

The 11th Asian-Australasian Conference on Precision Agriculture (ACPA 11)  
October 14-16, 2025, Chiayi, Taiwan

## DEVELOPMENT OF AN IN-LINE SC-ISE SENSOR SYSTEM FOR CLOSED HYDROPONIC NUTRIENT MONITORING

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### INTRODUCTION

Nutrient monitoring is crucial in closed hydroponic systems, where accurate control over individual ion concentrations directly influences crop yield and fertilizer efficiency. While electrical conductivity (EC) sensors are commonly used, they only measure total ionic strength and cannot distinguish between specific ions. Liquid-contact ion-selective electrodes (LC-ISEs) have been studied as an alternative but tend to suffer from durability issues and signal instability under the high-flow conditions typically found in hydroponic pipelines. These limitations make them difficult to use over the long term and unsuitable for large-scale hydroponic cultivation. Solid-contact ion-selective electrodes (SC-ISEs) possess structural stability and reduced signal drift, which help address the limitations of liquid-contact electrodes (Gao et al., 2024). In this study, SC-ISEs incorporating poly(3,4-ethylenedioxythiophene) (PEDOT), single-walled carbon nanotube (SWCNT), and multi-walled carbon nanotube (MWCNT) were developed and tested within an in-line sensing setup. The objective of this work is to evaluate their applicability for continuous ion monitoring in closed-loop hydroponic systems.

**Keywords:** SC-ISEs, Hydroponic nutrient solution management, In-line ion sensing

### MATERIALS AND METHODS

#### ELECTRODE FABRICATION

SC-ISEs were fabricated using poly(vinyl chloride) (PVC) rods as electrode bodies, with copper wires embedded to serve as internal conductors. Three solid-contact materials PEDOT:PSS, SWCNT, and MWCNT were drop-cast onto the exposed copper ends. The carbon nanotubes were first dispersed in tetrahydrofuran (THF) before coating, while PEDOT:PSS was mixed with cetyltrimethylammonium bromide (CTAB) prior to application. A potassium-selective ion-selective membrane (ISM) was prepared with reference to previously reported methods (Jung et al., 2015). The ISM solution, consisting of PVC, a plasticizer, and an ionophore dissolved in

THF, was cast onto the solid-contact layer and dried to form a stable membrane. All electrodes were conditioned in 0.01 M KCl solution prior to testing.

## DATA ACQUISITION

Electromotive force (EMF) measurements were conducted using a Raspberry Pi integrated with an MCP3208 analog-to-digital converter (ADC). The recorded signals were analyzed to evaluate the performance of each solid-contact material.

## RESULTS & DISCUSSION

The LC-ISE demonstrated a sensitivity of approximately 28 mV/dec. Among the SC-ISEs, the PEDOT-based electrode showed a moderate sensitivity of around 20 mV/dec, with an improvement trend at higher ion concentrations. However, it also exhibited noticeable signal noise. In contrast, both SWCNT and MWCNT-based electrodes failed to show clear sensitivity and experienced continuous signal drift at approximately  $-2$  mV/s. This problem likely resulted from fabrication process. Since the nanotubes were applied in powder form, it is possible that voids or air bubbles formed between the solid-contact layer and the ion-selective membrane, leading to unstable performance.

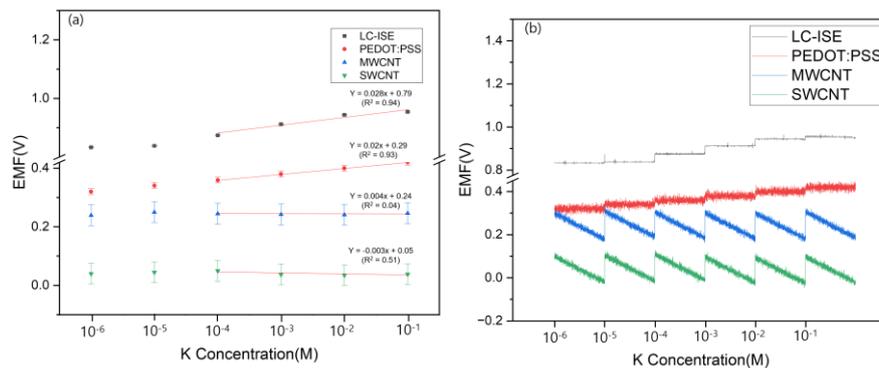


Fig.1 (a) Average measurement results at various  $K^+$  concentration, (b) Measurement results of electrodes with different materials at various  $K^+$  concentrations.

## CONCLUSIONS

This study evaluated the use of SC-ISEs for nutrient monitoring in hydroponic systems. The PEDOT-based SC-ISE showed reasonable sensitivity but was affected by signal noise. Electrodes using carbon nanotubes showed significant signal drift, likely caused by fabrication-related issues. In future studies, the fabrication process will be refined to improve the performance of the electrodes. Such improvements will be critical for the development of SC-ISEs that can support reliable, long-term, in-line nutrient monitoring in closed hydroponics.

## ACKNOWLEDGEMENTS

This research was supported by the project "Development and Commercialization of a Recirculating Nutrient Solution Supply System for Intelligent Smart Greenhouses Based on AI and Big Data for Crop Growth and Environmental Management" (RS-2025-0230299061382116530101) funded by the Korea Institute of Planning and Evaluation for

Technology in Food and “Establishment of a New Agricultural Climate Change Response System” (G24004007872) funded by the Rural Development Administration of Korea..

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