Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.30514

Investigating the Binding Mechanism of Organic Carbon and Minerals in Paddy Soil Using Synchrotron-Based 3D Computed Tomography and Projection X-ray Microscopy

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Soil, as the largest terrestrial carbon reservoir, plays a crucial role in regulating atmospheric CO_2 concentrations, where even slight changes in soil organic carbon (SOC) can have significant impacts. Therefore, enhancing SOC stability and long-term storage is essential for effective carbon emission reduction strategies. This study focuses on the role of mineral-associated organic matter (MAOM) in stabilizing SOC.

We collected 80 paddy soil samples from various soil orders in Taiwan and utilized synchrotron-based X-ray absorption spectroscopy (XAS) to identify iron species present in the soils. The results revealed that siderite dominated the iron mineral composition in the topsoil of all paddy soil orders, except for Ultisol/Oxisol soils. In Inceptiaol and Entisol soils, siderite accounted for more than 50% of the total iron minerals, reaching up to 95% in some cases, whereas Ultisol/Oxisol soils were primarily composed of ferric iron minerals.

To further investigate the organic-mineral interactions, we conducted synchrotron-based 3D computed tomography (3D-CT) to quantify the contact area between organic matter and mineral surfaces. Principal component analysis (PCA) of contact area, iron mineral type, and MAOC content revealed a strong positive correlation between contact area and ferric iron mineral content, confirming that SOC associated with ferric iron minerals is primarily present as MAOC.

In contrast, ferrous iron minerals exhibited a negative correlation with contact area, suggesting that in siderite-rich, fine soil particles (<53 μm), SOC is likely stabilized through organic-organic linkages rather than direct mineral associations. In this context, ferrous iron may act as a bridging agent between organic molecules, implying that SOC within <53 μm particles—classified as MAOC—has the potential for indefinite accumulation.

These findings provide new insights into the role of iron minerals in SOC stabilization, with potential implications for enhancing carbon sequestration in paddy soils through targeted soil management strategies.