

**PENGEMBANGAN *EARLY WARNING SYSTEM* KUALITAS UDARA
BERBASIS *INTERNET OF THINGS* STUDI KASUS LINGKUNGAN
INDUSTRI TAHU DESA SAMBAK KECAMATAN KAJORAN
KABUPATEN MAGELANG
INTISARI**

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Industri tahu skala kecil dan menengah di Desa Sambak merupakan salah satu sumber emisi partikulat dan gas pencemar yang berpotensi menurunkan kualitas udara di lingkungan. Penelitian ini merupakan bagian dari upaya mendukung Program Kampung Iklim (ProKlim) Desa Sambak dalam penyediaan data kualitas lingkungan berbasis teknologi. Penelitian bertujuan merancang, mengimplementasikan, dan mengevaluasi *Early Warning System* (EWS) kualitas udara berbasis *Internet of Things* (IoT) pada satu industri tahu terpilih. Sistem dirancang dengan mengintegrasikan sensor *industrial grade* (PM_{2.5}, PM₁₀, CO, SO₂, NO₂, O₃, suhu, kelembapan), mikrokontroler ESP32, *Human Machine Interface* (HMI), basis data, *dashboard*, dan *onsite notification* tiga warna untuk pemantauan ambien secara *real-time* dengan interval perekaman 1 menit dan pengolahan konsentrasi polutan menjadi Indeks Standar Pencemar Udara (ISPU) menggunakan pendekatan algoritma GLBB sebagai dasar prediksi peringatan dini. Sistem dipasang pada satu titik pengamatan yang mewakili area aktivitas pekerja. Pengambilan data lapangan dilaksanakan selama 7 hari (9–15 Maret 2026) melalui tiga metode secara simultan: (1) perekaman otomatis sensor ke basis data *cloud*, (2) pencatatan manual aktivitas produksi, dan (3) pengukuran paralel seluruh parameter sensor dengan alat pembanding terstandar untuk validasi. Evaluasi mencakup kinerja operasional, validasi sensor (R², MAPE, RMSE), dan ketepatan prediksi kategori EWS. Hasil menunjukkan sistem beroperasi kontinu dengan konsumsi daya 103 watt. Sensor PM_{2.5} dan PM₁₀ mencatat kinerja terbaik dengan R² sebesar 0,9926 dan 0,9711. Nilai ISPU selama pengamatan: PM_{2.5} 82,57-260,70 (sedang-sangat tidak sehat); PM₁₀ 43,54-167,08 (baik-tidak sehat); NO₂ 3,80-102,59 (baik-tidak sehat); O₃ 0,00–69,02 (baik-sedang); SO₂ 1,65-9,09 (baik); dan CO 0,00-13,46 (baik). Rata-rata ISPU PM_{2.5} selama periode pengamatan sebesar 141,79 (kategori tidak sehat), mengindikasikan adanya risiko paparan partikulat terhadap pekerja yang berkorelasi dengan aktivitas pembakaran *boiler* dan proses pemasakan tahu. EWS mencatat 11 kesalahan prediksi yang seluruhnya terjadi di sekitar ambang batas kategori ISPU. Sistem EWS berbasis IoT yang dikembangkan terbukti mampu berfungsi sebagai alat pemantauan dan peringatan dini kualitas udara *real-time*, sekaligus sebagai sarana perlindungan keselamatan kerja di lingkungan industri tahu Desa Sambak.

Kata kunci: Indeks Standar Pencemar Udara (ISPU), industri tahu, *Internet of Things*, kualitas udara, *Early Warning System*, PM_{2.5}

**DEVELOPMENT OF AN INTERNET OF THINGS-BASED AIR
QUALITY EARLY WARNING SYSTEM: A CASE STUDY OF THE TOFU
INDUSTRY ENVIRONMENT IN SAMBAK VILLAGE, KAJORAN
DISTRICT, MAGELANG REGENCY**

ABSTRACT

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Small and medium-scale tofu industries in Sambak Village are a significant potential source of particulate and gaseous pollutant emissions that can degrade local air quality. This research is part of broader efforts to support the Sambak Village Climate Program (ProKlim) by providing technology-based environmental data. The study aimed to design, implement, and evaluate an Internet of Things (IoT)-based Air Quality Early Warning System (EWS) at a selected tofu production facility. The system was developed by integrating industrial-grade sensors (PM_{2.5}, PM₁₀, CO, SO₂, NO₂, O₃, temperature, and humidity), an ESP32 microcontroller, a Human Machine Interface (HMI), a cloud database, a web dashboard, and a three-color onsite notification for real-time ambient monitoring at a 1-minute recording interval. Pollutant concentrations were processed into the Indeks Standar Pencemar Udara (ISPU) using a Uniformly Accelerated Motion (GLBB)-based algorithmic approach as the predictive basis for early warning. The system was deployed at a single monitoring point representative of the workers' activity area. Field data collection was conducted over 7 days (9–15 March 2026) through three simultaneous methods: (1) automatic sensor recording to a cloud database, (2) manual logging of production activities, and (3) parallel measurement of all sensor parameters against standardized reference instruments for validation. Evaluation covered operational performance, sensor validation (R², MAPE, and RMSE), and EWS category prediction accuracy. Results showed that the system operated continuously at a power consumption of 103 watts. The PM_{2.5} and PM₁₀ sensors achieved the best performance, with R² values of 0.9926 and 0.9711, respectively. ISPU values recorded during the observation period were as follows: PM_{2.5} 82.57–260.70 (moderate–very unhealthy); PM₁₀ 43.54–167.08 (good–unhealthy); NO₂ 3.80–102.59 (good–unhealthy); O₃ 0.00–69.02 (good–moderate); SO₂ 1.65–9.09 (good); and CO 0.00–13.46 (good). The mean PM_{2.5} ISPU over the observation period was 141.79 (unhealthy category), indicating a risk of particulate exposure for workers strongly correlated with boiler combustion activities and the tofu cooking process. The EWS recorded 11 prediction errors, all of which occurred near the ISPU category thresholds. The developed IoT-based EWS was demonstrated to function as a real-time air-quality monitoring and early-warning device, as well as a means of occupational safety protection within the tofu industrial environment of Sambak Village.

Keywords: air quality, early warning system, Indeks Standar Pencemar Udara (ISPU), Internet of Things, PM_{2.5}, tofu industry