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Role of Organic Matter in Pedogenic Soil Aggregation

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Soil organic matter (SOM) is a key driver of soil aggregation, influencing the formation and stabilization of micro- and macroaggregates. Aggregates enhance soil structure, improving water retention, aeration, nutrient availability, and resistance to erosion. SOM promotes aggregation through physical mechanisms (nucleation and enmeshment of soil particles), biological activity (microbial polysaccharides, glomalin, and root interactions), and chemical bonding (organo-mineral complexes with clay and cations). Well-aggregated soils support long-term carbon sequestration and soil fertility. Management practices such as organic amendments; reduced tillage, cover crops, mulching, and agroforestry enhance SOM and aggregate stability, contributing to sustainable soil health.

Keywords: Soil organic matter, Macroaggregate, Microaggregate

Introduction

Soil aggregation refers to the process by which primary soil particles—sand, silt, and clay—are bound together to form secondary structural units known as microaggregates and macroaggregates .[Soil aggregation = binding of primary soil particles (sand, silt, clay) into secondary units (micro- and macro-aggregates)].Organic matter (OM) is the main cementing agent in pedogenic aggregation. This process is fundamental to soil formation (pedogenesis) and strongly influences soil physical properties such as porosity, water infiltration, aeration, resistance to erosion, and root penetration. Among the various factors controlling soil aggregation, soil organic matter (SOM) plays a dominant and multifunctional role Tisdall (2020). Soil organic matter acts as the principal cementing agent in aggregate formation by providing physical binding materials, stimulating biological activity, and facilitating chemical interactions between organic compounds and mineral particles. Organic residues and their decomposition products serve as nuclei around which soil particles accumulate, while microbial by-products such as polysaccharides and fungal hyphae physically enmesh particles and enhance aggregate stability. In addition, functional groups present in organic matter form organo-mineral complexes with clay particles and polyvalent cations, further strengthening aggregate cohesion. Through these combined physical, biological, and chemical mechanisms, soil organic matter promotes the formation and stabilization of soil aggregates, making it a key driver of soil structure development and long-term soil health.

Soil Aggregate Dynamics and Their Role in Soil Organic Matter Stabilization: Soil aggregates—clusters of soil particles—are important for protecting SOM. Macroaggregates form rapidly and often contain fresh organic inputs, but they are less stable and decompose faster. Microaggregates form more slowly but are more stable, physically protecting SOM from decomposition. Essentially, SOM contributes to aggregate formation, and aggregates, in turn, help stabilize SOM by shielding it from microbial breakdown. This creates a feedback loop where aggregate dynamics control how much SOM is preserved in the soil, influencing soil fertility, water retention, and nutrient cycling (Even & Cotrufo., 2024).

Mechanisms

Soil organic matter forms aggregates these through three major mechanisms:
A. Physical binding (enmeshment & nucleus formation)
B. Biological binding (microbes, roots, fungi)
C. Chemical bonding (organo-mineral complexes)

A. Physical Mechanism (Nucleation & Enmeshment): In the physical mechanism of soil aggregation, soil organic matter initiates aggregate formation by providing a solid framework. Fresh organic residues such as plant litter, roots, and manure enter the soil and undergo partial decomposition to form **particulate organic matter (POM)**. This POM acts as a **nucleus or core** around which fine soil particles like clay and silt accumulate. As biological activity increases, roots and fungal hyphae grow through the soil and physically **enmesh and entangle** these particles and microaggregates, resulting in the formation of **stable macroaggregates (>250 µm)**. Thus, organic matter plays a key role by serving as a structural scaffold rather than a chemical cement in this mechanism.

1.Formation of particulate organic matter
Plant residues → Partial decomposition → Particulate Organic Matter (POM)
2. Nucleus-based aggregation
POM + Clay + Silt + Microbial products → Microaggregate formation

Enmeshment into macroaggregates

Microaggregates + Roots + Fungal hyphae → Macroaggregates (>250 µm)

B. Biological Mechanism (Microbial activity)

The biological mechanism is considered the most important process in soil aggregation because it directly links soil organic matter decomposition with aggregate formation and stabilization. Soil microorganisms utilize organic matter as an energy source and, during decomposition, produce various organic binding agents that cement soil particles together. **Glomalin** is especially resistant to decomposition → long-term stability.
Clay + OM + microbial products → **stable microaggregates (<250 µm)**
Microaggregates combine → macroaggregates

- **Role of Microbes:** Bacteria and fungi decompose organic residues and release extracellular substances such as polysaccharides, mucilage, and microbial gums. These sticky compounds coat soil particles and bind clay, silt, and organic matter into stable units. In addition, mycorrhizal fungi produce **glomalin**, a glycoprotein that strongly enhances aggregate stability by physically binding soil particles and protecting organic carbon within aggregates.
- Result of Microbial Activity:The interaction of clay particles, organic matter, and microbial binding agents leads to the formation of stable microaggregates (<250 µm). These microaggregates subsequently combine through further biological activity and physical enmeshment to form macroaggregates (>250 µm). Because glomalin and microbial polysaccharides are relatively resistant to decomposition, they contribute to the long-term stability of soil aggregates.

C. Chemical Mechanism (Organo-mineral bonding)

The chemical mechanism of soil aggregation involves interactions between soil organic matter (OM) and clay minerals. Functional groups in OM, such as **–COOH (carboxyl), –OH (phenolic), and –NH_2 (amino)**, chemically bind to **clay surfaces** and **Fe^{3+}/Al^{3+} oxides**, forming strong cation bridges and stable **organo-mineral complexes**. These complexes act as persistent cementing agents, enhancing aggregate stability and resistance to water erosion (Ashman *et al.*,2003).

1. Cation bridging:

$$Clay^{-} + Ca^{2+} + R\text{–}COO^{-} \rightarrow Clay\text{–}Ca\text{–}R$$ **(**stable organo-mineral complex)

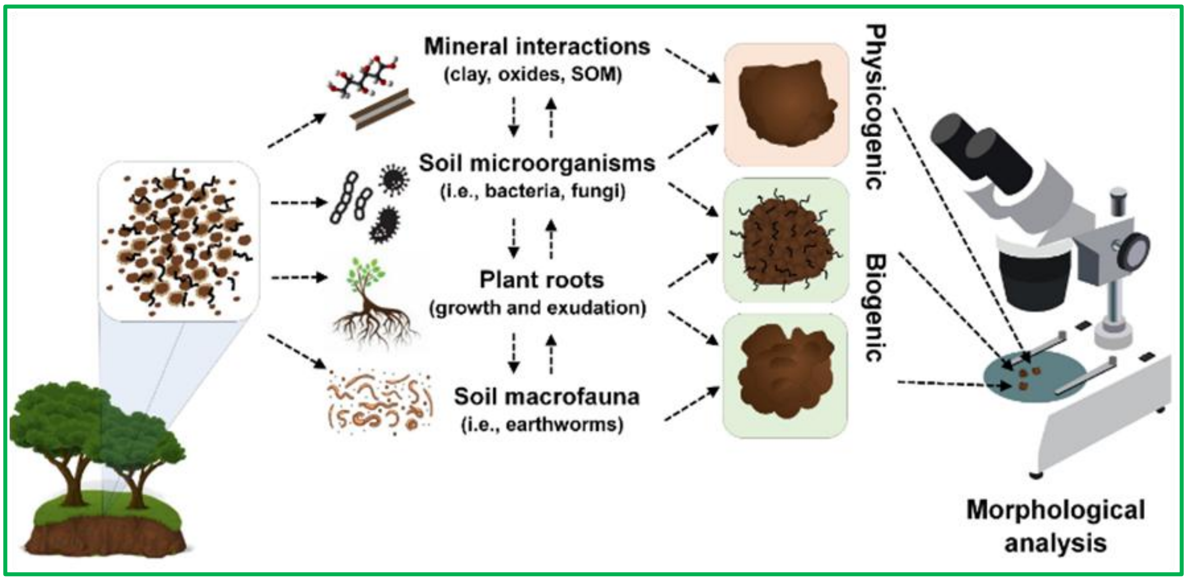
2. Organo-mineral complex formation:

Clay + Fe^{3+}/Al^{3+} + OM functional groups → (Stable organo-mineral aggregates)

Mechanism:

1. Functional groups in OM attach to clay particle surfaces.

2. Divalent/trivalent cations (Ca^{2+}, Fe^{3+}, Al^{3+}) form bridges between OM and clay.
3. The resulting organo-mineral complexes bind particles into stable **micro- and macroaggregates**.



The classification of aggregate formation pathway

Benefits of Well-Aggregated Soils

1. Improved Water Retention and Drainage: Well-formed soil aggregates create pores of different sizes. Macro-pores allow excess water to drain, preventing waterlogging, while micro-pores hold water tightly for plant use. This balance improves soil moisture availability and reduces drought stress for plants.
2. **Enhanced Root Growth and Nutrient Uptake**: Aggregates create a loose, porous structure that allows roots to penetrate easily. Better root access to soil increases the uptake of essential nutrients like nitrogen, phosphorus, and potassium, supporting healthier plant growth.
3. **Reduced Soil Erosion and Compaction**:Aggregates bind soil particles together, making the soil more resistant to wind and water erosion. They also prevent compaction by maintaining a friable structure, which allows air and water to move freely through the soil.
4. **Long-Term Carbon Sequestration**:Organic matter trapped within stable microaggregates is less accessible to microbes and decomposers. This slows down the breakdown of carbon, effectively storing it in the soil for decades and helping mitigate greenhouse gas emissions.

Management Practices to Enhance SOM and Aggregation

1. **Adding Organic Amendments:** Incorporating compost, manure, or crop residues introduces fresh organic carbon and nutrients into the soil. These inputs act as a substrate for microbial activity, which produces binding agents like polysaccharides that promote aggregate formation and stabilize SOM over time**.**
2. **Reduced Tillage:** Minimizing soil disturbance preserves the integrity of existing macro- and microaggregates. Reduced tillage maintains pore structure, protects microbial habitats, and slows the oxidation of SOM, enhancing long-term carbon storage and soil stability.
3. **Cover Crops and Crop Rotation:** Planting cover crops or rotating crops throughout the year provides continuous organic inputs and supports diverse soil microbial communities. Roots and root exudates enhance aggregate formation while preventing nutrient leaching and soil erosion.

4. Mulching: Applying mulch creates a protective layer on the soil surface that reduces erosion and temperature fluctuations. As mulch decomposes, it adds organic matter that strengthens aggregate formation and improves water retention within the soil matrix.

5. Agroforestry and Perennial Plants: Integrating deep-rooted trees and perennial plants increases the quantity and quality of organic inputs through leaf litter and root exudates. These systems enhance microbial activity, improve soil structure, and contribute to the formation of stable microaggregates that sequester carbon.

Conclusion

The integrity and functionality of soil are strongly influenced by the presence of organic constituents, which facilitate the assembly of soil particles into cohesive structural units. These structures regulate moisture distribution, aeration, nutrient availability, and resistance to physical degradation. Biological activity contributes significantly to the formation and endurance of these units, while chemical interactions between organic compounds and minerals provide persistent stabilization. Strategic management that enriches organic content and supports biological processes enhances soil resilience, productivity, and long-term carbon retention. Maintaining these structural networks is therefore critical for sustainable ecosystem functioning and agricultural efficiency.

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