ABSTRAK

Pertumbuhan populasi global dan proyeksi FAO bahwa 70% penduduk dunia akan tinggal di kawasan urban pada tahun 2050 menimbulkan tekanan signifikan terhadap sistem produksi pangan. Di Indonesia, 96% penduduk masih kurang mengonsumsi sayuran dengan rata-rata konsumsi 240,5 gram per hari, jauh di bawah rekomendasi WHO sebesar 400 gram per hari. Hidroponik indoor menawarkan solusi untuk meningkatkan produktivitas pangan di kawasan urban, namun manajemen manual parameter pH dan Electrical Conductivity (EC) larutan nutrisi memerlukan monitoring berkala 2-3 kali sehari yang time-intensive dan rentan terhadap human error. Review sistematis terhadap 89 studi sistem dosing nutrisi mengidentifikasi dua gap fundamental: minimnya implementasi kompensasi temperatur untuk pembacaan pH dan EC, serta kurangnya dokumentasi prosedur kalibrasi yang detail dan replicable.

Penelitian ini mengembangkan framework IoT komprehensif berbasis ESP32 dengan Rule-Based Control untuk sistem otomasi nutrisi hidroponik indoor pada sawi pagoda. Metode pengembangan sistem menggunakan prototyping dengan tahapan analisis kebutuhan, perancangan sistem, pembuatan prototipe, evaluasi, implementasi, dan pengujian. Framework mencakup arsitektur terintegrasi empat layer: sensing (pH, EC/TDS, DS18B20, DHT21, SGP30), processing (ESP32 dengan algoritma Rule-Based Control), communication (protokol MQTT), dan application (real-time dashboard monitoring dengan database Supabase). Sistem dilengkapi prosedur kalibrasi detail meliputi two-point pH calibration menggunakan buffer pH 4.0 dan 7.0, EC calibration pada 1413 μS/cm dengan temperature normalization ke 25°C, serta karakterisasi aktuator peristaltic pump. Evaluasi performa dilakukan melalui dual approach: metrik kontrol teknis (akurasi sensor, settling time, time-in-range) dan validasi biologis (pertumbuhan tinggi, jumlah daun, indeks SPAD).

Hasil penelitian menunjukkan seluruh sensor memiliki akurasi tinggi dengan error di bawah 5% sesuai standar IEC No 13B-23. Pompa peristaltik mencapai akurasi volume dispensing dengan error maksimal 10%. Sistem monitoring real-time beroperasi dengan response time ≤5 detik dan uptime 100%, dengan penyimpanan data historis setiap 10 menit ke cloud. Validasi biologis selama 35 hari membuktikan efektivitas sistem dengan korelasi kuat antara stabilitas parameter TDS dan pH terhadap pertumbuhan tanaman sawi pagoda. Penelitian ini berkontribusi menyediakan framework IoT yang replicable untuk implementasi hidroponik indoor skala kecil dengan dokumentasi lengkap meliputi wiring diagram, Bill of Materials, prosedur kalibrasi, dan evaluasi dual approach yang menjembatani gap antara metrik performa kontrol teknis dengan produktivitas tanaman.

Kata Kunci: Internet of Things, Hidroponik Indoor, Rule-Based Control, Monitoring Real-time, Sawi Pagoda

ABSTRACT

Global population growth and FAO projections that 70% of the world's population will live in urban areas by 2050 pose significant pressure on food production systems. In Indonesia, 96% of the population still lacks vegetable consumption, averaging 240.5 grams per day, far below the WHO recommendation of 400 grams per day. Indoor hydroponics offers a solution to increase food productivity in urban areas, however manual management of nutrient solution pH and Electrical Conductivity (EC) parameters requires 2-3 times daily monitoring which is time-intensive and prone to human error. A systematic review of 89 nutrient dosing system studies identified two fundamental gaps: minimal implementation of temperature compensation for pH and EC readings, and lack of detailed and replicable calibration procedure documentation.

This research develops a comprehensive ESP32-based IoT framework with Rule-Based Control for indoor hydroponic nutrition automation system for pak choi pagoda. The system development method uses prototyping with stages of requirement analysis, system design, prototype creation, evaluation, implementation, and testing. The framework includes an integrated four-layer architecture: sensing (pH, EC/TDS, DS18B20, DHT21, SGP30), processing (ESP32 with Rule-Based Control algorithm), communication (MQTT protocol), and application (real-time monitoring dashboard with Supabase database). The system is equipped with detailed calibration procedures including two-point pH calibration using pH 4.0 and 7.0 buffers, EC calibration at 1413 µS/cm with temperature normalization to 25°C, and peristaltic pump actuator characterization. Performance evaluation is conducted through a dual approach: technical control metrics (sensor accuracy, settling time, time-in-range) and biological validation (height growth, leaf count, SPAD index).

Research results show that all sensors have high accuracy with errors below 5% according to IEC No 13B-23 standards. Peristaltic pumps achieve volume dispensing accuracy with a maximum error of 10%. The real-time monitoring system operates with a response time of ≤5 seconds and 100% uptime, with historical data storage every 10 minutes to the cloud. Biological validation over 35 days proves system effectiveness with strong correlation between TDS and pH parameter stability on pak choi pagoda plant growth. This research contributes by providing a replicable IoT framework for small-scale indoor hydroponics implementation with complete documentation including wiring diagrams, Bill of Materials, calibration procedures, and dual approach evaluation that bridges the gap between technical control performance metrics and plant productivity.

Keywords: *Internet of Things, Indoor Hydroponics, Rule-Based Control, Real-time Monitoring, Pak Choi Pagoda*