciences, v. 1. Boca Raton: CRC Press, 2012. p. 20.1-20.72. https://doi.org/10.1201/b11267.

CHURCHMAN, G. J.; SINGH, M.; SCHAPEL, A.; SARKAR, B.; BOLAN, N. Clay minerals as the key to the sequestration of carbon in soils. **Clays and Clay Minerals**, v. 68, n. 2, p. 135-143, 2020. DOI: doi.org/10.1007/s42860-020-00071-z.

CICERI, D.; MANNING, D. A. C.; ALLANORE, A. Historical and technical developments of potassium resources. **Science of Total Environment**, v. 502, p. 590-601, 2015. doi: https://doi.org/10.1016/j.scitotenv.2014.09.013.

COTRUFO, M. F.; RANALLI, M. G.; HADDIX, M. L.; SIX, J.; LUGATO, E. Soil carbon storage informed by particulate and mineral-associated organic matter. **Nature Geoscience,** v. 8, n. 12, p. 968-971, 2015. DOI: doi.org/10.1038/s41561-019-0484-6.

CRUSCIOL, Carlos Alexandre Costa et al. Broadcast application of ground silicate rocks as potassium sources for grain crops. **Pesquisa Agropecuária Brasileira**, v. 57, p. e02443, 2022.DOI: https://doi.org/10.1590/S1678-3921.pab2022.v57.02443.

CUNHA, J. C.; RUIZ, H. A.; FREIRE, M. B. G.; ALVAREZ, V. H.; FERNANDEZ, R. B. Quantification of permanent and variable charges in reference soils of the state of Pernambuco, Brazil. **Revista Brasileira de Ciência do Solo**, v. 38, p. 1162-1169, 2014. doi: https://doi.org/10.1590/S0100-06832014000400012.

DERPSCH, Rolf et al. Nature's laws of declining soil productivity and Conservation Agriculture. **Soil Security**, v. 14, p. 100127, 2024. DOI: https://doi.org/10.1016/j.soisec.2024.100127

DUARTE, W. M.; MAFRA, A. L.; FORESTI, M. M.; PICCOLA, C. D.; ALMEIDA, J. A. Potencial de olivina melilitito, granito e sienito nefelínico na disponibilização de potássio em solos. **Revista de Ciências Agroveterinárias**, v. 12, p. 68-77, 2013.

DUNGAIT, J. A. J.; HOPKINS, D. W.; GREGORY, A. S.; WHITMORE, A. P. Soil organic matter turnover is governed by accessibility not recalcitrance. **Global Change Biology**, v. 18, n. 6, p. 1781-1796, 2012. DOI: https://doi.org/10.1111/j.1365-2486.2012.02665.x.

ESSINGTON, M. E. **Soil and water chemistry: an integrative approach**. Boca Raton: CRC Press, 2003. https://doi.org/10.1201/b12397.

FONTES, M. P. F.; CAMARGO, O. A.; SPOSITO, G. Eletroquímica das partículas coloidais e sua relação com a mineralogia de solos altamente intemperizados. **Scientia Agricola**, v. 58, p. 627-646, 2001. doi: https://doi.org/10.1590/S0103-90162001000300029.

GLORIEUX, J.; DELMELLE, P. **Assessing the potential of enhanced silicate weathering in a tropical soil to remove atmospheric CO2 and improve soil fertility: a modeling study**. Faculté des bioingénieurs, Université catholique de Louvain, 2022. Prom. : Delmelle, Pierre. http://hdl.handle.net/2078.1/thesis:38227

GRANT, K. E.; GALY, V. V.; HAGHIPOUR, N.; EGLINTON, T. I.; DERRY, L. A. Persistence of old soil carbon under changing climate: The role of mineral-organic matter interactions. **Chemical Geology**, v. 587, 120629, 2022. DOI: doi.org/10.1016/j.chemgeo.2021.120629.

GUO, L.; QU, C.; ZHOU, Y.; CHEN, Y.; CAI, P.; CHEN, W.; ...; HUANG, Q. Trade-off between Pore-Throat Structure and Mineral Composition in Modulating the Stability of Soil Organic Carbon (2024). **Environmental Science & Technology**. DOI: doi.org/10.1021/acs.est.3c09886?urlappend=%3Fref%3DPDF&jav=VoR&rel=cite-as.

GUO, F.; SUN, H.; YANG, J.; ZHANG, L.; MU, Y.; WANG, Y.; WU, F. Improving food security and farmland carbon sequestration in China through enhanced rock weathering: Field evidence and potential assessment in different humid regions. **Science of The Total Environment**, v. 903, 166118, 2023. doi://doi.org/10.1016/j.scitotenv.2023.166118.

HEFFER, P.; PRUD'HOMME, M. Fertilizer Outlook 2013-2017. **International Fertilizer Industry Association (IFA), 2013.** Disponível em: http://www.fertilizer.org. Acessado em: 03 abr. 2015.

HINSINGER, P.; BOLLAND, M. D. A.; GILKES, R. J. Silicate rock powder: effect on selected chemical properties of a range of soil from Western Australia and on plant growth as assessed in a glasshouse experiment. **Fertilizer Research**, v. 45, p. 69-79, 2001.

HOLGERSSON, Stellan et al. Biotite dissolution kinetics at pH 4 and 6.5 under anaerobic conditions and the release of dissolved Fe (II). **Chemical Geology**, v. 662, p. 122204, 2024. DOI://doi.org/10.1016/j.chemgeo.2024.122204

JILLING, A.; SOKOL, N. W.; MORÁN-RIVERA, K.; GRANDY, A. S. Wet-dry cycling influences the formation of mineral-associated organic matter and its sensitivity to simulated root exudates. **Geoderma**, v. 445, 116869, 2024. DOI: doi.org/10.1016/j.geoderma.2024.116869.

JOBBÁGY, E. G.; JACKSON, R. B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. **Ecological Applications**, v. 10, n. 2, p. 423-436, 2000. DOI: doi.org/10.1890/1051-0761(2000)010[0423]2.0.CO;2.

KLEBER, M.; BOURG, I. C.; COWARD, E. K.; HANSEL, C. M.; MYNENI, S. C.; NUNAN, N. Dynamic interactions at the mineral–organic matter interface. **Nature Reviews Earth & Environment**, v. 2, n. 6, p. 402-421, 2021. DOI: //doi.org/10.1038/s43017-021-00162-y.

KLEBER, M.; EUSTERHUES, K.; KEILUWEIT, M.; MIKUTTA, C.; MIKUTTA, R.; NICO, P. S. Mineral–organic associations: formation, properties, and relevance in soil environments. **Advances in Agronomy**, v. 130, p. 1-140, 2015. DOI: doi.org/10.1016/bs.agron.2014.10.005. a)

KLEBER, M.; SOLLINS, P.; SUTTON, R. A conceptual model of organo-mineral interactions in soils: Self-assembly of organic molecular fragments into zonal structures on mineral surfaces. **Biogeochemistry**, v. 85, p. 9-24, 2015. DOI: 10.1007/s10533-007-9103-5. b)

KÖNIG, Uwe; PÖLLMANN, Herbert; ANGÉLICA, Rômulo Simões. O Refinamento de Rietveld como um método para o controle de qualidade de minérios de ferro. Rem: **Revista Escola de Minas**, v. 55, n. 2, p. 111-114, 2002. DOI: https://doi.org/10.1590/S0370-44672002000200007

KOTTEGODA, Nilwala et al. Climate smart agriculture: The role of fertilizer innovations and efficient plant nutrient management. **Vidyodaya Journal of Science,** v. 1, n. s1, 2023. DOI: https://doi.org/10.31357/vjs.v1is1.6709

KRAHL, L. L.; MARCHI, G.; PAZ, S. P. A.; ANGÉLICA, R. S.; SOUSA-SILVA, J. C.; VALADARES, L. F.; MARTINS, É. D. S. Increase in cation exchange capacity by the action of maize rhizosphere on Mg or Fe biotite-rich rocks**. Pesquisa Agropecuária Tropical**, v. 52, 2022. https://doi.org/10.1590/1983-40632022v5272376.

KUZYAKOV, Y.; DOMANSKI, G. Carbon input by plants into the soil. **Review. J Plant Nutr Soil Sci**., v. 163, p. 421-431, 2000. DOI: doi.org/10.1002/1522-2624(200008)163:4%3C421::AID-JPLN421%3E3.0.CO;2-R.

LAL, R. Carbon sequestration. **Philosophical Transactions of the Royal Society B: Biological Sciences**, v. 363, p. 815–830, 2008. DOI: doi.org/10.1098/rstb.2007.2185.

LEHMANN, J.; KLEBER, M. The contentious nature of soil organic matter. **Nature,** v. 528, n. 7580, p. 60-68, 2015. DOI: http://www.nature.com/doifinder/10.1038/nature16069.

LOPES, K. S. M., YOKOBATAKE, K. L. A., & PINHEIRO, R. S. B. Sistemas de produção de bovinos e a emissão de metano. **Periódico Eletrônico Fórum Ambiental de Alta Paulista**, v. 9, p. 153-158, 2013.

LUCHESE, A. V.; DE CASTRO LEITE, I. J. G.; ALVES, M. L.; DOS SANTOS VIECELI, J. P.; PIVETTA, L. A.; MISSIO, R. F. Can Basalt Rock Powder be Used as an Alternative Nutrient Source for Soybeans and Corn?. **Journal of Soil Science and Plant Nutrition**, v. 23, n. 3, p. 4044-4054, 2023. doi: https://doi.org/10.1007/s42729-023-01322-3.

MANNING, D. A.; THEODORO, S. H. Enabling food security through use of local rocks and minerals**. The Extractive Industries and Society**, v. 7, n. 2, p. 480-487, 2020. https://doi.org/10.1016/j.exis.2018.11.002.

MARTINS, E.; HARDOIM, P. R.; MARTINS, É. S. **Efeito da aplicação dos remineralizadores no solo**. Informe Agropecuário, v. 44, n. 321, p. 49-56, 2023.

MARTINS, Eder de Souza et al. **Produção brasileira de remineralizadores e fertilizantes naturais: 2019 a 2023**. 2024.

MEDEIROS, F. D. P.; CARVALHO, A. M. D.; GINDRI RAMOS, C.; DOTTO, G. L.; CARDOSO, I. M.; THEODORO, S. H. Rock Powder Enhances Soil Nutrition and Coffee Quality in Agroforestry Systems. **Sustainability**, v. 16, n. 1, p. 354, 2023. https://doi.org/10.3390/su16010354.

MIKUTTA R., MIKUTTA C., KALBITZ K., SCHEEL T., KAISER K.; JAHN R. (Biodegradation of forest floor organic matter bound to minerals via different binding mechanisms. **Geochimica et Cosmochimica Acta**, v. 71, n. 10, p. 2569-2590, 2007. DOI: https://doi.org/10.1016/j.gca.2007.03.002

NEWCOMB, C. J., QAFOKU, N. P., GRATE, J. W., BAILEY, V. L., & DE YOREO, J. J. Developing a molecular picture of soil organic matter–mineral interactions by quantifying organo–mineral binding. **Nature communications**, v. 8, n. 1, p. 396, 2017. DOI: 10.1038/s41467-017-00407-9

NGUYEN, T.-T.; MARSCHNER, P. Retention and loss of water extractable carbon in soils: effect of clay properties. **Science of the Total Environment**, v. 470–471, p. 400–406, 2014. DOI: doi.org/10.1016/j.scitotenv.2013.10.002.

PARKS, G. A.; BRUYN, P. L. The zero point of charge of oxides. **Journal of Physical Science**, v. 66, p. 967-973, 1962.

PEREIRA, L. F.; RIBEIRO JUNIOR, W. Q.; RAMOS, M. L. G.; SANTOS, N. Z. D.; SOARES, G. F.; CASARI, R. A. D. C. N.; SOUSA, C. A. F. D. Physiological changes in soybean cultivated with soil remineralizer in the Cerrado under variable water regimes. **Pesquisa Agropecuária Brasileira**, v. 56, e01455, 2021. doi: https://doi.org/10.1590/S1678-3921.pab2021.v56.01455.

RAMOS, C. G.; HOWER, J. C.; BLANCO, E.; OLIVEIRA, M. L. S.; THEODORO, S. H. Possibilities of using silicate rock powder: An overview. **Geoscience Frontiers**, v. 13, n. 1, p. 101185, 2022. doi: https://doi.org/10.1016/j.gsf.2021.101185.

REATTO, A.; MARTINS, E. S. **Classes de solo em relação aos controles de paisagem do Bioma Cerrado**. In: SCARIOT, A.; SILVA, J. C. S.; FELFILLI, J. M. (Eds.), Cerrado: Ecologia, Biodiversidade e Conservação. Brasília: Ministério do Meio Ambiente, p. 47-59, 2005.

SANTOS, H.G dos ; JACOMINE, P.K.T ; ANJOS, L.H.C dos ; OLIVEIRA, V.A de ; LUMBRERAS, J.F. ; COELHO, M.R. ; ALMEIDA, J.A. de ; ARAÚJO FILHO, J.C. de ; OLIVEIRA, J.B. de ; CUNHA, T.J.F. **Sistema Brasileiro de Classificação de Solos**.– 5. ed., rev. e ampl. − Brasília, DF : Embrapa, 2018.

SANTOS, L. F. D.; SODRÉ, F. F.; MARTINS, É. D. S.; FIGUEIREDO, C. C. D.; BUSATO, J. G. Effects of biotite syenite on the nutrient levels and electrical charges in a Brazilian Savanna Ferralsol. **Pesquisa Agropecuária Tropical**, v. 51, 2021. DOI: https://doi.org/10.1590/1983-40632021v5166691.

SCHNEIDER, M. P. W., SCHEEL, T., MIKUTTA, R., VAN HEES, P., KAISER, K., & KALBITZ, K. Sorptive stabilization of organic matter by amorphous Al hydroxide. **Geochimica et Cosmochimica Acta**, v. 74, n. 5, p. 1606-1619, 2010. DOI: https://doi.org/10.1016/j.gca.2009.12.017

SCHLESINGER, W. H.; ANDREWS, J. A. Soil respiration and the global carbon cycle. **Biogeochemistry**, v. 48, p. 7–20, 2000.

SCHMIDT, M. W. I.; TORN, M. S.; ABIVEN, S.; DITTMAR, T.; GUGGENBERGER, G.; JANSSENS, I. A.; KLEBER, M.; KÖGEL-KNABNER, I.; LEHMANN, J.; MANNING, D. A. C.; NANNIPIERI, P.; RASSE, D. P.; WEINER, S.; TRUMBORE, S. E. Persistence of soil organic matter as an ecosystem property. **Nature**, v. 478, n. 7367, p. 49-56, 2011. DOI: doi:10.1038/nature10386.

SINGH, M.; SARKAR, B.; BISWAS, B.; CHURCHMAN, J.; BOLAN, N. S. Adsorption-desorption behavior of dissolved organic carbon by soil clay fractions of varying mineralogy. **Geoderma**, v. 280, p. 47-56, 2016. https://doi.org/10.1016/j.geoderma.2016.06.005.

SINGH, M.; SARKAR, B.; SARKAR, S.; CHURCHMAN, J.; BOLAN, N.; MANDAL, S. Stabilization of soil organic carbon as influenced by clay mineralogy. **Advances in Agronomy**, v. 148, p. 33-84, 2018. https://doi.org/10.1016/bs.agron.2017.11.001.

SIX, J.; CONANT, R. T.; PAUL, E. A.; PAUSTIAN, K. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. **Plant and Soil**, v. 241, p. 155–176, 2002.

SOUZA JUNIOR, I. G. D.; COSTA, A. C. S. D.; SAMBATTI, J. A.; PETERNELE, W. S.; TORMENA, C. A.; MONTES, C. R.; CLEMENTE, C. A. Contribuição dos constituintes da fração argila de solos subtropicais à área superficial específica e à capacidade de troca catiônica. **Revista Brasileira de Ciência do Solo**, v. 31, p. 1355-1365, 2007. https://doi.org/10.1590/S0100-06832007000600014.

SOUZA, M. E. P.; CARVALHO, A. M. X.; DELIBERALI, D. C.; JUCKSH, I.; BROWN, G. G.; MENDONÇA, E. S.; CARDOSO, I. M. Vermicomposting with rock powder increases plant growth. **Applied Soil Ecology**, v. 69, p. 56–60, 2013. doi: https://doi.org/10.1016/j.apsoil.2013.01.016.

SPOHN, M., DIÁKOVÁ, K., ABURTO, F., DOETTERL, S., & BOROVEC, J. Sorption and desorption of organic matter in soils as affected by phosphate. **Geoderma**, v. 405, p. 115377, 2022. DOI: https://doi.org/10.1016/j.geoderma.2021.115377

SPOSITO, G. **The surface chemistry of soils**. Oxford University Press, 1984.

SPOSITO, G. **The chemistry of soils**. Oxford University Press, Oxford, 277 p., 2. ed., 2008.

SWOBODA, Philipp; DÖRING, Thomas F.; HAMER, Martin. Remineralizing soils? The agricultural usage of silicate rock powders: A review. **Science of The Total Environment**, v. 807, p. 150976, 2022.DOI: 10.1016/j.scitotenv.2021.150976

TAIZ, L.; ZEIGER, E. **Fisiologia Vegetal**. Artmed, Porto Alegre, 5ed. 2013 721p.

TAN, K. H.; BINGER, A. Effect of Humic Acid on Aluminum toxicity in corn plants. **Soil Science**, v. 141, p. 54-67, 1985.

THENG, B. K. **Clay mineral catalysis of organic reactions**. CRC Press, 2018.

TONG, Y.; XIANG, H.; JIANG, J.; CHEN, W. Interfacial interactions between minerals and organic matter: Mechanisms and characterizations. **Chemosphere**, 142383, 2024. DOI: doi.org/10.1016/j.chemosphere.2024.142383.

TORN, M. S.; TRUMBORE, S. E.; CHADWICK, O. A.; VITOUSEK, P. M.; HENDRICKS, D. M. Mineral control of soil organic carbon storage and turnover. **Nature**, v. 389, p. 170–173, 1997.

UEHARA, G.; GILLMAN, G. P. Charge Characteristics of Soils with Variable and Permanent Charge Minerals: II. Experimental. **Soil Science Society of America Journal**, v. 44, n. 4, 1980.

UROZ S, CALVARUSO C, TURPAULT MP, FREY-KLETT P. Mineral weathering by bacteria: ecology, actors and mechanisms. **Trends in microbiology**, v. 17, n. 8, p. 378-387, 2009.

VINOD, P. N.; CHANDRAMOULI, P.; KOCH, M. Estimation of nitrate leaching in Groundwater in agriculturally used area in the State Karnataka, India, Using existing Model and GIS. **Aquatic Procedia**, v. 4, p. 1047-1053, 2015. doi: https://doi.org/10.1016/j.aqpro.2015.02.132.

VOLF, M. R.; BENITES, V. M.; AZEVEDO, A. C.; MORAES, M. F.; TIRITAN, C. S.; ROSOLEM, C. A. Soil mineralogy and K reserves in soils from the Araguaia River valley, Brazil. **Geoderma Regional**, v. 33, e00654, 2023. https://doi.org/10.1016/j.geodrs.2023.e00654.

WANG, G.; POST, W. M.; MAYES, M. A.; FRERICHS, J. T.; SINDHU, J. Parameter uncertainty of the CENTURY model and its impact on the estimation of soil organic carbon dynamics. **Environmental Modelling & Software**, v. 47, p. 128-139, 2013. DOI: doi.org/10.1371/journal.pone.0082029.

WANG, Y.-H.; SHI, Y.-M.; SUN, G.-D.; LI, J.-T.; CHEN, H.; CHOW, A. T.; YANG, Z.-B.; MAJIDZADEH, H.; WANG, J.-J. Soil organic carbon signature under impervious surfaces. **ACS Earth Space Chem**., v. 4, p. 1785–1792, 2020. DOI: doi.org/10.1021/acsearthspacechem.0c00174.

WEBER, O. L. S.; CHITOLINA, J. C.; CAMARGO, O. A.; ALLEONI, L. R. F. Cargas elétricas estruturais e variáveis de Solos tropicais altamente intemperizados. **Revista Brasileira de Ciência do Solo**, v. 29, p. 867-873, 2005. doi: https://doi.org/10.1590/S0100-06832005000600004.

WILCKE, W.; LILIENFEIN, J. Nutrient Leaching in Oxisols Under Native and Managed Vegetation in Brazil. **Soil Science Society of America Journal**, v. 69, p. 1152-1161, 2005. https://doi.org/10.2136/sssaj2004.0350.

ZINN, Yuri L.; LAL, Rattan; RESCK, Dimas VS. Changes in soil organic carbon stocks under agriculture in Brazil. **Soil and Tillage Research**, v. 84, n. 1, p. 28-40, 2005. DOI: https://doi.org/10.1016/j.still.2004.08.007

DECLARAÇÕES

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DECLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, Luiz Fernando dos Santos, Ewerton Gonçalves de Abrantes, Giuliano Marchi e Éder de Souza Martins declaramos que o manuscrito intitulado "Artigo de Revisão: Inovações na Fertilização do Solo e o Papel dos Remineralizadores."

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