間歇灌溉影響水稻田土壤的有機質微生物轉化與碳固存品質

Alternative wetting and drying irrigation transforms soil organic matter quality and microbial processes in rice paddies

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摘要

再生農業專注於提升土壤健康並促進長期碳穩定。本研究探討灌溉制度對水稻土壤有機碳 (SOC) 分子組成的影響，及其對微生物群落結構和功能潛力的作用。透過 ^{13}C 固態核磁共振光譜技術，我們觀察到間歇灌溉 (AWD) 增加了芳香族碳的相對豐度，但降低了烷基碳/含氧烷基碳比值，顯示微生物轉化加劇並形成更穩定、腐殖化的碳結構。相較之下，傳統灌溉 (CI) 與較高比例的烷基碳和含氧烷基碳相關，反映了相對不穩定的植物來源化合物的累積。

儘管總有機碳含量在兩種處理間保持穩定，但間歇灌溉顯著提高了微生物生物量碳和可溶性碳組分，表明微生物活性和周轉率增加。16S rRNA 基因定序和 qPCR 分析揭示了間歇灌溉下獨特的群落結構，隨後基於 PICRUSt2 的功能預測進一步闡明了微生物代謝潛力。這些發現突顯間歇灌溉促進碳腐殖化並增強微生物驅動的生物地球化學過程，為農業生態系統中灌溉誘導的土壤碳品質調節提供了新的見解。

中文關鍵字：間歇灌溉、水稻、土壤有機碳、^{13}C 核磁共振光譜、土壤微生物、碳固存

Abstract

Regenerative agriculture focuses on enhancing soil health and promoting long-term carbon stabilization. This study investigates the impact of irrigation regimes on the molecular composition of soil organic carbon (SOC) and their effects on microbial community structure and functional potential in paddy soils. Using ^{13}C solid-state NMR spectroscopy, we observed that alternative wetting and drying (AWD) increased the relative abundance of aromatic carbon but decreased the alkyl C/O-alkyl C ratio, indicating intensified microbial transformation and the formation of more stabilized, humified carbon structures. In contrast, conventional irrigation (CI) was associated with higher proportions of alkyl and O-alkyl carbon, reflecting the accumulation of relatively labile plant-derived compounds. Although total SOC content remained stable between treatments, AWD significantly enhanced microbial biomass carbon and soluble carbon fractions, suggesting greater microbial activity and turnover. 16S rRNA gene sequencing and qPCR analyses revealed distinct community structures under AWD, with subsequent PICRUSt2-based functional predictions to further elucidate microbial metabolic potential. These findings highlight that AWD irrigation promotes carbon humification and enhances microbial-driven biogeochemical processes, providing novel insights into irrigation-induced regulation of soil carbon quality in agroecosystems.

英文關鍵字： alternate wetting and drying, rice paddy soil, soil organic carbon fractionation, ^{13}C NMR spectroscopy, microbial community structure, carbon stabilization