Resource Efficiency Analysis of Hierarchical ANN-Supervised Gain-Scheduled PID Control in Inline Fertigation: A Fertilizer Over-Injection Quantification Framework

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Abstract

Electrical conductivity (EC)-based fertigation systems are widely used in precision agriculture for automated nutrient delivery; however, transient EC overshoot caused by inadequate gain adaptation can lead to fertilizer over-injection, increased input costs, and potential risks to crop health. Although adaptive control strategies have been introduced to improve EC regulation, quantitative frameworks linking closed-loop performance to fertilizer waste and economic impact remain limited. This study presents a resource-efficiency quantification framework for a hierarchical artificial neural network (ANN)-supervised gain-scheduled proportional–integral–derivative (PID) control architecture in inline fertigation systems. The proposed framework converts the over-injection index (OII), defined as the cumulative EC deviation above the setpoint, into equivalent excess fertilizer mass using an experimentally calibrated EC-to-concentration coefficient, and subsequently estimates fertilizer cost based on representative commercial pricing. The framework was evaluated using 1,000 synthesized operating regimes covering heterogeneous hydraulic conditions, comparing the hierarchical ANN-supervised controller (H-ANN) with two fixed-gain PID baselines representing aggressive (R1) and conservative (R2) tuning strategies. Results show that H-ANN reduces excess fertilizer consumption by 92.90% relative to R1 and 47.98% relative to R2, with corresponding cost reductions. H-ANN also achieves a 100% acceptable response rate, compared with 86.10% for R1 and 95.80% for R2. These findings indicate that hierarchical supervisory adaptation can improve EC regulation while providing quantifiable fertilizer and cost savings, supporting resource-efficient precision fertigation.

Keyword: fertigation, electrical conductivity regulation, gain-scheduled PID, artificial neural network, precision agriculture