IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, June 2021
Impact Factor: 5.731

Multimodal Deep Learning for Soil Health Assessment and Sustainable Fertilizer Recommendation Using Hyperspectral and Sensor Data

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Abstract: *Soil degradation and imbalanced fertilizer application threaten global food security, affecting over 33% of arable land worldwide. Traditional soil assessment relies on labor-intensive laboratory testing and generalized recommendation systems, failing to capture spatial heterogeneity and dynamic nutrient interactions. We propose a Multimodal Deep Learning Framework for Soil Health and Fertilizer Optimization (MDL-SHFO) that integrates hyperspectral imagery with in-situ sensor data using a novel attention-fusion architecture. Our framework employs three analytically distinct components: (1) a Dual-Stream Spectral-Sensor Encoder that extracts hierarchical features from hyperspectral cubes (400-2500 nm) and IoT sensor streams (pH, EC, moisture, temperature); (2) a Cross-Modal Attention Fusion Module that dynamically weights modality-specific contributions based on field-specific uncertainty; and (3) a Sustainable Recommendation Generator using integrated gradients and attention visualization to produce interpretable, site-specific fertilizer prescriptions. Validated on multi-region agricultural datasets (N=4,215 field plots), MDL-SHFO achieves 96.2% accuracy in soil health classification, 94.8% precision in nutrient deficiency detection, and reduces fertilizer over-application by 31.4% compared to conventional methods. The framework provides transparent decision rationales, highlighting spectral absorption features linked to organic matter and sensor-derived moisture-nutrient interactions, thereby supporting precision agriculture and environmental sustainability.*

Keywords: Soil Health Assessment, Multimodal Deep Learning, Hyperspectral Imaging, Precision Agriculture, Sustainable Fertilization, Explainable AI, IoT Sensors