



Preliminary Study on the Treatment of Aluminum Slag Hazardous Waste

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Abstract:

Background. Hazardous and toxic waste (B3) requires special attention because it can harm the environment and human health if not managed properly.

Aim. This study aimed to evaluate the initial performance of a prototype for treating aluminum slag waste housed in a wooden container, using temperature and gas levels as monitoring parameters

Methods. The methods used are (1) Prototype design and monitoring system. The prototype is an aluminum *slag storage box* with a length, width, and height of (100 × 100 × 100) cm³ using multiplex material with a thickness of 18 mm; (2) Fabrication of a prototype aluminum slag storage box using four locking wheels, air circulation vents, MQ-2 gas sensors, DHT22 temperature and humidity sensors, 12 V DC blowers, Arduino Nano, and LCD. Sensors. The tests included temperature tests and pressure-related gas-level tests. Aluminum slag samples were mixed with sulfuric acid (H₂SO₄) and without H₂SO₄.

Results. Samples without solution showed a relatively stable response, while samples mixed with 10% H₂SO₄ solution showed a much greater increase in temperature and gas levels, exceeding the device program threshold of 400 in the second and third sessions. The available data are also insufficient to determine the gas type or concentration or to assess the success of B3 waste stabilization.

Conclusions and Implications. Further research needs to include actual cooling measurements, MQ-2 calibration, gas identification, chemical parameter measurement, material characterization, and validation of process safety criteria.

Keywords: Hazardous and Toxic Waste; Aluminum Slag; Sulfuric Acid



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INTRODUCTION

Industrial waste results from production activities and must be managed based on its characteristics and potential hazards. The management of hazardous and toxic material (B3) waste requires control from the stage of storage, handling, processing, and reuse so that risks

to workers and the environment can be minimized (Nurlina, 2021; Wiryawan, 2024; Pratiwi et al., 2023; Alfianti et al., 2025; Sari et al., 2025). In the aluminum smelting industry, one residue is aluminum dross or slag, which can still contain activated aluminum, metal oxides, and reactive compounds (Bursabrina et al., 2021; Pramestie & Wilujeng, 2023; Pratistita & Triadi, 2024; Rizki et al., 2022).

Characteristics of aluminum dross (Figure 1) depend on the raw material and the smelting process. The literature reports that slag can contain Al_2O_3 , residual metals Al, MgO, CaO, SiO_2 , AlN, and other compounds of varying proportions. Reactive contact with water or moisture can trigger a reaction and release of gases, so early handling and monitoring of storage conditions is important (Saraswati & Razif, 2020; Praadilla et al., 2022; Ali & Yassen, 2018). On the other hand, once hazard characteristics are controlled, aluminum residues can be reused, among other things, as a substitute for cement-based materials and geopolymers (Lukita et al., 2022; Putra et al., 2022; Elseknodhi et al., 2020). Stabilization/solidification (S/S) is one approach used to reduce contaminant mobility and improve waste stability before final storage or utilization. Previous research has shown the potential of aluminum slag utilization in lightweight concrete, cement materials, and geopolymers (Saraswati & Razif, 2020; Elseknidi et al., 2020; Sholekah & Risdiananto, 2022; Jayamto et al., 2021). However, the implementation of the processing process requires a structured handling system and monitoring of material conditions, especially temperature and gas indications, so that changes in internal conditions can be detected without opening the container directly (Suhartawan et al., 2023). The aim of the study was to evaluate the prototype aluminum slag storage box's initial response to changes in temperature and gas levels in pure aluminum slag and in slag mixed with sulfuric acid (H_2SO_4).



Figure 1. Aluminum Slag

METHOD

Flow Chart

The flow of research activities is shown in the *Flow Chart* Figure 2, with the following work steps: (1) Prototype design and monitoring system. The prototype is an aluminum slag storage box with a length, width, and height of $(100 \times 100 \times 100)$ cm³ using multiplex material with a thickness of 18 mm (Figure 3). (2) Fabrication of a prototype aluminum slag storage box using four locking wheels, air circulation vents, MQ-2 gas sensors, DHT22 temperature and humidity sensors, 12 V DC blowers, Arduino Nano, and LCD. The sensor reads the container's internal conditions and transmits signals to the microcontroller; the information is displayed on the LCD, while the blower acts as an actuator to improve air circulation when needed. The mechanical and electronic arrangement is shown in Figure 4. (3) Preparation of tools and materials, (4) Testing of prototypes of aluminum *slag storage* boxes, (5) analysis of results, and drawing of conclusions.

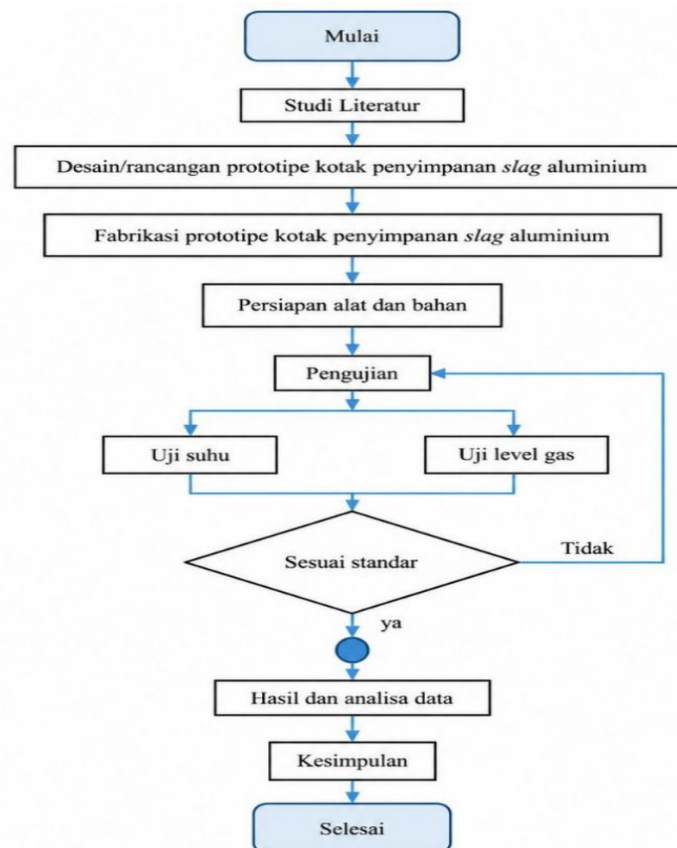


Figure 2. Research *Flow Chart*

Prototype Design Stages

The prototype design stages are carried out gradually and systematically, from identifying system needs and preparing tools and materials to creating mechanical structures, installing electronic components, and integrating and testing prototypes. Each stage considers the prototype's main function: a safer aluminum slag storage container equipped with an internal condition-monitoring system. The design focuses not only on the container's physical shape but also on safety, ease of movement, air circulation, and the system's ability to provide information about changes in the container's conditions. The monitoring parameters include temperature, humidity, and changes in gas concentration detected by the sensor. The sensor readings are then used to determine the condition of aluminum slag during storage and observation.

Identify Design Needs

The first stage of design is to identify the prototype's needs. This is done by determining the functions and components needed so the container can store aluminum slag while monitoring internal conditions. The container is designed with a structure strong enough to accommodate aluminum slag, a dedicated space for sensor placement, and an air circulation path so the conditions inside the container can be monitored properly. In addition, the prototype includes a ventilation system with a blower to improve airflow and support cooling an temperatures rise. The sensor placement is also considered so it can collect data that better represents the material's condition. By identifying needs from the beginning, each component can be adjusted to the prototype's function and purpose.

Preparation of Tools and Materials

After determining the design needs, the next stage is to prepare the tools and materials needed for the prototype manufacturing process. The main material used to build the container structure is 18 mm thick multiplex. Multiplex was chosen as the main material because it is easy to cut and assemble and strong enough to serve as a prototype structure. In the electronics section, the Arduino Nano is used as a microcontroller to receive and process sensor data. The MQ-2 sensor detects gas changes in the container, while the DHT22 sensor measures temperature and humidity. The sensor readings are displayed on the LCD so that the measured conditions can be known directly. The prototype also includes a 12 V

DC blower as a ventilation system and four wheels with locks to facilitate movement while keeping the prototype stable during use.

Mechanical Structure Manufacturing

The mechanical structure is built based on the predetermined size and design. The multiplex is cut and adjusted to the prototype design size, about $100 \times 100 \times 100 \text{ cm}^3$. The multiplex pieces are then assembled into a storage box, with attention to connection strength and structural stability. The container includes space for sensors and other supporting components. The inner structure also considers the air circulation path so that air can move properly when the blower is activated. The bottom of the prototype is then fitted with four wheels to provide mobility, so the container can be moved more easily. The wheels include a locking mechanism so the prototype does not move easily during observation or testing.

Electronic System Installation

The next stage is installing the electronic system on the finished mechanical structure. The MQ-2 and DHT22 sensors are placed to read the environmental conditions inside the container. The MQ-2 sensor responds to gas changes, while the DHT22 measures temperature and humidity. The Arduino Nano then connects to the sensors as the data control and processing center. The Arduino processes the sensor data and displays it on the LCD for direct observation during testing. A 12 V DC blower is also installed as part of the ventilation system. When the blower is activated, the airflow inside the container can help reduce heat build-up and improve air circulation. Each component is installed with attention to position, cable paths, and safety so the system works properly during testing.

Prototype Integration and Testing

After completing the mechanical structure and electronic system, all components are integrated into a single system. At this stage, an examine the function of each component, from the MQ-2 sensor and DHT22 sensor to the Arduino Nano, LCD, and blower. The inspection ensures the sensor can read conditions in the container and that the measurement data can be displayed on the LCD. After confirming all components work, tests are carried out using two conditions of aluminum slag samples. The test aims to determine the prototype's response to changes in material conditions, especially changes in temperature and gas levels detected by the sensor. During the test, observations and sensor readings are

recorded in each session. The data is then used to assess the prototype's ability to monitor internal conditions in real time and to identify changes under each sample condition. The test results can then be used as evaluation material to identify the prototype's advantages and the parts that still need improvement.

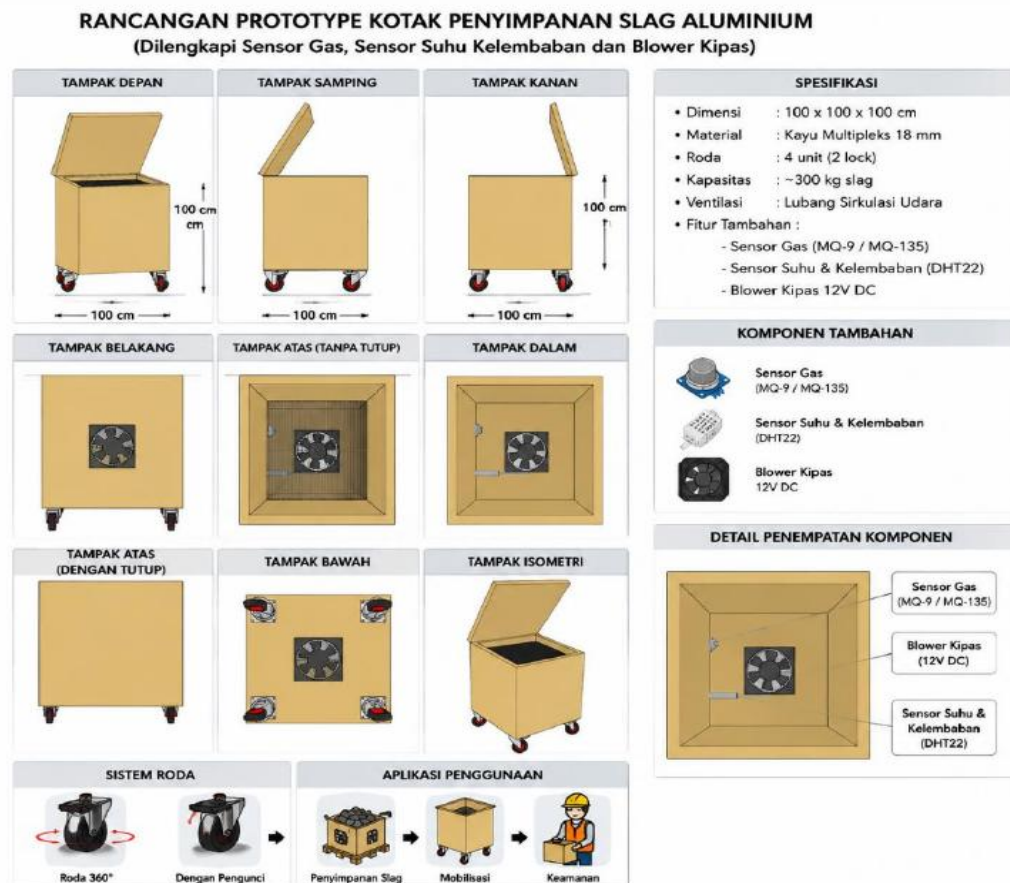


Figure 3. Prototype design of aluminum *slag* storage box

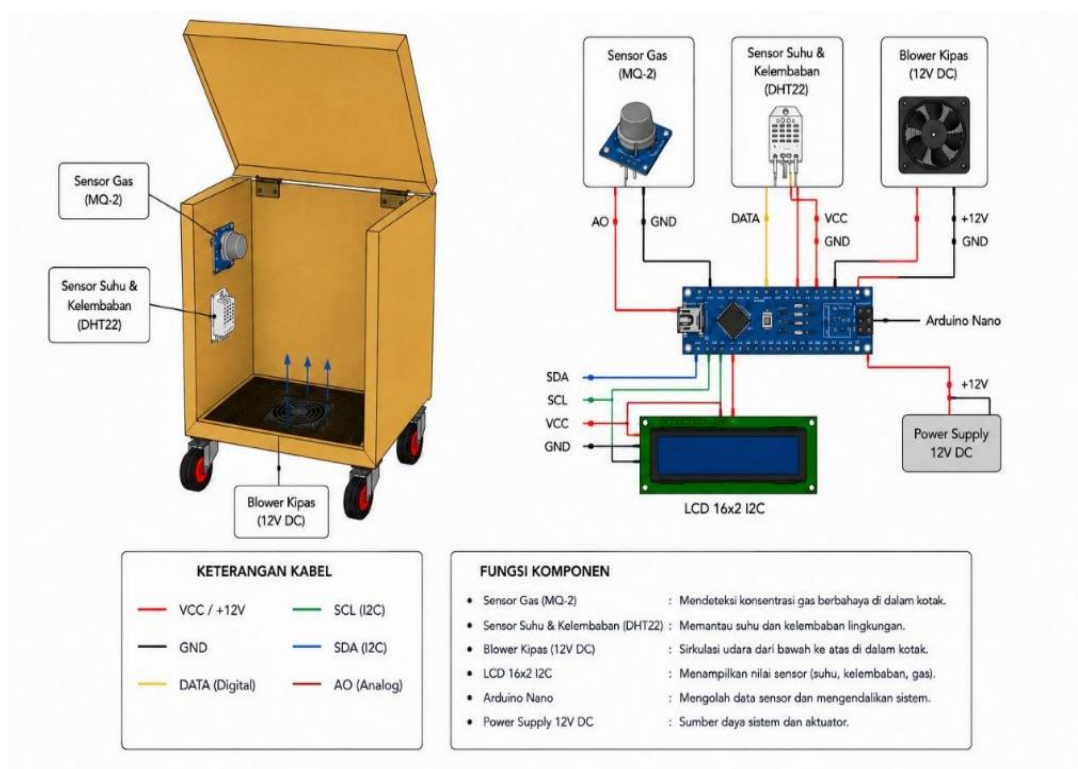


Figure 4. Mechanical and electronic arrangement of the prototype box Aluminum *slag* storage

How the electronics work: Prototype Storage box for aluminum slag as follows: sample stroke. The aluminum is placed inside the prototype, the temperature sensor is positioned on the material, then the container is closed, and the monitoring system is ensured to be active. The main test was carried out in three sessions, each for 5 minutes, with *the blower in the OFF condition so that temperature changes and gas sensor readings could be observed without cooling intervention*. After the third session, the blower was turned on (ON), and the cooling stage was carried out in three sessions, 5 minutes each. The parameters monitored were the temperature and gas level of the MQ-2 sensor. The analysis was descriptive, comparing inter-session values and trends. A value of 400 was used as an indicative threshold in the research program/device to distinguish safety and hazard status; it was not a limit for raw gas concentration. Because the sensor was not calibrated to a specific gas concentration, the gas level was treated as a relative reading without a concentration unit and was not used to identify the type of gas (Puja et al., 2025).

Mixing of Aluminum Slag with Sulfuric Acid (H_2SO_4) Solution 10%

Mixing aluminum with 10% sulfuric acid (H_2SO_4) mainly extracts or recovers the aluminum content remaining in the waste (Isyantimah et al., 2022). This chemical process is referred to as the leaching process (*leaching*) or acidification (Li et al., 2022). Sample *Stroke* Testing aluminum consists of 10 kg of *scrap* aluminum divided into two samples of 5 kg each. Sample 1 is tested without adding 10% H_2SO_4 solution. Sample 2 uses 5 kg of scrap aluminum mixed with 5 kg of 10% H_2SO_4 solution at a mass ratio of 1:1. A 10% H_2SO_4 solution is prepared from 98% concentrated H_2SO_4 based on the mass balance: $\text{mass H}_2\text{SO}_4\ 98\% = (5,000\ \text{grams} \times 10\%)/98\% = 510.2\ \text{grams}$. With a density of $\text{H}_2\text{SO}_4\ 98\%$ of about 1.84 grams/ml, the amount is equivalent to about 277.3 mL. The water required to reach the mass of a 5 kg solution is 4,489.8 grams or about 4,490 ml (Figure 5).



Figure 5. Aluminum slag *mixing process* with H_2SO_4) 10%

Dilution was carried out as part of the material preparation stage, following laboratory safety principles: a concentrated H_2SO_4 solution was slowly added to water while stirring, not the other way around, because H_2SO_4 dilution is exothermic (Ulbandiah et al., 1998). The work was carried out using appropriate Personal Protective Equipment (PPE), acid- and heat-resistant containers, and adequate ventilation. The solution was allowed to reach the required temperature before use in the test. Table 1 summarizes the test composition details. The prototype of the box *Stroke* aluminum is shown in Figure 6(a), and the *Stroke* aluminum is shown on the prototype box *Stroke* aluminum (Figure 6(b)).

Table 1. Test conditions and parameters

Sample	Composition	Observation time	Blower parameters/conditions
1	5 kg of aluminum slag, without solution	3×5 minutes	Gas temperature and level; main test OFF, cooling ON
2	5 kg aluminum slag + 5 kg 10% H_2SO_4 solution	3×5 minutes	Gas temperature and level; main test OFF, cooling ON



(a)



(b)

Figure 6 (a) Prototype of a finished aluminum slag box
 (b) Laying aluminum slag in a prototype box of finished aluminum slag box

Testing and Data Analysis Procedures

Testing procedures and data analysis are as follows: Samples are placed inside a prototype box of finished aluminum slag, a temperature sensor is positioned on the material, then the container is closed, and the monitoring system is ensured to be active. The main test was carried out in three sessions, each for 5 minutes, with the blower in the OFF condition, so temperature changes and gas sensor readings could be observed without cooling intervention. After the third session, the blower was turned on (ON), and the cooling stage was carried out in three sessions, each 5 minutes. The parameters monitored were the temperature and gas level of the MQ-2 sensor. The analysis was descriptive, comparing inter-session values and trends. The research program/device used 400 as an indicative threshold to distinguish safety and hazard status; it was not a limit for raw gas concentration. Because the sensor was not calibrated to a specific gas concentration, the gas level was treated as a

relative reading without a concentration unit and was not used to identify the gas type (Hakim et al., 2025).

DISCUSSION

Sample test results 1

In sample 1, temperatures were recorded at 30.1 °C, 30.4 °C, and 30.8 °C in three consecutive sessions. The gas level increased from 26 to 27 to 28. All readings remained safe. A total temperature increase of 0.7 °C and a gas level increase of 2 showed a relatively small response during the 15 minutes of observation. All main test data were obtained with the blower OFF.

Table 2. Sample test results 1

Sessions	Duration	Temperature (°C)	Gas level
1	5 minutes	30,1	26 (Safe)
2	5 minutes	30,4	27 (Safe)
3	5 minutes	30,8	28 (Safe)

The low response in samples without solution indicates that the material conditions during the observation period were relatively stable based on the two parameters monitored. However, aluminum slag has variable composition and may contain reactive phases, so these results describe only the sample and the test conditions used (Padilla et al., 2022; Ali & Yassen, 2018; Lukita et al., 2022; Hakim et al., 2025).

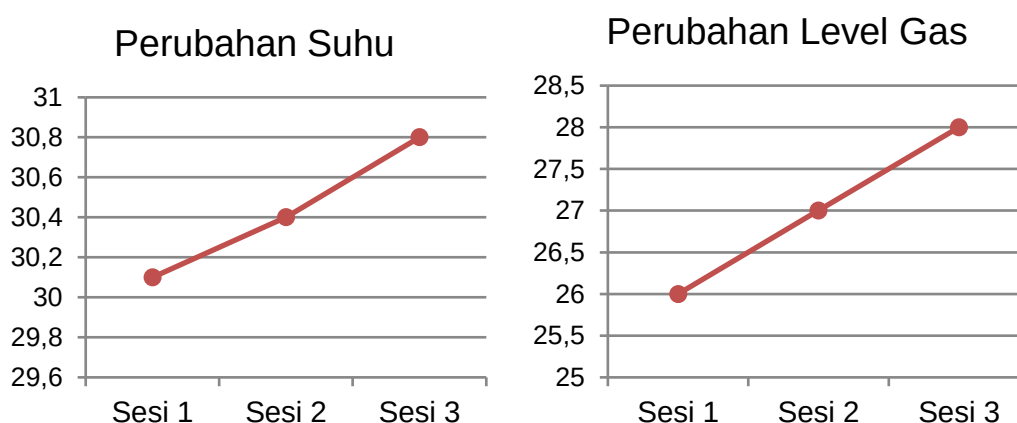


Figure 7. Sample Change Graph 1

All observation sessions were conducted under safe conditions and showed relatively stable changes during the process. Based on the results, values increased very slightly in each session, but the increases remained within reasonable limits and did not show significant change. This indicates that the process was carried out in a controlled manner, without drastic improvements or changes in conditions that could compromise safety during the test. Thus, overall, all sessions can be categorized as safe and stable, with the increase still very low.

Sample test results 2

In sample 2, after mixing 5 kg of aluminum slag with 5 kg of 10% H₂SO₄ solution, the temperature in the first session was 44.8 °C, with a gas level of 72 and a safe status. In the second session, the temperature increased to 65.6 °C, and the gas level reached 438, so the system showed a hazard status. In the third session, the temperature reached 72.12 °C, and the gas level was 500, which is also a hazard status. The three main test sessions were carried out when the blower was OFF.

Table 3. Sample test results 2

Sessions	Duration	Temperature (°C)	Gas level
1	5 minutes	44,8	72 (Safe)
2	5 minutes	65,6	438 (Danger)
3	5 minutes	72,12	500 (hazard)

From the first to the third session, the temperature increased by 27.32 °C and the gas level increased by 428. The increase was much greater than that of sample 1. Scientifically, the addition of an acid solution changed the chemical condition of the material and was followed by heat release and an increase in the response of the gas sensor (Refalista et al., 2023). However, without gas identification, before-and-after chemical characterization, and sensor calibration curves, this data is insufficient to establish the reaction mechanism, gas type, or concentration.

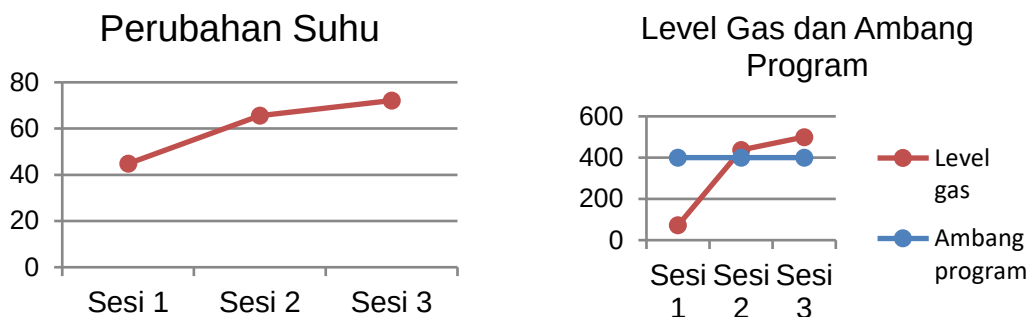


Figure 8. Sample Change Graph 2

Adding 10% H_2SO_4 caused a more noticeable change in conditions during the test. After adding the acid solution, the sample temperature rose above the initial condition, indicating a reaction response. In addition, the gas sensor also showed a much greater response, so it can be said that the addition of 10% H_2SO_4 had a significant effect on the condition of the sample during observation. Overall, the increase in heat and the gas sensor response were among the main changes observed during the test session with the addition of 10% H_2SO_4 .

Cooling Reconstruction Data

The data in this subsection are reconstructed/estimated to complete the cooling-stage recording format, not the actual measurement results. The cooling-stage procedure used the ON blower for three sessions, 5 minutes each. Therefore, the following temperature and gas level figures are used as an illustration of the analysis format and are not used as primary experimental evidence.

Sample cooling 1

After the third session of the main test of sample 1 is completed, the blower is switched on (ON) for the cooling stage. The temperature sensor and MQ-2 are monitored in three sessions, 5 minutes each. Since actual recordings at this stage are not yet available, the values in Table 4 are reconstructions/estimates.

Table 4. Sample cooling reconstruction data 1

Cooling session	Duration	Temperature (°C)	Gas level/status
1	5 minutes	30,6	27 / Safe
2	5 minutes	30,3	26 / Safe
3	5 minutes	30,1	25 / Safe

Illustratively, the temperature of sample 1 gradually decreases, and the gas level remains in a safe state. The pattern describes the conditions theoretically expected when the sample returned to the initial condition, but it could not yet be declared a research finding before it was verified through actual measurements.

Sample cooling 2

After the third session of the main test of sample 2 was completed at an actual temperature of 72.12 °C and a gas level of 500, the blower was switched on (ON) for the cooling stage. Monitoring was designed in three sessions, 5 minutes each. The values in Table 5 remain in reconstruction/estimation status, as actual cooling data have not been recorded.

Table 5. Sample cooling reconstruction data 2

Cooling session	Duration	Temperature (°C)	Gas level/status
1	5 minutes	64,8	455 / Danger
2	5 minutes	57,3	380 / Safe
3	5 minutes	51,6	315 / Safe

Illustratively, the reconstruction data show a tendency for temperature and MQ-2 readings to decrease during blower ON. The status changed from hazard in the first session to safe in the second and third sessions based on a program threshold of 400. This pattern cannot yet be used to determine the blower's effectiveness experimentally before actual cooling measurements are made.

Comparison of the two samples

Table 6. Comparison of sample response 1 and sample 2

Parameters	Sample 1	Sample 2	Comparison
Initial temperature	30.1 °C	44.8 °C	Sample 2 is higher by 14.7 °C
Final temperature	30.8 °C	72.12 °C	Sample 2: higher by 41.32 °C
Temperature rise	0.7 °C	27.32 °C	Sample 2 is much larger
Initial gas	26	72	Sample 2 is higher: 46
Final gases	28	500	Sample 2 is higher: 472
Gas rise	2	428	Sample 2 is much larger

Comparisons show a clear difference in response. Sample 1 maintained temperature and gas levels at a relatively stable range, while sample 2 experienced a sharp increase and crossed the indicative threshold of 400 in the second and third sessions. These results support the prototype's function as an early-detection tool for changes in internal conditions. The integration of sensors, LCDs, and blowers also provided the basis for developing automatic alarm and ventilation systems, but control limits required further calibration and validation.

The cooling data for sample 1 and sample 2 in this article are still reconstructed/estimated, so they cannot be compared quantitatively with previous studies. The actual cooling procedure used an ON blower after three main test sessions with an OFF blower. Retesting should record ambient temperature, humidity, time interval, sample temperature, and MQ-2 level during operation so the cooling rate and ventilation effectiveness can be analyzed based on actual data.

The increase in temperature after the addition of a 10% H₂SO₄ solution is also relevant to the study of aluminum spraying using sulfuric acid (Sahrani et al., 2024) as well as hydrometallurgy studies of secondary aluminum dross (Risdianto, 2023), which suggests that acid conditions, temperature, time, and liquid-solid ratios affect the process. However, the material conditions and objectives of the previous study did not match those of this study. Therefore, the previous study was used to compare the phenomenon's general trend, not as evidence that the reaction mechanism was the same.

Comparative discussion with previous research

The results show that sample 2 produced a much larger thermal response and MQ-2 readings than sample 1. These findings are relevant to Padilla et al. (Refalista et al., 2023; Sathiyaseelan et al., 2025; Phanypha et al., 2025). This suggests that dross aluminum residues can react and produce gases when in contact with water or moisture. The similarity lies in dross material's tendency to increase gas activity. However, the MQ-2 readings in this study are relative levels and cannot determine gas type or concentration without appropriate calibration.

Other research on CO, CO₂, and HC gas/smoke emission tests yielded data that complied with the 2017 RI Minister of Environment and Forestry Regulation requirements. Semi-bio briquettes showed a less hollow and denser microstructure than synthetic briquettes. (Harmi et al., 2025). Setiawan et al. (2025) study guides policymakers in

developing low-cost, sustainable waste management through community-based waste-to-energy (WtE) initiatives that reduce emissions and support a circular, resilient city.

CONCLUSION

The prototype monitored changes in temperature and gas levels using an MQ-2 sensor under two aluminum slag conditions during three main test sessions with the blower off. Samples without solution showed a relatively stable response, while samples mixed with 10% H₂SO₄ solution showed a much greater increase in temperature and gas level, exceeding the device program threshold of 400 in the second and third sessions. After the main test, the blower was operated (ON) at the cooling stage. However, because the available cooling data is still reconstructed/estimated, this study cannot infer the blower's effectiveness. The available data are also insufficient to determine the gas type or concentration or to assess the success of B3 waste stabilization. Further research needs to include actual cooling measurements, MQ-2 calibration, gas identification, chemical parameter measurement, material characterization, and validation of process safety criteria.

INVOLVEMENT

Implications for Treatment Design

The test results show that temperature and gas-level monitoring using the MQ-2 is relevant for the initial slag handling and storage stage. During the main test, the blower is deliberately switched off, and it is activated after the test for the cooling stage. This design allows the initial sample response to be observed separately from the ventilation intervention. However, because actual cooling data is not yet available, the blower's effectiveness cannot yet be quantitatively assessed. Subsequent developments need to include MQ-2 calibration, moisture and pH measurements, gas identification, material characterization, and stability criteria for S/S results so that "stable" decisions are not based solely on sensor readings.

The use of H₂SO₄ in sample 2 should be understood as an experimental condition, not as evidence that the addition of acid is a validated stabilization method. Increased temperature and gas levels indicate the need for controlled temperature, ventilation, mixing ratios, addition procedures, and measurable emergency response. For the purpose of utilizing the processing results, the literature on aluminum slag in cement and geopolymer materials

can be the basis for development, but verification of waste characteristics and environmental requirements is still required [29]–[31].

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