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Prototype development of an early warning system for methane, sulphur dioxide, and nitrogen dioxide exposure in municipal landfills

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ABSTRACT

Municipal solid waste landfills in developing countries often operate under poor environmental controls, leading to high emissions of hazardous gases such as methane (CH_4), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). These gases contribute to climate change, poor air quality, and respiratory health issues among nearby populations, particularly informal waste workers. Despite these risks, most landfill sites lack affordable, real-time monitoring systems. This study presents the design and development of a prototype early warning system for landfill gas exposure, integrating environmental health risk assessment with embedded sensor technology. The system uses MQ-series sensors to detect CH_4, NO_2, and SO_2, calibrated to convert output into µg/m³. Safe concentration thresholds were calculated based on inhalation rate, exposure duration, and reference doses (RfC), enabling the device to activate alarms when gas concentrations exceed health-based limits. Simulation tests were conducted in four scenarios: inorganic waste combustion, organic waste combustion, lighter gas exposure, and vehicle exhaust. Results showed strong detection performance for CH_4, particularly under lighter gas exposure (peak: 1.589 µg/m³), with rapid response time (< 10 seconds) and high model accuracy ($R^2 = 0.977$). NO_2 and SO_2 remained at low or undetectable levels, indicating a need for improved sensitivity. The prototype offers a low-cost, portable, and replicable solution for high-risk landfill settings. It enables early hazard detection and supports risk-informed decision-making for landfill workers and local authorities. Future work should include sensor enhancement, digital integration, and field validation to strengthen the system's applicability in real-world landfill environments.

Keywords: air pollution, early warning system, landfill ga, methane, nitrogen dioxide, sulphur dioxide.

INTRODUCTION

Climate change and global warming remain the most pressing global environmental challenges, driven primarily by the uncontrolled release of greenhouse gases (GHGs) and air pollutants into the atmosphere (Blair and Mataraarachchi, 2020; Soeder, 2025). Among the major contributors to this problem are municipal solid waste (MSW) landfills, especially in developing countries where the majority of waste disposal sites still operate under the open dumping method. These sites are characterized by poor waste management practices, lack of gas capture infrastructure, and minimal environmental oversight. As a result, landfills become significant sources of methane (CH_4), a greenhouse gas that is 25 times more potent than carbon dioxide (CO_2) in terms of global warming potential over 100 years (Odubo and Kosoe, 2024). In addition to methane, landfills emit other hazardous air pollutants such as nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), which contribute to poor air quality, respiratory diseases, and environmental degradation (Ofremu et al., 2024; Rathod et al., 2024).

The anaerobic decomposition of organic matter in landfills leads to the accumulation and eventual

release of methane (Yaashikaa et al., 2022; Long et al., 2023). Meanwhile, the combustion of waste whether intentional through open burning or accidental due to heat buildup generates NO_2 and SO_2. These gases can severely deteriorate ambient air quality, especially in and around landfill environments. Methane, being highly flammable, also increases the risk of fires and explosions at landfill sites, while NO_2 and SO_2 are known to exacerbate chronic respiratory illnesses such as asthma, bronchitis, and even cardiovascular conditions (Auvinen et al., 2021a; WHO, 2021; Singh et al., 2025). Their combined presence in ambient air not only contributes to regional smog formation but also interacts with volatile organic compounds (VOCs) and sunlight, forming ground-level ozone a harmful secondary pollutant (Dubey and Dubey, 2024; Auvinen et al., 2021b). Despite these known risks, most municipal landfills in low- and middle-income countries remain unequipped with continuous air quality monitoring systems, let alone real-time hazard detection and response tools (Montenegro and Epling, 2023; Yang et al., 2021; Fazakas et al., 2024).

In the context of Indonesia, a rapidly urbanizing nation with growing waste generation, the issue is particularly alarming. Many large landfills, including the Sarimukti landfill in West Bandung Regency, have experienced significant increases in waste volume, reaching more than 146,000 tons in a single year (National Waste Management Information System, 2024). These landfills serve densely populated urban areas, yet are managed with limited technological intervention. Consequently, the emission of hazardous gases remains largely unmonitored, leaving nearby communities vulnerable to health hazards and increasing the risk of environmental disasters such as fires, gas explosions, or landslides due to internal pressure from accumulated landfill gases (Xiu et al., 2021; McKinney and Thomson, 2022; Lamma, 2021). Informal waste pickers who work at landfill sites are among the most at-risk groups, as they are directly exposed to these gases without adequate protection or awareness of the associated health risks (Rashkevich et al., 2021).

Although various efforts have been made globally to monitor and mitigate landfill emissions, most existing approaches focus solely on estimating GHG emissions or measuring concentrations of specific pollutants without integrating them with public health frameworks. Traditional monitoring stations for air pollutants are often cost-prohibitive, require sophisticated maintenance, and are typically centralized in urban hubs making them inaccessible to remote landfill sites (Hassebo and Tealab, 2023; Park et al., 2024; Boucif et al., 2024). Moreover, these monitoring systems rarely provide real-time alerts that can facilitate preventive or emergency responses. There is a lack of technological tools that are affordable, portable, and tailored specifically for use in municipal landfills in developing countries.

This research seeks to address these shortcomings by introducing an innovative and practical solution: a prototype early warning system for air pollution in municipal landfills, developed based on the safe concentration by environmental health risk assessment approach. The system is designed to detect the presence and concentration levels of CH_4, NO_2, and SO_2 in real-time, and to automatically activate an alert (via a buzzer or light signal) when the measured concentrations exceed predefined safety thresholds for human health. These thresholds are not arbitrarily set; they are based on quantitative health risk assessments using environmental health exposure models. The integration of RQ analysis allows the prototype to go beyond mere gas detection, enabling it to interpret the data in terms of potential health impacts on exposed populations.

This approach introduces a novel combination of environmental sensing technology and public health risk modeling. To our knowledge, no existing monitoring system for landfill gases in Indonesia or comparable contexts applies the RQ methodology in an embedded, automated device format. Most air pollution sensors are used for environmental compliance or research purposes, not for active hazard prevention based on risk thresholds. Therefore, the proposed system marks a substantial advancement over conventional pollutant monitoring approaches. It brings together multiple disciplines, including environmental engineering, health risk analysis, embedded systems programming, and waste management, to produce an integrated solution that is both functional and replicable. The use of affordable and widely available components, such as MQ-series gas sensors and Arduino-based microcontrollers, ensures that the technology can be deployed even in resource-limited settings.

The prototype also includes a visual interface using an LCD module and a programmable threshold logic for interpreting gas concentrations concerning health-based safety limits. These

concentration thresholds are determined through environmental health risk assessment, taking into account pollutant levels, exposure frequency, and average human body weight. When the detected gas concentrations exceed these safety thresholds, the system is triggered to issue a warning. This enables immediate action to be taken by landfill managers, local authorities, or workers, thereby serving as a preventive tool against acute exposure and environmental incidents. The device is especially valuable in dynamic landfill environments where gas concentrations may fluctuate rapidly depending on weather conditions, waste composition, or operational practices.

The overarching objective of this study is to develop, calibrate, and test a risk-based early warning system for landfill gas exposure. This includes assembling the hardware components, developing the software logic for data interpretation, conducting laboratory simulations to calibrate the sensors, and performing field testing in real landfill environments. The outcomes of this study will not only demonstrate the technical feasibility of the system but also contribute to the broader discourse on sustainable waste management, public health protection, and climate change mitigation. By providing real-time, health-relevant data, the prototype has the potential to support decision-making processes at the community and governmental levels, enhance the safety of waste workers, and reduce the environmental footprint of unmanaged landfills.

MATERIALS AND METHODS

Study area and sampling location

This prototype early detection system for air pollution based on safe concentration calculations was developed with a focus on application in the Indonesia West Bandung Regency Sarimukti Landfill (TPA) area, which is the primary source of landfill gas emissions such as CH_4, NO_2, and SO_2. Although the prototype has not yet been directly tested in the landfill environment, the location serves as the primary reference for system design and calibration. Future field applications of the prototype will prioritize air quality monitoring at points vulnerable to exposure to hazardous gases resulting from the decomposition of waste in landfills.

Instrumentation and sensor setup

Measurements of hazardous gas concentrations are performed using MQ4 gas sensors, which are sensitive to methane, MEMs sensors which can detect nitrogen dioxide and MQ136 detect sulfur dioxide gases (Viciano-Tudela et al., 2023; Yu and Yoon, 2024). These sensors are connected to an electronic circuit integrated with an Arduino Uno microcontroller, which serves as the central data processing and recording unit. Each sensor produces an analog signal that is then converted into digital data through an analog-to-digital converter (ADC) on the Arduino. To ensure high accuracy in sensor readings, calibration is first performed using standard gases at known concentrations. This calibration produces a linear relationship curve between sensor output and gas concentration, which is then used to convert sensor output values during actual measurements into concentration values in units of $\mu g/m^3$.

Data acquisition and processing

Data from the sensor is collected periodically at 10-minute sampling intervals. Arduino processes analog signals into actual gas concentration values based on previous calibration results. All data obtained is stored locally and can be transferred to a computer device for further analysis. Additionally, the conversion of concentration values takes into account environmental conditions such as temperature and air pressure, which can affect measurement accuracy. This process ensures that the values obtained reflect the actual gas concentration in the environment surrounding the prototype.

Calculation of safe concentration

To determine the safe concentration limit for gases, a safe concentration (C_safe) calculation is performed based on the reference dose (RfC) set by environmental agencies such as the WHO or EPA. This calculation takes into account the average human body weight, air inhalation rate, and duration of exposure to the hazardous gas. The formula (Equation 1) used states that the safe concentration is the result of dividing the product of the reference concentration, time of average (t_{avg}), and body weight (Wb) by the result of multiplying the inhalation rate (R), time of exposure (tE), frequency of exposure (fE) and duration time. Thus, C_safe indicates the

maximum concentration of gas that is still considered safe for human health. The actual gas concentration measured by the sensor will then be compared with this C_safe value to determine the safety status of the monitored air.

The calculation of air pollutant safe concetration value is calculated in Equation 1.

$$Cnk = \left(\frac{RfC \times Wb \times tavg}{R \times tE \times fE \times Dt} \right) \quad (1)$$

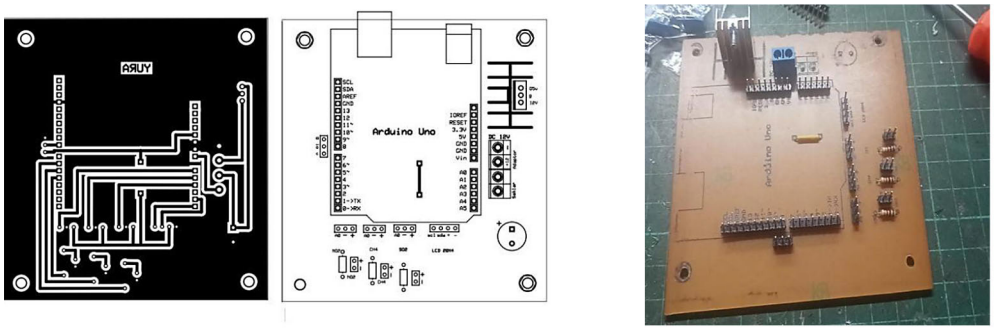
Early warning system development

Based on the results of gas concentration measurements and calculations, an early warning system was developed using Arduino as the main controller. This system automatically compares actual concentration values with predetermined safe concentration values. If the actual value exceeds the safe concentration limit, Arduino will activate the buzzer module to provide an alarm warning. Additionally, gas concentration values and warning status are displayed in real time on an LCD screen integrated with the device. The system design is intended to be user-friendly and easy to install in landfill environments, enabling continuous air quality monitoring and responsive action to potential health risks from landfill gas exposure (Figure 1).

RESULTS AND DISCUSSION

The prototype model was validated through several simulations. The simulations were conducted in an engineered environment. In the first condition, the model was exposed to incinerated inorganic waste within a 30 cm radius for one minute. The second condition involved exposure to incinerated organic waste, the third condition involved exposure to lighter gas, and the fourth condition involved exposure to motor vehicle exhaust.

Figure 2 is a graph showing the results of inorganic waste combustion, illustrating the dynamics



(a) Design and print printed circuit boards

(b) Printed circuit board assembly process

(c)Sensor calibration and activation test

(d) Early Detection System Prototype

Figure 1. Prototype design model for air pollutant early detection system

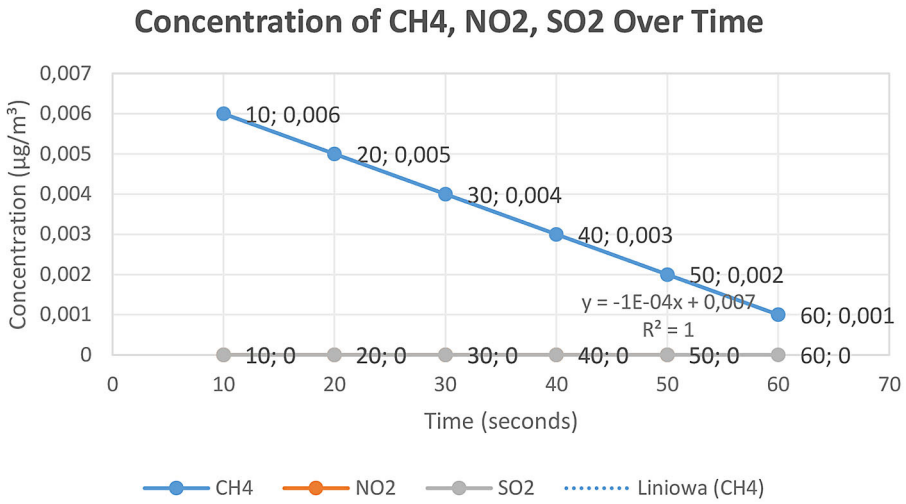


Figure 2. Prototype detection results for inorganic waste incineration exposure

of CH_4, NO_2, and SO_2 gas concentrations during 60 seconds of observation. From the graph, it can be seen that only CH_4 gas was detected by the sensor, while NO_2 and SO_2 did not show any increase in concentration, remaining at zero throughout the entire monitoring period. The CH_4 concentration was recorded at 0.006 µg/m³ at the 10th second and decreased gradually to 0.001 µg/m³ at the 60th second. This decrease forms a highly consistent linear pattern, with the regression line equation y = -0.0001x + 0.007 and a coefficient of determination (R^2) of 1, indicating perfect agreement between the empirical data and the trend model. Figure 3shows the detection results of the prototype for exposure to organic waste burning,

Figure 4 is a graph showing the results of organic waste combustion, indicating a gradual increase in CH_4 gas concentration over a 60-second observation period. At the 10-second mark, the CH_4 concentration was recorded at 0 µg/m³ and began to rise to 0.005 µg/m³ at the 20-second mark, continuing to increase to 0. 007 µg/m³ at the 30th second, 0.01 µg/m³ at the 40th second, 0.012 µg/m³ at the 50th second, and reaching its peak at 0.014 µg/m³ at the 60th second. The graph shows a fairly consistent upward trend, with a regression line equation of y = 0.0003x – 0.0014 and an R^2 value of 0.971, indicating that the linear model can explain most of the data variation, although not as well as in the previous inorganic exposure. Figure 4 below shows the detection results of the prototype for exposure to lighter gas.

Figure 4 is a graph illustrating the sensor's rapid and significant response to the presence of lighter gas, particularly CH_4, upon exposure. At the start of the observation, the CH_4 concentration was 0 µg/m³ at seconds 10 and 20, then rapidly increased to 0.841 µg/m³ at second 30. A drastic spike occurred at seconds 40 and 50, with concentrations of 1.589 µg/m³ respectively, before finally decreasing slightly to 1.519 µg/m³ at second 60. This pattern indicates that the prototype is highly sensitive to exposure to lighter gas, which typically contains light hydrocarbon compounds such as butane or propane.

Figure 5 is a graph showing the results of motor vehicle gas exposure, indicating a fluctuating pattern of CH_4 gas concentration during 60 seconds of observation. At the 10th second, the CH_4 concentration was detected at 0.024 µg/m³, increasing to 0.053 µg/m³ at the 20th second, then slightly decreasing to 0.044 µg/m³ at the 30th second. Another spike occurred at the 40th second with the highest value of 0.059 µg/m³, followed by a significant decrease to 0.034 µg/m³ at the 50th second, and then increased again to 0.047 µg/m³ at the 60th second. Although the variations are visible, the overall trend still shows a slight increase, as illustrated by the trend line equation y = 0.0002x + 0.0362 with a coefficient of determination R^2 = 0.0936, indicating a very weak linear relationship between time and CH_4 concentration.

These concentration fluctuations reflect the unstable emission characteristics of motor vehicles, which depend on engine RPM intensity, fuel type, and environmental conditions such as temperature and wind direction. Increases in CH_4 concentration at certain time points indicate moments when the engine emits exhaust gases at higher intensities, while decreases may be

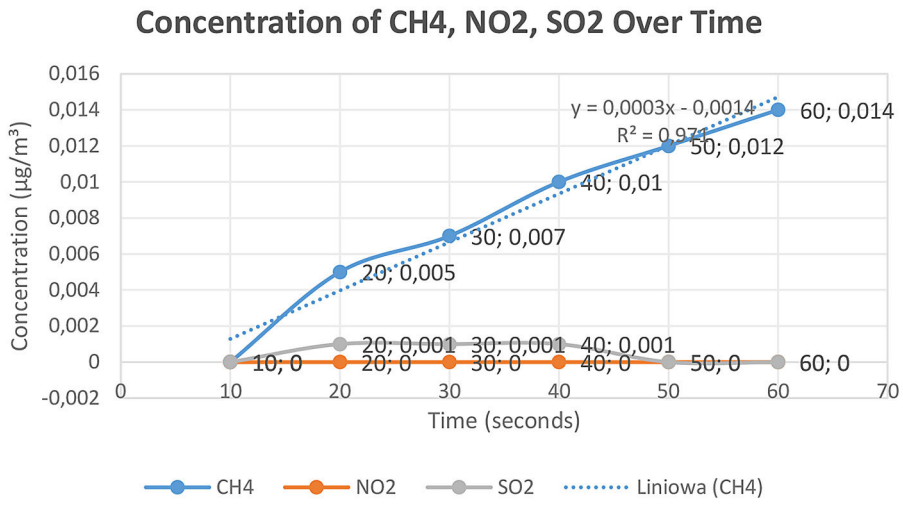


Figure 3. Prototype detection results for organic waste incineration exposure

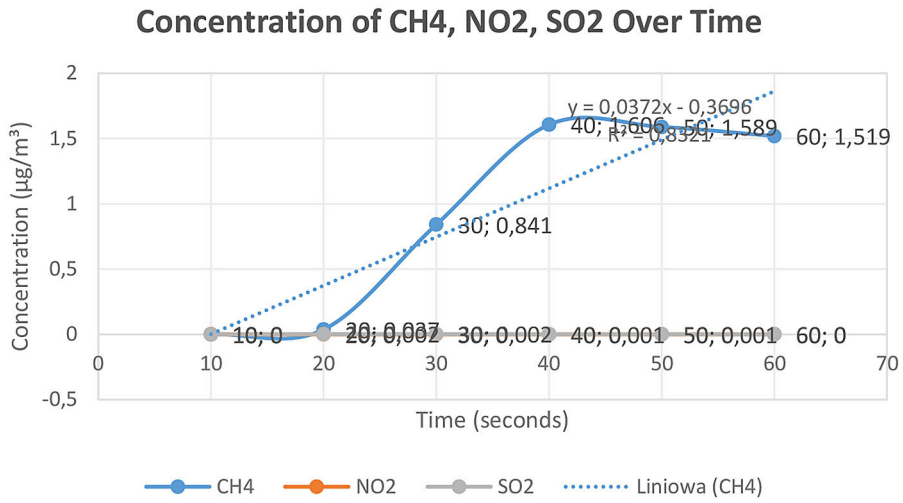


Figure 4. Prototype detection results for match gas exposure simulation

caused by pauses, changes in exhaust position, or the dispersion of gases into the surrounding environment before reaching the sensor.

As for NO_2 and SO_2 gases, they remained at very low or undetectable concentrations throughout the observation period. The readings were only 0.001 µg/m³ at some points (e.g., seconds 30 and 40), while at other points they remained at zero. This indicates that although motor vehicles are known to produce nitrogen and sulfur oxides, the concentrations of these emissions in this simulation are likely to be small or below the detection limit of the sensor used.

Interpretation of this pattern (Figure 2) shows that the burning of inorganic waste produces significant methane gas emissions at the beginning of the process, most likely due to the burning of synthetic materials such as plastic or rubber (La and Hettiaratchi, 2022; Fromme, 2023). Over time, the concentration of CH_4 gas decreases, which can be interpreted as the result of diffusion and dilution of the gas in the open air, or because the source of emissions is weakening. The undetectability of NO_2 and SO_2 may indicate that the concentrations of both gases are too low to be detected by the sensors used, or that they are not formed in significant quantities during the combustion process. This may also indicate that the type of waste used does not contain precursor compounds that can produce nitrogen or sulfur oxides.

The increase in CH_4 concentration during combustion (Figure 3) indicates that organic material releases methane gas gradually as the combustion process progresses. This is consistent

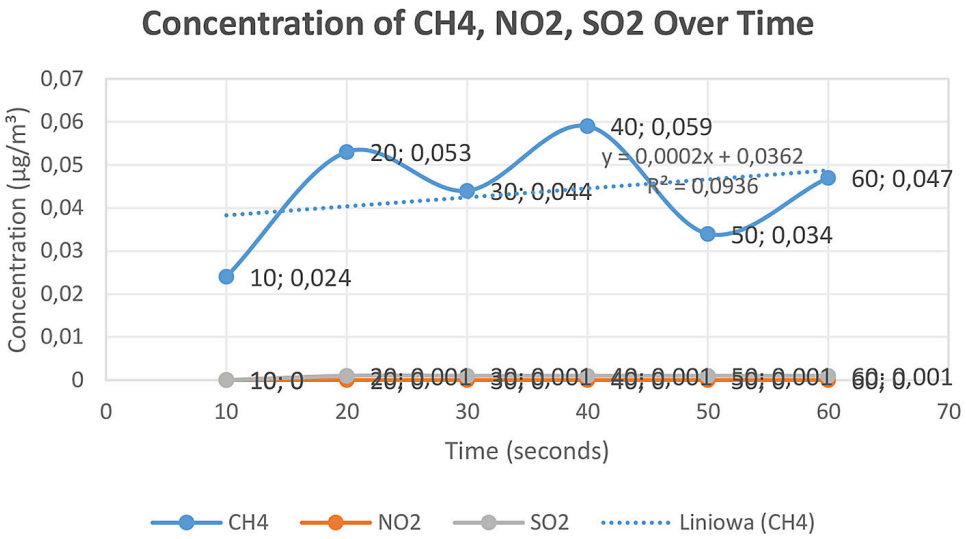


Figure 5. Prototype detection results for vehicle gas exposure simulation

with the characteristics of organic waste such as food scraps, leaves, or wood, which release hydrocarbon compounds through a slower thermal decomposition process when burned (Chavan et al., 2022; Zwolińska and Basta, 2024; Dabrowska et al., 2024). Unlike inorganic waste, which tends to produce an immediate burst of emissions at the start of combustion, the release of gases from organic waste occurs slowly and cumulatively.

Meanwhile, neither NO_2 nor SO_2 showed any change in concentration during the observation period, remaining within the range of 0.001 µg/m³ from the 20th to the 50th second, and 0 µg/m³ at other points. This indicates that the combustion of organic waste does not produce sufficient amounts of nitrogen or sulfur oxides to be detected, or that the sensor used has low sensitivity to these types of gases in the context of this test.

Overall, this graph reinforces the prototype's ability to detect CH_4 gas from organic sources with a progressive response pattern. Despite the low initial concentration, the gradual increase indicates that the prototype is capable of recognizing cumulative exposure in a short period of time. This finding is important in the context of air quality monitoring in environments facing open burning of organic waste, such as rural areas or around landfills. However, the low detection of NO_2 and SO_2 indicates the need to strengthen the gas oxide detection function to produce a more comprehensive risk mapping.

The linear trend line for CH_4 has the equation $y = 0.0372x - 0.3696$ with a coefficient of determination R^2 of 0.977 (Figure 4), indicating a very good level of agreement between the actual data and the regression model. The sharp and consistent sensor response shows that gas concentrations increase cumulatively in a very short time, with saturation point reached after 40 seconds. A small decrease at 60 seconds indicates that some of the gas began to disperse or disappear from the sensor area, but it was still at a high level and detectable.

Meanwhile, NO_2 and SO_2 concentrations remained very low or undetectable throughout the period, with zero values at all observation points. This confirms that the type of lighter gas does not produce significant amounts of nitrogen or sulfur oxides, emphasizing that the CH_4 sensor is the primary component in detecting this type of exposure. Several limitations were encountered in this study. First, the prototype has not yet been field-tested in actual landfill environments such as the Sarimukti Landfill, which limits the generalizability of the findings. Laboratory simulations, while informative, do not fully replicate environmental variables such as wind, humidity, and interference from multiple gas sources. Second, the detection sensitivity for NO_2 and SO_2 was found to be limited, potentially due to the specific gas sensor range or environmental noise during the test. Third, while the health-based thresholds were calculated using standard exposure models, these were based on average adult values and may not reflect specific vulnerabilities of at-risk populations like children or elderly waste workers. Lastly, the system operates on a local alarm basis (buzzer), and lacks integration with remote or real-time digital communication platforms for broader environmental monitoring and emergency response.

CONCLUSIONS

This study successfully developed a functional early warning prototype for air pollution exposure in municipal landfills, focusing on three hazardous gases: CH_4, NO_2, and SO_2. The system was designed and tested through four simulation scenarios, including exposure to inorganic waste combustion, organic waste, lighter gas, and motor vehicle emissions. Results showed high sensitivity and accuracy in detecting CH_4, particularly during exposure to lighter gas, with a peak concentration of 1.589 μg/m³ and a strong linear relationship ($R^2 = 0.977$). The prototype demonstrated the ability to detect gradual increases in gas levels over short durations, with a consistent response pattern. Although NO_2 and SO_2 were detected at lower or undetectable levels during testing, the system's modularity allows for further sensor enhancement. Overall, the integration of environmental risk assessment parameters such as safe concentration (C_safe) based on inhalation rate and exposure time provides a novel, health-based interpretation framework for air quality data, making the device suitable for use in high-risk landfill environments..

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