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Development and laboratory validation of a low-cost $PM_{2.5}$ and CO sensor network for indoor air quality assessment in residential heating environments

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Low-cost air quality sensors have emerged as a powerful tool to complement traditional monitoring networks by enabling high spatial and temporal resolution observations at a fraction of the cost of reference instruments. However, their application in indoor environments, particularly in residential settings affected by combustion-based heating, remains limited despite the significant health risks associated with indoor air pollution.

In this study, we present the development and laboratory validation of a low-cost, modular sensor designed for real-time monitoring of fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), temperature, and relative humidity in residential indoor environments. The system is based on open-source hardware and integrates an optical $PM_{2.5}$ sensor, a CO gas sensor, and environmental sensors coupled to an ESP32 microcontroller, enabling continuous data acquisition, local storage (microSD), real-time visualization (OLED display), and wireless data transmission. The device is housed in a custom-designed 3D-printed enclosure optimized for airflow, sensor protection, and portability.

Following laboratory validation against certified reference instruments, the sensor units will be deployed inside dwellings equipped with different residential heating systems, including wood-burning stoves, kerosene heaters, and electric heating. The instruments will be distributed across multiple indoor spaces within each household (e.g., living rooms, bedrooms, and kitchens) to characterize the spatial distribution of pollutants and to assess how combustion emissions propagate through different indoor microenvironments under real living conditions.

A total of ten sensor units were assembled and evaluated under controlled laboratory conditions through side-by-side comparison with reference instruments. The validation protocol focused on accuracy, temporal stability, inter-sensor consistency, and operational robustness. The results show good agreement with reference measurements for both $PM_{2.5}$ and CO, demonstrating that

the system provides reliable and stable observations suitable for indoor air quality applications.

The inclusion of CO, temperature, and humidity monitoring represents a key advancement of the system, allowing for a more comprehensive characterization of combustion emissions, ventilation conditions, and indoor comfort. This integrated approach supports both chronic exposure assessment and acute risk detection, including the identification of potentially lethal CO accumulation events in poorly ventilated dwellings.

This work demonstrates the feasibility of deploying low-cost sensor networks for high-resolution indoor air quality monitoring and highlights their potential for citizen science initiatives, stove replacement programs, environmental health studies, and policy support in regions affected by residential combustion emissions.