Abstract

Intensified rice–wheat rotations increase greenhouse gas emissions through straw incorporation and puddled transplanted rice. While combining rotary straw return with furrow-irrigated, directly dry-seeded rice (DDR) shows promise in mitigating emissions, a decision support tool to guide such practices remains underdeveloped. Such a tool is essential for optimizing energy and water footprints, methane (CH_4) emission risks, and tailwater reuse. Moreover, the mechanistic basis for integrating these optimizations with water conservation practices remains unclear. Therefore, this study proposes a finite element (FE)-model predictive control (MPC) framework, developed by coupling Hydrus 2D/3D with a closed-loop optimal model. The system is designed to optimize energy costs and water use in DDR under straw return and varying field conditions, including bare soil, biodegradable film mulching, and tailwater reuse. Experimental validation, data collection, and field case studies were conducted in Babaiqiao, Nanjing, China, during 2023 and 2024 seasons. These activities included rotary straw incorporation, furrow-ridge layouts, dry-seeded rice cultivation, soil hydraulic experiments, tailwater recovery and reuse, and relevant agronomic management. Hydrus 2D/3D effectively simulated wetting rates and soil moisture content for bare and film-mulched ridges, at R^2 of 0.79 and 0.89, and 0.80 and 0.90, respectively. Predictive control and tailwater reuse had statistically significant ($p < 0.05$) effects on energy and water consumption. Integrating film mulching with the FE-MPC framework reduced cumulative water use by 38.0 %. When applied with tailwater reuse, the system offset up to 34.9 % of freshwater demand. In bare furrow-ridge, the controller achieved energy cost savings of up to 32.8 and 41.8 % without and with tailwater reuse, respectively. Film mulching increased energy savings by 53.7 and 62.7 % compared to conventional alternating wetting and drying. The study provides practical strategies, which optimize energy costs and mitigate soil anoxia and tailwater-related pollution risks, thereby reducing the environmental footprint of rice–wheat rotations.