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Soil Organic Matter Dynamics and Carbon Sequestration

Lunjapimon Haokip[1]*, R. P. Sharma[2], Neha Chauhan[3] and Umesh Kumar[4]

[1,4]M.Sc. Scholar, [2]Principal Scientist, [3]SMS Soil Science,
Department of Soil Science, CSK HPKV, Palampur, HP, India-176062

Corresponding Author
Lunjapimon Haokip
Email: lunjapimonhaokip@gmail.com

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ABSTRACT

Soil organic matter (SOM) is a dynamic and complex component of soil formed from plant residues, microbial biomass, and other organic inputs. It has an immense role in improving overall soil quality. In recent decades, its importance has expanded to climate change mitigation through carbon sequestration, as SOM governs carbon storage within soils. Understanding of SOM dynamics is crucial to manage carbon sequestration efficiently. Recent advances, particularly the Microbial Efficiency-Matrix Stabilization (MEMS) framework explains the formation of stable soil carbon by emphasizing substrate efficiency and stabilization mechanism. Soil carbon is classify broadly as particulate organic matter (POM) and mineral associated organic matter (MAOM), based on their stability and turnover. The carbon saturation concept disprove the idea of unlimited carbon storage in soil. Carbon storage is largely controlled by soil texture, mineral composition and microbial efficiency.

INTRODUCTION

A vital part of terrestrial ecosystem, Soil organic matter (SOM plays a crucial role in soil fertility, ecosystem productivity, and environmental sustainability (Hoffland *et al.*, 2020). It is a dynamic and complex mixture plant residues, microbial biomass and transform organic compounds that are under processed continuously in the soil system (Lehmann & Kleber, 2015). SOM is a key indicator of soil quality and ecosystem functioning, it impact greatly soil physical, chemical and biological properties (Brady & Weil, 2016). Soil properties such as aggregate formation, bulk density, porosity, buffering capacity, nutrient availability and microbial diversity etc are all influence by SOM. Sources of soil include plant litters, the primary source, organic manures applied in fields, waste from towns and cities such as sewage and night soil, carcases of dead animal etc. Below ground inputs including rhizodseposition, released chemical compounds such as sugars, polysaccharides, organic acids etc. which also contribute to SOM addition in soil (Jones *et al*., 2009).

Human activities also influence SOM significantly, it can either enhanced or deteriorate the SOC in soil. In agricultural system were organic amendments such as compost, farm yard manure etc are applied, SOC level will be higher than those manage conventionally. When organic amendments are added, they provide substrate for microbial processing enhancing SOM content and supporting soil functional capacity (Lal. 2020). All these different inputs are continuously processed by microbe in soil, which govern its decomposition, transformation and stabilization of SOM (Cotrufo *et al*., 2013).

Soil system have a profound importance on global carbon cycle and climate regulation as it is one of the largest reservoirs, containing more carbon than the atmosphere and terrestrial combined (Schmidt *et al*., 2011). Soil carbon in soil is regulated by the amount of SOM inputs, its quality and quantity and the actions of different soil microbes. In recent decades, increasing concerns over climate change have highlighted the importance of SOM as a key component of carbon sequestration strategies (Sierra & Crow, 2022). SOM influences water regulation, nutrient cycling, soil erosion, soil-atmosphere interaction including greenhouse gas emission and carbon sequestration (Lal, 2004). Consequently, maintaining and enhancing SOM is very important both from agricultural and climate change mitigation point of view.

Composition and Fractions of Soil Organic Matter

Soil organic matter (SOM) is a heterogeneous complex material derived from plant, microbial, and animal sources, existing at different stages of decomposition (Lehmann & Kleber, 2015). It consist of decaying debris mainly of plant origin including fallen leaves, stems, and crop residues, organic inputs etc. that provide the foundational substrate for stable soil organic carbon formation ((Islam *et al*., 2022). Living beings including the diverse soil fauna are also part of SOM. Also soil fauna, both macro and micro fauna, plays a critical role in SOM dynamics. They are responsible for fragmenting plant residues, releasing enzymes, formation of substrate that ultimately leads to formation of soil carbon.

Classical classification of soil organic pools is based on turnover period (Cotrufo *et al*., 2013). Three pools, active- those that are under rapid composition having a turnover period of 2 months to 2.5 years, slow pool- these pools include partially decomposed SOM with turnover period of 8-50 years, passive pool- these are stable fraction having turnover period of upto 2000 years and are very important for carbon sequestration. Modern frameworks further refined this classification into functional pools based on their accessibility and stabilization mechanism. Broadly modern framework has two pools- particulate organic matter (POM) and mineral associated organic matter (MAOM) (Lavallee *et al*., 2019). POM are further sub-classify by many researchers as fresh (fPOM) - represent unprotected plant residue undergoing rapid decomposition comparable to the active pool of classical classification, occluded (oPOM)- those protected physically within aggregates and comparable to the slow pool of classical classification. MAOM are those that are strongly bound to mineral surfaces present in soil, they are very stable and comparable to passive pool. The modern pools can be obtain practically by manipulating the density and size of different SOM. POM corresponds to organic carbon associated with soil particle size greater than 50 µm and density less than 1.65 g/cm^3 and MAOM with soil particles less than 50 µm and density greater than 1.65 g/cm^3 (Lavallee *et al*., 2019).

Soil Organic Matter Dynamics: MEMS Framework (Cotrufu *et al.* 2013)

SOM dynamic refers to process that leads to the transformation of fresh organic matter to formation of stable soil carbon in the soil. One way to understand this transformation is through a framework proposed by Cotrufu *et al*. (2013) - The Microbial Efficiency-Matrix Stabilization (MEMS) framework. This framework differ from classical humus theory on their concept on the formation of stable soil carbon. MEMS framework state that stable soil carbon is mainly a result of stabilization mechanism whereas humus theory conclude stable soil carbon is due to its recalcitrant nature. With the advancement in technology, with more refined research and experiments, many evidences seems to agree with the MEMS framework.

MEMS framework emphasis on two pillars, substrate use efficiency (SUE) and stabilization mechanism. The process begin with input of organic matter into soil, these inputs are attacked by microbes in soil, undergoing bio-chemical processes. The inputs differ in their quality, some may have high C:N ratio, more lignin content etc. These influence their decomposition rate, organic material with high lignin content will required more enzymes to decomposed resulting in more energy spend by microbes and loss of C in the form of CO_2 through respiration. Hence that material has low SUE and is not favourable for C sequestration. After this is stabilization, the by-products of decomposition can be stabilize by three mechanism a) Chemical- stable carbon is due to the recalcitrant nature of the compound itself b) Physical- here, soil carbon are trapped inside soil aggregates c) Mineral surface protection- stabilization here is due to formation of bonds, adsorption on Fe, Al oxides etc. Physical and chemical stabilization are not for a very long period and they corresponds to the slow pools. MAOM correspond to the passive pool that are important for long term carbon storage.

Carbon Sequestration in Soil and carbon saturation concept

Carbon sequestration in simple term means capturing atmospheric CO_2 storing it in the soil (Lal, 2004). The process begins with plant photosynthesis where atmospheric C is converted into organic carbon and allocated into various plant components, including leaves, stems, and roots (Das *et al*., 2025). Then the C enter the soil system as litter fall, rhizodesposition, carcases of dead animals etc. Once in the soil, as mentioned before, organic carbon undergoes transformation through microbial processes that regulate its fate. During this process, some carbon are loss to the atmosphere through microbe's respiration and others form microbial by-products which are substrate for formation of stable soil carbon.

Earlier, it was assume that, as long as there is continuous supply of organic matter to soil, the soil carbon content increase indefinitely. Hassink (1997) was one the pioneer researcher to disprove this concept. Through his experiment he showed that soil has limited capacity to stored C. He revealed that even when total soil carbon differs due to different land-use, carbon associated with mineral particles relatively constant indicating a saturation limit. The findings establish that the type of soil texture influence the upper boundary of carbo storage. Soils with higher amount of fine texture can stored more C than those that have coarse or sandy texture. This is so because fine texture soil like clay has huge number of stabilization site and also large surface area.

CONCLUSION

The role of SOM is central not only to soil fertility and quality but also in climate change mitigation through carbon sequestration. The dynamics of SOM are governed by organic inputs, microbial activity and stabilization mechanisms. Modern concept- MEMS framework, and the distinction between different pools of SOM provide a clear understanding of how stable carbon in soil is formed. Carbon saturation concept highlights the limitation of carbon storage, emphasizing the importance of soil texture and stabilization than continuous organic matter input alone. Furthermore, the quality of SOM, their chemical composition influence SUE, subsequently carbon stabilization. Interaction between organic materials and soil minerals such as Fe, Al oxidese etc and also soil aggregation are crucial in stabilization of soil carbon. Hence, carbon sequestration is a result of complex interaction between biological, chemical and physical processes that regulate long term carbon storage in soils.

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