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Formation of Organo-Mineral Complexes and their Importance in Soil Carbon Stabilization

Varalakshmi V.[1] and Shivakumar Mirji[2]
[1]Ph.D. Scholar, [2]M.Sc. (Agri.), Dept. of Soil Science and Agricultural Chemistry, College of Agriculture, VC Farm, Mandya, Karnataka, India

SUMMARY

Organo-mineral complexes are fundamental to soil carbon stabilization, facilitating the persistence of organic matter through strong physicochemical interactions with mineral surfaces. These complexes arise via mechanisms such as ligand exchange, cation bridging, hydrogen bonding and van der Waals forces, predominantly involving clay minerals, iron and aluminium oxides. By encapsulating soil organic matter within mineral matrices, they limit microbial access and enzymatic degradation, thereby enhancing carbon persistence on centennial to millennial timescales. The formation and stability of these complexes are governed by soil mineralogy, pH, ionic strength and redox conditions. Their role in biogeochemical cycling extends beyond carbon sequestration, influencing soil fertility, aggregate stability and resilience to environmental perturbations. Deciphering the molecular-scale interactions within organo-mineral assemblages is critical for advancing predictive models of soil carbon dynamics and developing strategies for climate change mitigation and sustainable land management.

INTRODUCTION

Global climate change resulting from greenhouse gas emission is becoming a concern in all regions of the world. An exponential increase in the level of greenhouse gases has been recorded since the beginning of the industrial revolution.The atmospheric concentration of carbon dioxide (CO_2) has increased globally by 40% from 278 ppm in the pre industrial era to the current value of 410 ppm. Soil organic carbon is one of the largest pools of organic carbon and plays a primary role in global C balance and also soil functioning. Indeed,OC content in soils is approximately three times more than that of atmospheric or terrestrial vegetation pools and it has been recognized that a small variation in soil C stock can have a significant effect on atmospheric C concentration.

Soil as a sink and source of carbon:

Sink:

Organic Matter Accumulation: Dead plant material (leaves, stems, roots) decomposes and becomes part of the soil organic matter. Decomposed organic material further breaks down into humus, a stable form of organic carbon.

Microbial Activity: Soil microbes decompose organic matter, converting it into stable organic compounds that can be stored in the soil for long periods. Microbial biomass itself can become part of the soil organic carbon pool when microbes die and decompose. **Retention:** Soil holds the organic carbon by different physical and chemical protection measures.

Source:

Respiration: Soil organisms (including plant roots and microbes) respire, releasing carbon dioxide (CO2) back into the atmosphere.**Decomposition**: When organic matter decomposes, carbon is released as CO2 through microbial respiration.**Disturbances**: Human activities like deforestation, land use can expose soil carbon and lead to decomposition of carbon.

The major area was covered by desert and semidesert and the forest land contribute to the major soil carbon pool among the different habitats.

Composition of Soil organic matter:

Organic matter consists of 75% water and 25% dry matter in that 25% there is 62% carbohydrates,26 % lignin,11%protein and 1% other components.The elemental composition includes 44% carbon,40% oxygen,8% hydrogen and other 8% elements.

Decomposition of organic matter in soil, categorized into easily, moderately, and difficulty degradable components. Easily degradable substances (simple sugars, amino acids, etc.) are quickly broken down by microbes into minerals like CO_2, H_2O, and NH_3. Moderately degradable substances (hemicelluloses, celluloses, proteins, etc.) decompose into simpler compounds, some of which resist further degradation. Difficulty degradable substances (tannins, lignin, etc.) break down into complex substances like quinones and polyphenols, which eventually condense to form stable humus and rest are converted into minerals which are available to plants . Throughout these processes, microbial activity is crucial for transforming organic matter into either minerals or humus, contributing to soil fertility and carbon cycling.

1. Additions: When roots and leavesdie, they become part of the soilorganic matter.

2. Transformations: Soil organismscontinually consume plant residueand other organic matter, and thencreate by-products, wastes, and celltissue.

3. Microbes feed plants: Some of the wastes released by soil organisms are nutrients that canbe used by plants.

4. Stabilization of organic matter: Eventually, soil organic compounds become stabilized andresistant to further changes. This compound, known as "humus", is the end result of organic matter decomposition by microbes.

Organic matter in soil consists of Stabilized organic matter 41%, active fractions 41%,fresh organic residues 12% and living organisms 6%.

Importance of Soil Organic Matter

Nutrient Supply:

Slow Release of Nutrients: SOM acts as a reservoir of essential nutrients like nitrogen, phosphorus, and sulfur, releasing them slowly as it decomposes.

Improved Fertility: Enhances soil fertility by providing a steady supply of nutrients to plants.

Soil Structure:

Aggregation: SOM promotes the formation of soil aggregates, improving soil structure and reducing erosion.

Porosity and Aeration: Improved soil structure increases porosity and aeration, facilitating root growth and water infiltration.

Water Retention:

Increased Moisture Holding Capacity: SOM enhances the soil’s ability to retain water, making it available to plants during dry periods.

Drought Resistance: Soils with higher SOM levels are more resistant to drought conditions, supporting plant growth even in adverse conditions.

Microbial Activity:

Habitat for Microorganisms: Provides a habitat and energy source for beneficial soil microorganisms.

Nutrient Cycling: Microorganisms decompose organic matter, releasing nutrients back into the soil, promoting healthy nutrient cycling.

Cation Exchange Capacity (CEC):

Improved Nutrient Retention: SOM increases the soil’s CEC, enabling it to retain and supply more cations (e.g., potassium, calcium, magnesium) to plants.

Soil Buffering: Enhances the soil’s ability to buffer pH changes and maintain nutrient availability.

Carbon Sequestration:

Climate Change Mitigation: SOM stores carbon, reducing the amount of CO2 in the atmosphere and mitigating climate change.

Long-term Carbon Storage: Stabilized SOM contributes to long-term carbon storage in the soil.

Soil Health:

Enhanced Resilience: Soils rich in organic matter are more resilient to environmental stresses such as drought, heavy rainfall, and temperature fluctuations.

Biodiversity: Supports a diverse soil ecosystem, including plants, microorganisms, and soil fauna, which contributes to overall soil health and productivity.

Erosion Control:

Soil Stability: Improves soil cohesion and stability, reducing the risk of erosion by wind and water.

Surface Protection: Organic matter on the soil surface protects against raindrop impact and surface runoff.

Soil organic matter is divided into three pools Active soil organic matter pool,slow soil organic matter pool and passive soil organic matter pool.Active soil organic matter is formed by recently deposited organic material which decomposes very rapidly and it takes 1-2 years to complete decomposition 10-20% of som is active soil organic matter.Slow soil organic matter is formed by intermediate age organic material which decompose slowly and it takes 15-100 years for complete decomposition. 10-20% of som is active soil organic matter. Passive soil organic matter is formed by very stable organic material, which is extremely slow in decomposition and it takes 500-5000 years for decomposition. Humus, a vital component of soil organic matter, is composed of humic substances that include humic acids, fulvic acids, and humins. Humic acids are high-molecular-weight compounds that contribute to soil structure by binding soil particles together, enhancing water retention, and nutrient holding capacity. Fulvic acids, with lower molecular weight, are more soluble in water and can readily interact with plant roots, aiding in nutrient uptake. Humins are the most stable and recalcitrant part of humus, resistant to microbial decomposition, and play a crucial role in long-term carbon storage. Together, these components of humus improve soil fertility, structure, and overall health by enhancing nutrient availability, water retention, and soil microbial activity (Bolan *et al.*, 2012).

Clay minerals

Clay minerals in soil are fine-grained natural materials that play a crucial role in determining the soil's physical and chemical properties. They are formed from the weathering of primary minerals and are characterized by their small size, high surface area, and ability to hold water and nutrients. The primary types of clay minerals found in soil include Kaolinite which has 1:1 layer silicate, consisting of one tetrahedral sheet linked to one octahedral sheet. Relatively low surface area and cation exchange capacity (CEC), but highly stable and less prone to swelling and shrinking. Smectite has 2:1 layer silicate, with two tetrahedral sheets sandwiching one octahedral sheet. High surface area and CEC, with significant swelling and shrinking potential due to water absorption between layers. Illite which has 2:1 layer silicate, similar to smectite but with potassium ions between layers that reduce swelling. Moderate CEC and surface area, with less swelling than smectite. Vermiculite which has 2:1 layer silicate, with layers that can expand but are more stable than smectite. High CEC and water holding capacity, with moderate swelling. Chlorite which has 2:1:1 layer silicate, with an additional hydroxide sheet. Low to moderate CEC and swelling capacity.sesquioxides are universally occurring minerals which contain oxide and hydroxides of iron and aluminum, other minerals includes carbonates and sulphates (Saidy *et al.*, 2013).

Organo Mineral Complex:

Organo-mineral complexes are crucial components in soil that result from the interaction between organic matter (OM) and mineral particles.The clay humic complex includes two fractions which consists of mineral fraction and organic fraction.Mineral fraction include clay and clay minerals.Organic fractions include living organic matter,fresh organic matter,humus,and transient organic matter.

Mechanisms		Functional groups/Surfaces
Ligand exchange	Anion exchange	OH group on mineral surfaces and edges (Allophane , imogolite)
		Carboxyl groups and phenolic OH groups(Replaces hydroxyl group)
		Amines, ring-NH, heterocyclic-N(lone pair e- and bind to cationic site)
Polyvalent cation bridge	Electrostatic cation bridge ($Fe^{3+}<Al^{3+}<Ca^{2+}<Mn^{2+}<Mg^{2+}$) (multiple positive charge)	Negatively charged functional groups(OH- , COO-)
		Expandable layer silicates e.g. smectite, vermiculite ,illite
		OM functional groups; carboxyl, alcoholic
Weak interactions	Hydrophobic interactions	Non polar, uncharged surface

	Van der Waals forces	Non expandable layer silicates(kaolinite) , neutral microsites on smectites
		OM; uncharged, Non polar group(aromatic ,alkyl-C)
H-Bonding		e.g. Kaolinite
		OM functional groups ; carboxyl, phenolic-OH ,amines , heterocyclic-N groups

Importance of Organo-Mineral Complexation

It helps in nutrient retention, slow release of nutrients, soil structure improvement, contamination binding, improve water holding capacity, microbial activity support and stabilization of organic carbon.

Soil carbon stabilization:

Soil carbon stabilization can be termed as any action which slows down the decomposition of SOM by reducing the mineralization rate, preventing its rapid decomposition and release back into the atmosphere as carbon dioxide (CO_2).The stabilization of C in soil is not only important for mitigating greenhouse gases (CO_2, CH_4), but also for improving the soil fertility, and hence sustainable farming (Kottkamp *et al.*, 2022).

Carbon Stabilization Mechanisms (Plaza *et al.*, 2013)

Physical Stabilization:

Aggregation: Soil particles form aggregates that physically protect organic matter from microbial attack. Organic carbon trapped inside soil aggregates is less accessible to decomposers.

Micro- and Macro-aggregation: Fine particles (micro-aggregates) and larger clumps (macro-aggregates) encapsulate organic matter, enhancing its stability.

Chemical Stabilization:

Humification: Conversion of plant and microbial residues into complex humic substances that are resistant to microbial decomposition.

Mineral Associations: Binding of organic molecules to soil minerals (clay particles, sesquioxides) through chemical bonds, protecting them from decomposition.

Biological Stabilization:

Microbial Products: By-products of microbial metabolism, such as microbial biomass and necromass (dead microbial cells), can form stable organic matter.

Enzymatic Protection: Some enzymes produced by soil microorganisms can inhibit the decomposition of organic matter.

CONCLUSION

Organo-mineral complexes are pivotal in soil carbon stabilization, reducing organic matter decomposition and enhancing long-term sequestration. Their formation, governed by mineralogy and environmental factors, sustains soil health, fertility and resilience. Understanding these interactions is crucial for improving soil management strategies, mitigating climate change and fostering sustainable agricultural and ecological practices.

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