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# MOBILE GAS SENSING FOR LABORATORY INFRASTRUCTURE

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***ABSTRACT:*** Indoor air quality has become a growing concern in modern society due to prolonged indoor working hours that lead to the frequent exposure to numerous toxic gases from various sources. These pollutants, including volatile organic compounds (VOCs), pose severe health risks such as asthma and lung cancer. To address this critical issue, this project focuses on developing and evaluating an advanced gas detection system that explicitly targets VOCs by integrating two novel metal oxide semiconductor (MOX)-based gas sensors, ENS 160 and TED110. Different sensor parameters, such as the air quality index (AQI) and volatile organic compounds (VOCs), were evaluated using 12 volatile organic chemicals. The findings revealed that the ENS 160 sensor performs excellently, detecting 60 gas samples out of 72, with an average detection rate of approximately 83%. In contrast, the TED110 sensor demonstrated considerably lower performance and response in 24 out of 72 gas samples, with a detection rate of about 33%. The results contribute insights into the gas sensor's characteristics, providing essential information to enhance indoor air quality monitoring technology, particularly in laboratory environments.

A***BSTRAK***: Kualiti udara dalam bangunan semakin mendapat perhatian di kalangan masyarakat moden kerana waktu bekerja yang panjang di dalam bangunan dan ini berpotensi terdedah kepada gas toksik dari pelbagai sumber. Pencemaran ini, adalah termasuk kepada sebatian organik mudah meruap (VOCs), yang menimbulkan resiko kesihatan yang teruk, seperti asma dan kanser paru-paru. Bagi menangani isu kritikal ini, projek ini memfokuskan tentang sistem pembangunan dan penilaian secara eksplisit mensasarkan VOCs dengan mengintegrasikan dua pengesan gas berasaskan semikonduktor logam oksida (MOX), ENS 160 dan TED110 yang baru. Parameter berbeza pada pengesan, seperti indeks kualiti udara (AQI) dan sebatian organik mudah meruap (VOCs), dinilai menggunakan 12 bahan kimia organik mudah meruap. Dapatan menunjukkan pengesan ENS 160 berjaya mengesan 60 jenis gas daripada 72 jenis, dengan purata kadar identifikasi sebanyak 83%. Secara perbandingan pengesan TED110 hanya mengesan 24 daripada 72 sampel gas, dengan kadar pengesanan sebanyak 33%. Dapatan ini menyumbang kepada pemahaman tentang ciri-ciri pengesan gas, penyumbang kepada pengetahuan penting tentang teknologi pemantauan kualiti udara iaitu secara khususnya dalam persekitaran makmal.

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***KEY WORDS:*** *Mobile gas sensing, hazardous gas detection, volatile organic compounds, environmental gases, gas sensors, toxic gases.*

# 1. INTRODUCTION

In laboratory infrastructure, employees should be familiar with the chemicals they may come across, potentially reactive or explosive liquids and gases that can be highly hazardous. Accidental or uncontrolled chemical reactions are significant causes of severe personal injury and property damage. Dangerous gases are sufficiently toxic or reactive substances that vigorously or violently give off heat and energy, and become poisonous in contact with air, water, or some other common material. They can be classified in various ways, including acutely toxic, corrosive, flammable, dangerously reactive, and oxidizing compounds [1–7]. Toxic compounds include hydrogen chloride, benzene or toluene, dioxin, and volatile organic compounds (VOCs, such as hydrocarbons, fluorocarbons, chlorofluorocarbons.), or elements such as cadmium, mercury, and chromium. Different VOCs in indoor air are produced from building materials, for instance, wood, cement, stones, asbestos used during construction, and utility items placed inside the building, such as carpets. These are sources of hazardous/toxic gases that can be inorganic, organic, biological, or even radioactive.

In the laboratory infrastructure for learning and experimentation purposes, the laboratory staff must handle a variety of dangerous, poisonous, and reactive chemicals or gases. A particular quantity of hazardous/toxic gases pollutes the atmosphere and can significantly influence human health, creating severe illnesses and threatening worker safety. This expanding number of dangerous gases is sometimes the cause of catastrophic incidents, ruining assets and the causing the deaths of many people [4], [8–10]. Therefore, toxic gases may be acidic, explosive, and extremely dangerous, depending on the concentration and surroundings. A hazardous gas may harm living tissues, affect the central nervous system, cause severe disease, or, in the worst situations, result in death when consumed, breathed, or absorbed by the skin or eyes, according to specialists in gas detection. Furthermore, the employee may regularly be in contact with various hazardous gases in the chemical research laboratory [11], [12]. For instance, long-time exposure to the following gases, $CO_2$, carbon monoxide, and nitrogen oxide ($NO_2$), can cause headaches, dizziness, restlessness, tingling, or pins or needles feeling, difficulty breathing, sweating, tiredness, increased heart rate, elevated blood pressure, coma, asphyxia, and convulsions [13–15]. The effects of different VOCs on human health, such as carbonyl and aromatic compounds, like HCHO, $CH_3CHO$, $C_6H_6$, $C_6H_5CH_3$, and $C_8H_{10}$, severely impact human health and are causes of cancer. Besides, inhaling these compounds can lead to lung cancer [13–17], so experimenting with the effect of these compounds on human health is worthwhile for researchers. Numerous commercial gas detection sensors are available, such as MOX, electrochemical, catalytic, and optical infrared, detect hazardous gases including volatile organic compounds (VOCs). These sensors can be portable or fixed devices and provide alarms when gas concentrations exceed specified thresholds. Several criteria should be considered to evaluate the performance of gas sensors, such as sensitivity, selectivity, stability, response time, reversibility, energy consumption, adsorptive capacity, and fabrication cost. These factors play a crucial role in determining the effectiveness and reliability of gas detection systems in different applications [18] [19].

Neubert et al. [20] discussed a modular Internet of Things (IoT)-based sensor node for hazardous gas detection and monitoring. This experiment used two MOX gas sensors which are BME688 (Bosch Sensortec, Reutlingen, Germany) and SGP30 (Sensirion AG, Stafa, Switzerland). Moreover, a WROOM WiFi module (Espressif Systems, Shanghai, China) transfers the collected data to an IoT cloud for data monitoring and storage. The processing unit for this project was an NXP MKL27Z128VLH4 (NXP Semiconductors N.V., Eindhoven, Netherlands) ARM microcontroller. Furthermore, the experiments were done with various VOCs as a standalone unit and hosted by a stationary and mobile robot.

Two metal oxide (MOX) gas sensors were tested with Al-Okby et al., namely SPG30 and SPG40 (Sensirion AG, Stäfa, Switzerland), to measure the indoor air quality parameters IAQ index and the total volatile organic compound TVOC [7]. The WeMos D1 Mini is a WiFi-based Microcontroller for IoT applications that has been used in the following project with the chip ESP8266 (Espressif Systems, Shanghai, China). The sensors have been tested on various VOC compounds in two different test conditions. Several sensor placements, including a moving robot, were utilized to assess the effectiveness of the two sensors based on the recorded characteristics (IAQ-index and TVOC) [19–21].

Demonstrating a gas sensor system for domestic air quality monitoring, K. Gupta et al. [24] applied Tin Dioxide ($SnO_2$) based MOX gas sensors MQ-135, MQ-6, and MQ-4 ( Winsen Electronics Technology, Zhengzhou, China.). They detected ammonia (NH3), nitrous gases (NOx), nicotine, benzene, carbon dioxide ($CO_2$), butanes, LPG, propane, and LNG, and natural gases (methane, $CH_4$) with an Arduino UNO microcontroller and ESP8266 (Espressif Systems, Shanghai, China) for the WiFi communication interface. Data was shown on the LCD screen and stored on the server. This system can be used as a wireless sensor network for environmental monitoring. Similar technology is utilized for multiple purposes in [23–26].

W. Wojnowski et al. employed electrochemical sensors in E-noses [29]. The sensors included DGS-CO 968-034, DGS-Ethanol 968-035, DGS-$H_2S$ 968-036, DGS-$NO_2$ 968-037, DGS-SO2 968-038, DGS-RESPIRR 968-041, 2E 50, 3E 100 SE (SPEC Sensors LLC, Newark, CA, USA). They were used for the measurement of carbon monoxide (C.O.), ethanol, hydrogen sulfide ($H_2S$), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), VOC, and ammonia ($NH_3$). The communication interface used a USB driver with an LTC2433 ADC (Linear Technology, Milpitas, California, United States) to transfer the data to a PC-class computer.

A. Somov et al. presented a wireless sensor-actuator system for methane detection using a catalytic sensor (NTC-IGD, Stockport, Russia) [30]. Using the Micro Controller Unit (MCU) ADuC836 (One Technology Way, Norwood, USA), the node was connected to the WSN via the ETRX3 module; the communication interface was UART. The calibration notices were recorded in EEPROM M95640, connected to MCU using SPI. Apart from the calibration information, the memory chip stored information on the occurring events, e.g., emergencies.

S. Esfahani et al. developed an electrical nose for VOC, carbon dioxide ($CO_2$), and methane (CH4) using optical and infrared sensors such as LFP3144C-337, LFP-3850C-337, LFP-8850-337, and 90 V LFP- 8850-337 (InfraTec GmbH, Dresden, Germany) [31]. This work used a Teensy 3.6 (PJRC, Portland, USA) microcontroller with a UART communication interface. A laptop with a USB serial port was connected for storing and displaying data. This portable optical e-nose can be applied to a robot for environment monitoring.

A fumigant gas trace detection system (FGTDS) based on a photoionization detector (PID) was designed for the inspection and quarantine port to monitor the gas leakage within the dosing room of the fumigant warehouse [32]. It used PID-A1 (Alphasense, Braintree, U.K.) with MCU STC12LE5A60S2 (Shenzhen LCSC Electronics Technology, Shenzhen, China) and ADS8325 A/D (Texas Instruments, Texas, United States) converter, which was applied for MCU controls.

This research focused on developing and evaluating an advanced volatile organic compounds (VOCs) detection system using novel metal oxide semiconductor (MOX)-based gas sensors. Besides, the study investigated the sensor performance, such as sensitivity, selectivity, and detectable gas limit, focusing on distinct sensor parameters, including the air quality index (AQI) and total volatile organic compounds (VOCs). Overall contribution was to develop an advanced gas detection system specifically for VOCs using two novel MOX-based gas sensors, ENS160 (Sciosense B.V., Eindhoven, Netherlands) and TED110 (Wise Control Inc, Seoul, Korea). In addition, it evaluated distinct sensor parameters, such as AQI and TVOCs, in a typical chemical hood environment with 12 distinct VOCs. It also analyzed the sensors' different characteristics, such as sensitivity, accuracy, response, and recovery time. The comparison of the system's stability, accuracy, and effectiveness with existing design from the University of Rostock, including sensors BME688 (Bosch Sensortec, Reutlingen, Germany), SGP 40, and SGP 30 (Sensirion AG, Stäfa, Switzerland), offers valuable benchmarks and validates the system's performance. In a nutshell, the findings from this research enhance the understanding of gas detection technology and provide essential insights for improving indoor air quality monitoring systems and safety, particularly in laboratory environments [7], [20].

## 2. MATERIALS AND METHODS

### 2.1. Sensor Selection

One of the significant challenges of a gas detection system is determining the appropriate gas sensor type. Different gas sensor technologies have limitations; none can be used for all gas types or applications. The primary goal of this project is the detection of indoor TVOC with a specific focus on a quick response for the safety laboratory employees. The initially chosen MOX gas sensor ENS160 (Sciosense B.V., Eindhoven, Netherlands; see Fig. 1) can measure three separate parameters, AQI (100 to 500), TVOC (0-65,000 PPB-Parts per billion), and $eCO_2$ (0-65,000 PPM-Parts per Million). The TED110 (WISE Control Inc, Seoul, Republic of Korea), shown in Fig. 2, was chosen as a second gas sensor for the detection of a wide range of gases in concentrations between 1 and 1,000 ppm, including VOCs, carbon monoxide, ethanol, methane, nitrogen dioxide, toluene, and hydrogen sulfide. Detailed descriptions of both sensor specifications are provided in Table 1:

Fig. 1: ENS 160 Gas Sensor, Sciosense B.V., Eindhoven, Netherlands [33]

Fig. 2: TED110 sensor, Wise control inc., Seoul, Republic of Korea [34].

Table 1: Selected Sensor Specifications

| Sensor Specifications | ENS 160 | TED 110 |
|---|---|---|
| Structure | Metal Oxide (MOX) | MOX type Micro-Electro-Mechanical System (MEMS) |
| Measure Gases | AQI (100-500), TVOC (0 – 65,000 PPB), (400 – 65,000 PPM) | TVOC (VOCs, CO, EtOH, CH4, NO2, Toluene, H2S et) (1-1000 PPM) |
| Humidity and temperature | Yes | Yes |
| Response time | 1s | 10s |
| Warm-up | < 3 min | < 50 seconds |
| Communication Interface | I2C and SPI | I2C |
| Positive supply | 1.8V(VDD) & 3.6V(VDDIO) | 3.3 V |
| Lifetime | 10 years | 5 years |
| Package dimension | 3.0 × 3.0 × 0.9 mm3 | 3 × 3 × 1 mm3 |
| Cost | $6.06 | |
| | $12.50 | |
| Manufacturers | Sciosense B.V., Eindhoven, Netherlands | Wise control inc., Seoul, Republic of Korea. |

## 2.2. Microcontroller Selection

Microcontrollers are used to analyze and process the measured data, in decision-making, and in sending the proper action signals to the output ports. The Kinetics KL27 Microcontroller, illustrated in Fig. 3, was chosen for this experiment, which uses an MKL27Z128VLH4 processor (NXP Semiconductors, Eindhoven, Netherlands). The project selected this Microcontroller [18], which was tested before with two gas sensors (BME 688 and SGP 30). It is optimized for cost-sensitive and battery-powered applications requiring low-power USB connectivity. The specification of the MCU is shown in Table 2.

Table 2: Specification of the Microcontroller

| Specifications | Values |
|---|---|
| Core Type | Arm Cortex-M0+ |
| Operating Frequency (MHz) | 48 |
| Number of bits | 32bit |
| Temperature range (°C) | -40° to 105 °C |
| Flash (kB) | 128 |
| SRAM (kB) | 32 |
| Serial Communication | 2 × $I^2C$,2 × SPI,3 × UART |
| Supply Voltage (V) | 1.71 V to 3.6 V |
| Power supply and data Transfer | USB-C |

## 2.3. Experimental Setup

This project is the extension of an existing developed system called CELISCA at the University of Rostock, Germany [20], which consists of two sensors in the sensing layers, such as BME688 (Robert Bosch GmbH, Stuttgart, Germany) and SGP40 (Sensirion AG, Stäfa, Switzerland), as shown in Figure 5(a). The sensor layer was tested with the processing layer

NXP MKL27Z128LH4 MCU (NXP Semiconductors N.V., Eindhoven, Netherlands) board. Since gas sensors are heat sensitive, these sensor layers were designed in two fingers to keep a particular air gap. The heat generated by the sensors may interfere with the degradation of their function. The main objective of the current project was the extension of a novel sensor layer and the design of a relevant system. For the extension, two novel gas sensors, ENS160 (Sciosense B.V., Eindhoven, Netherlands), TED110 (Wise Control Inc, Seoul, Korea), and the processing layer MKL27Z128LH4 MCU board (NXP Semiconductors, Eindhoven, Netherlands) were added. Developing the design idea from the previous project, the first selected sensor, ENS160, was placed in the middle of the previous two sensors, shown in Fig. 5 (b). Finally, by adding the TED110, the overall sensor board then has four fingers - TED110, BME688, ENS160, and SGP40 as seen in Fig. 5(c). All selected sensors and necessary electronics were designed on a printed circuit board (PCB) by Autodesk Eagle software (Autodesk, San Rafael, California, USA). After manufacturing the PCB, sensors and relevant electronics were mounted on the board.

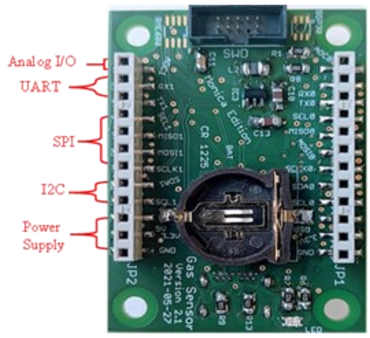


Fig. 3: MKL27Z128VLH4 MCU board

This project consists of two main layers, as shown in Fig. 4. The first layer is the sensing layer, which detects various gas parameters. The second layer is the processing layer (MCU) with the power supply, which receives the measured data from the sensing layer and processes it. The MCU acts as a master, communicating with the sensors (working as slaves) using the I2C communication protocol. The MCU sends a register address to initiate the sensor's I2C clock, baud rate, and data length; after receiving the initiate acknowledgment command from the sensor, the MCU requests the sensor data. Then the MCU writes register addresses on the sensors for individual parameters, reads them as gas data, and converts all the data into appropriate units. The MCU's programming was performed using MCUxpresso IDE (NXP Semiconductors N.V., Eindhoven, Netherlands) and debugged using J-Link EDU (SEGGER Microcontroller GmbH, Monheim am Rhein, Germany). The detection results were displayed in Tera Term (open-source software under the BSD License) serial monitor connected via USB-C and saved in a CSV file.

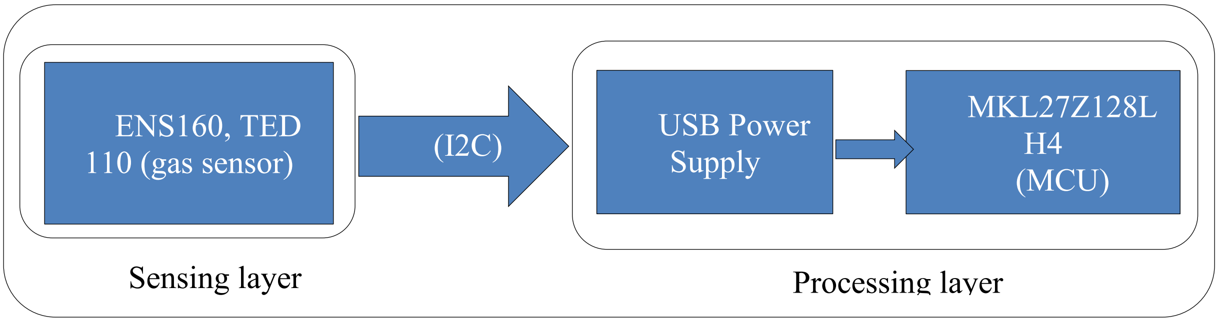


Fig. 4: Overall project structure

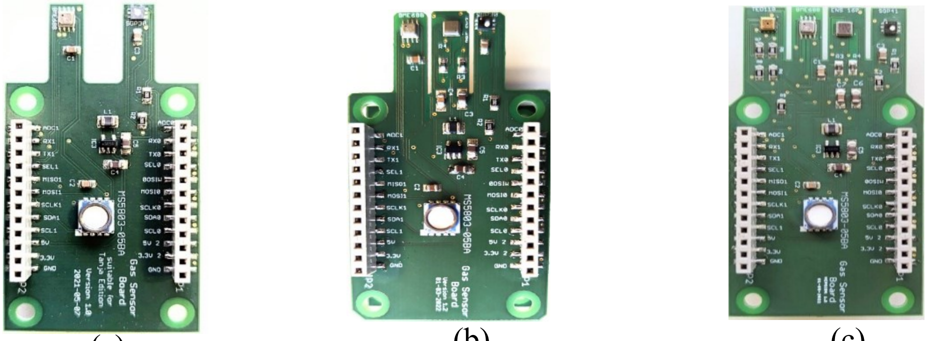

(a) (b) (c)

Fig. 5**:** (a) Sensor board with BME688 and SGP40; (b) BME688 and SGP40 and ENS 160; (c) TED110, BME688, ENS160 and SGP40

## 2.4. Experimental Procedure

To evaluate the sensor characteristics, 12 different low volatile organic compounds were selected, which are commonly used in the laboratory [7], [12], [35]. Among the 12 VOCs, benzene, toluene, and formic acid are exceptionally toxic and carcinogenic, posing significant risks of long-term health effects, including leukemia and cancer, even at low exposure levels [36]. Additionally, acetone, acetonitrile, dichloromethane, diethyl ether, ethanol, heptane, hexane, and iso-propanol are harmful to human health as they can cause respiratory irritation, dizziness, and in severe cases, damage to organs such as the liver and nervous system when exposed to elevated concentrations [2], [37]. So, detecting all these gases is crucial for ensuring safety in the laboratory and assisting in developing better gas detection technologies. Table 3 displays the selected 12 gases with their molecular formulas and the boiling point [7]. The entire experiment was done in a classical chemical hood (Waldner Holding GmbH and Co. KG, Wangen im Allgäu, Germany); Fig. 6 illustrates a hood design for a laboratory for chemical and analytical purposes. Eppendorf pipettes were used to inject the testing samples within a Petri dish (Eppendorf AG, Hamburg, Germany). In addition, the sensor node was mounted on a movable stand with a manually adjustable height. The experiment was performed for 5 minutes, during which data was taken for 300 s. The amount of the gas samples were 5μL, 10μL, and 50μL; all experiments were done from 40 cm and 100 cm sensor node distance from the testing vapors. For the ENS160, the target parameter is the air quality index AQI (100 to 500), total volatile organic compounds concentration TVOC (0 – 65,000 ppb), and $CO_2$ (400 – 65,000 ppm). The target parameter for the TED 110 gas sensor is the Gas Density (0 – 1,000 ppm). Every second of data was stored in a CSV file for further graphical visualization. Table 4 displays the various levels of gases for ENS160.

Table 3: Selected 12 gases with the molecular formula and the boiling point [7]

| Name | Molecular Formula | Boiling point in °C |
|---|---|---|
| Acetone | $C_3H_6O$ | 56 |
| Acetonitrile | $C_2H_3N$ | 82 |
| Benzene | $C_6H_6$ | 80.1 |
| Dichloromethane | $CH_2Cl_2$ | 39.6 |
| Diethyl ether | $C_4H_{10}O$ | 34.6 |
| Ethanol | $C_2H_6O$ | 78.37 |
| Formic Acid | $CH_2O_2$ | 100.8 |
| Heptane | $C_7H_{16}$ | 98.42 |
| Hexane | $C_6H_{14}$ | 69 |
| Iso propanol | $C_3H_8O$ | 82.5 |
| Methanol | $CH_3OH$ | 64.7 |
| Toluene | $C_7H_8$ | 110.6 |

**Table 4:** ENS160 concern for different gas concentrations [33]

| Level | AQI | TVOC (ppb) | $CO_2$ (Without baseline 400) (ppm) |
|---|---|---|---|
| Unhealthy | 500 | >2,200 | >1500(1100) |
| Poor | 400 | 660-2,200 | 1000-1500(600-1100) |
| Moderate | 300 | 220-660 | 800-1000(400-600) |
| Good | 200 | 65-220 | 600-800(200-400) |
| Excellent | 100 | 0-65 | 400-600(0-200) |

To avoid any influence from air ventilation, the ventilation system of the hood was shut off during system testing. The chemical hood is shown in Fig. 6.

Fig. 6: Experiment in a traditional chemical hood

## 3. RESULTS AND DISCUSSION

The goal of the tests in all scenarios and positions was to determine the smallest quantity of VOC detected by the two utilized sensors from the testing distance (e.g., the length between the VOC leakage source and the sensors). The sensor responses were analyzed by presenting all the experimented data in a graph. The result can be defined for ENS 160 from Table 4 as low response (all parameters are in excellent level), moderate response (all parameters are good & moderate level), and excellent response (all parameters are poor & unhealthy level). Additionally, TED110 has low performance in this experiment, so in this research, just its response was tested.

The ENS 160 gas sensor demonstrates high effectiveness and performance for acetone ($C_3H_6O$) detection, showing excellent response to sample amounts >5µL and all desired parameters, including AQI, TVOC, and $CO_2$ . Its reliable performance at lower sample concentrations showcases its sensitivity and ability to detect acetone accurately. On the other hand, the TED110 sensor's low response to acetone, except at >50µL and 100 cm distance, indicates a low gas detectable limit, assuming a reason of cross-sensitivity or environmental interference. The principle of the MOX gas sensor is that its surface is adsorbed by oxygen, changing the sensor's response quickly [38], so that the ENS160 gas sensor strongly reacts to oxygen containing compounds, but TED 110 needs intensive investigation to improve performance and expanding detection limit. Both sensor responses for acetone are presented in Fig. 7.

Acetonitrile ($C_2H_3N$) has an excellent response with ENS160's required parameters with a volume >5µL, illustrated in Figure 8, showing a good sensitivity and detection level. The AQI, TVOC, and $CO_2$ exhibit an excellent response for >10µL. TED110 gas sensor (gas density) has no response for any amounts of acetonitrile 40 cm and 100 cm. ENS 160 has good performance without oxygen-containing compounds, but TED110 failed in this context; further improvement is necessary.

Detecting low benzene concentrations ($C_6H_6$) is essential because inhaling it for a long time can cause cancer. ENS160 has an excellent response with the benzene samples concentration of >10µL for all required parameters, such as AQI, TVOC, and $CO_2$, presented in Fig. 9. Although it has no oxygen compounds, ENS 160 is responding, but the TED110 gas sensor has no response for benzene. ENS160's ability to detect benzene at concentrations >10µL demonstrate that it has a low detection limit (has no oxygen compounds); further calibration is necessary to enhance its gas detectable limit and broaden its application range for benzene detection.

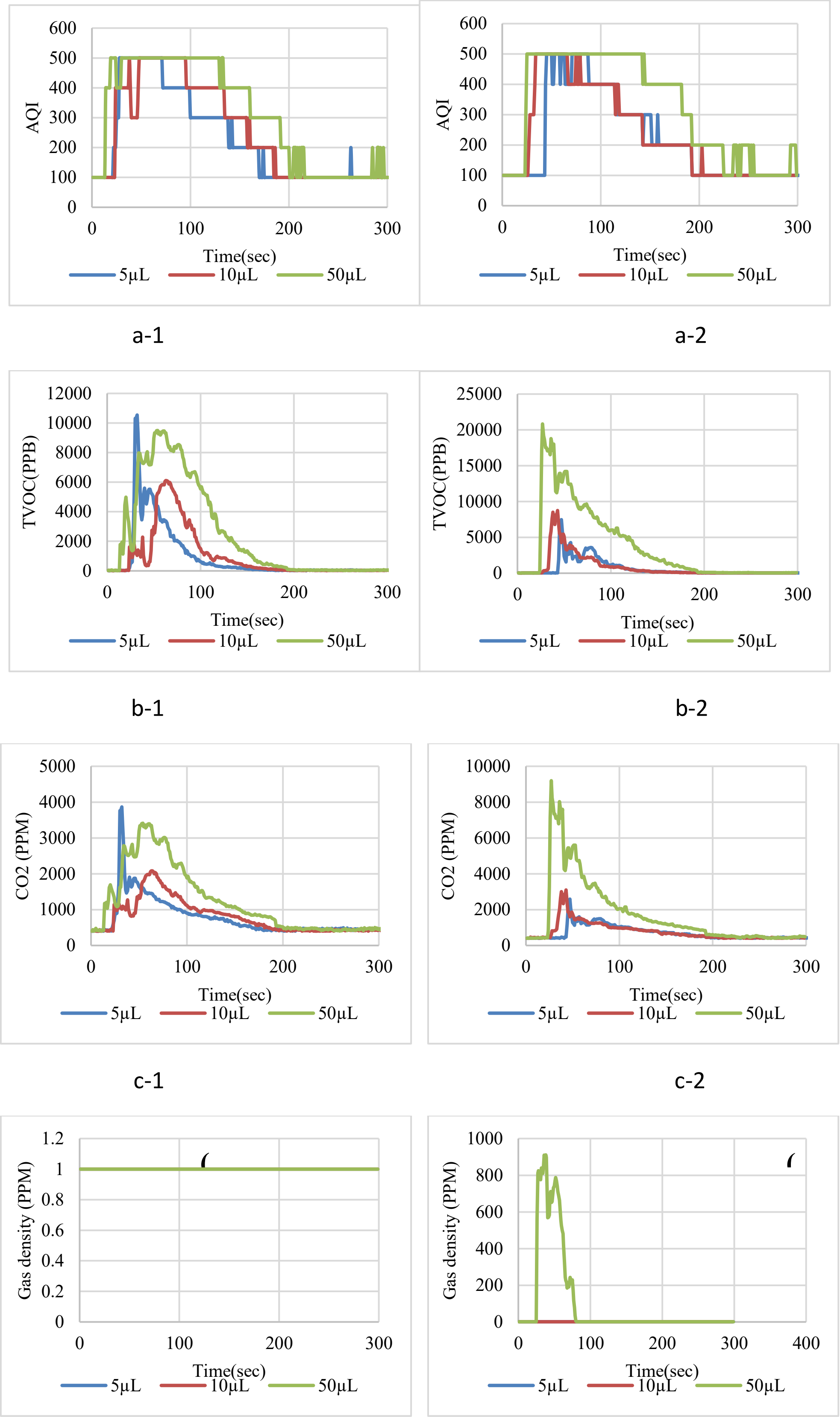
Dichloromethane ($CH_2Cl_2$) increases the risk for several specific cancers, including brain, liver, and biliary tract cancer. Unfortunately, as seen in Fig. 10, ENS 160 has a low response to this vapor, and the TED110 gas sensor has no response for all the required parameters. The low response of both sensors creates concern about the sensor's traceability, testing methods, sensitivity, and selectivity, probably following the MOX sensor principle. In short, to improve accuracy and eliminate external factor contamination, a more extensive experimental procedure must be developed or choosing gas sensors with appropriate sensitivity and selectivity.

ENS160 has an excellent response to diethyl ether ($C_4H_{10}O$) from the sample amount of >5 µL for all the necessary parameters, indicating its significant effectiveness and detection capability, illustrated in Fig. 11. The AQI, TVOC, and $CO_2$ showed excellent responses for the sensor node distances, such as 40 cm and 100 cm. ENS 160 has an excellent response; although no oxygen compound, the TED110 gas sensor (Gas Density) declines to respond to diethyl ether.

Ethanol ($C_2H_6O$) has an excellent response of >5µL for all the desired parameters in ENS160. Similarly, the TED110 gas sensor (gas density) has a reaction for ethanol in all gas sample concentrations. Fig. 12 exhibits both sensor responses for ethanol. Overall, based on the MOX gas sensor principle, both sensors possess appropriate gas detectable limits and sensitivity, which makes them suitable for ethanol detection.

Formic Acid ($CH_2O_2$) has a low response in the ENS 160 gas sensor for all the expected parameters (AQI, TVOC, and $CO_2$). On the other hand, the TED110 gas sensor (gas density) has a response to formic acid, showing the highest reaction for sample size at >5µL at 40 cm. Similarly, for the 100 cm distance, the TED110 gas sensor (Gas Density) has a response from >10µL gas samples. Both sensors' response to formic acid are shown in Fig. 13. Based on oxygen compounds, ENS160 should have had a reaction but failed; TED110 has a response but low detection level, so both sensors require more calibration and intensive investigation to improve sensitivity, effectiveness, and performance to the formic acid.

As shown in Fig. 14, heptane ($C_7H_{16}$) has a low response for all the desired parameters at the ENS160 gas sensor. Similarly, the TED110 gas sensor (Gas Density) has no response. As no oxygen compounds, both sensors declined to respond. As a result, testing methods for the current sensors or the adoption of a heptane-specific sensor, need to improve.



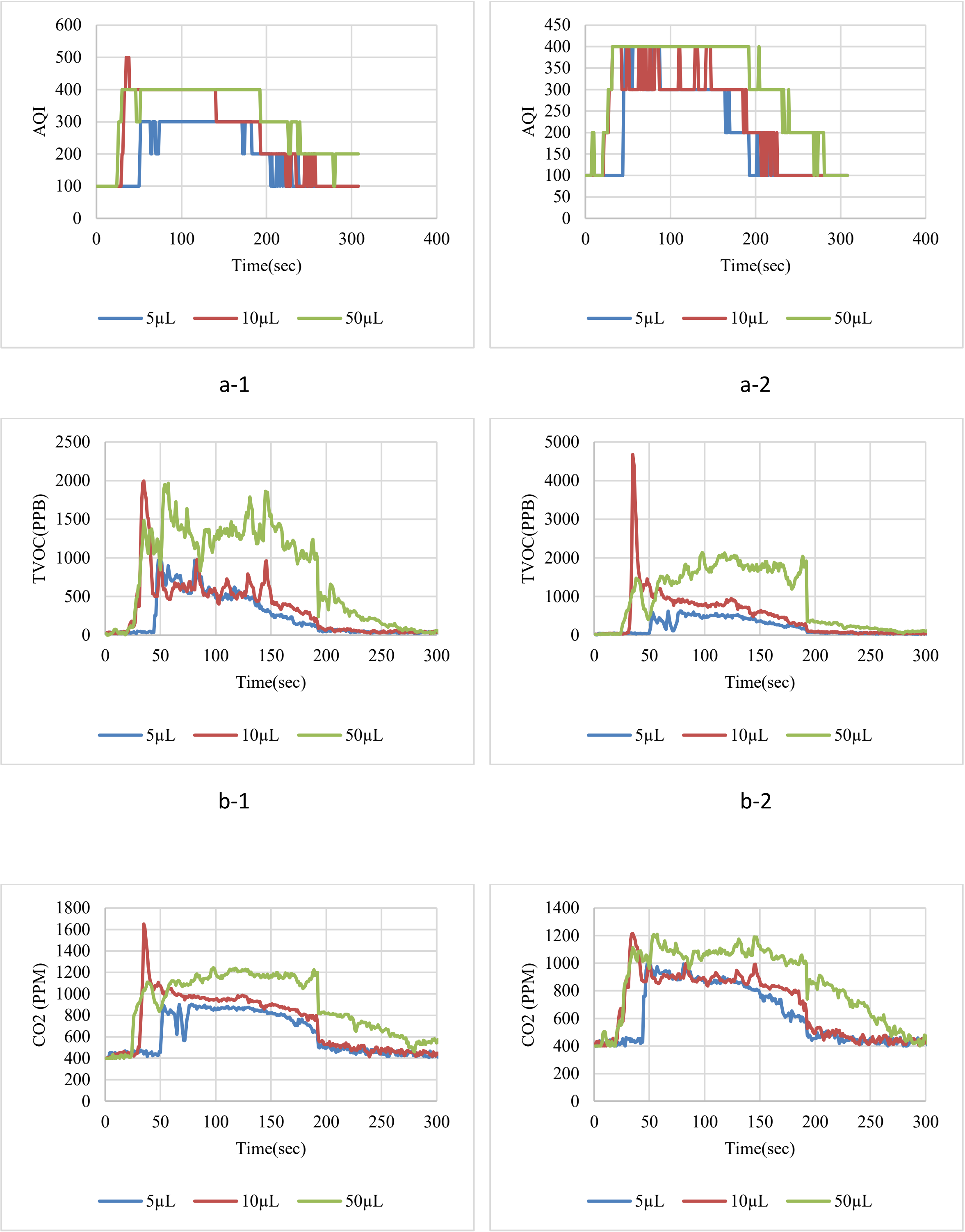
a-1 a-2

b-1 b-2

c-1 c-2

d-1 d-2

Fig. 7: Acetone ($C_3H_6O$) response for ENS160 (a, b, c) and TED110 (d) at 40 cm (1) and 100 cm (2)

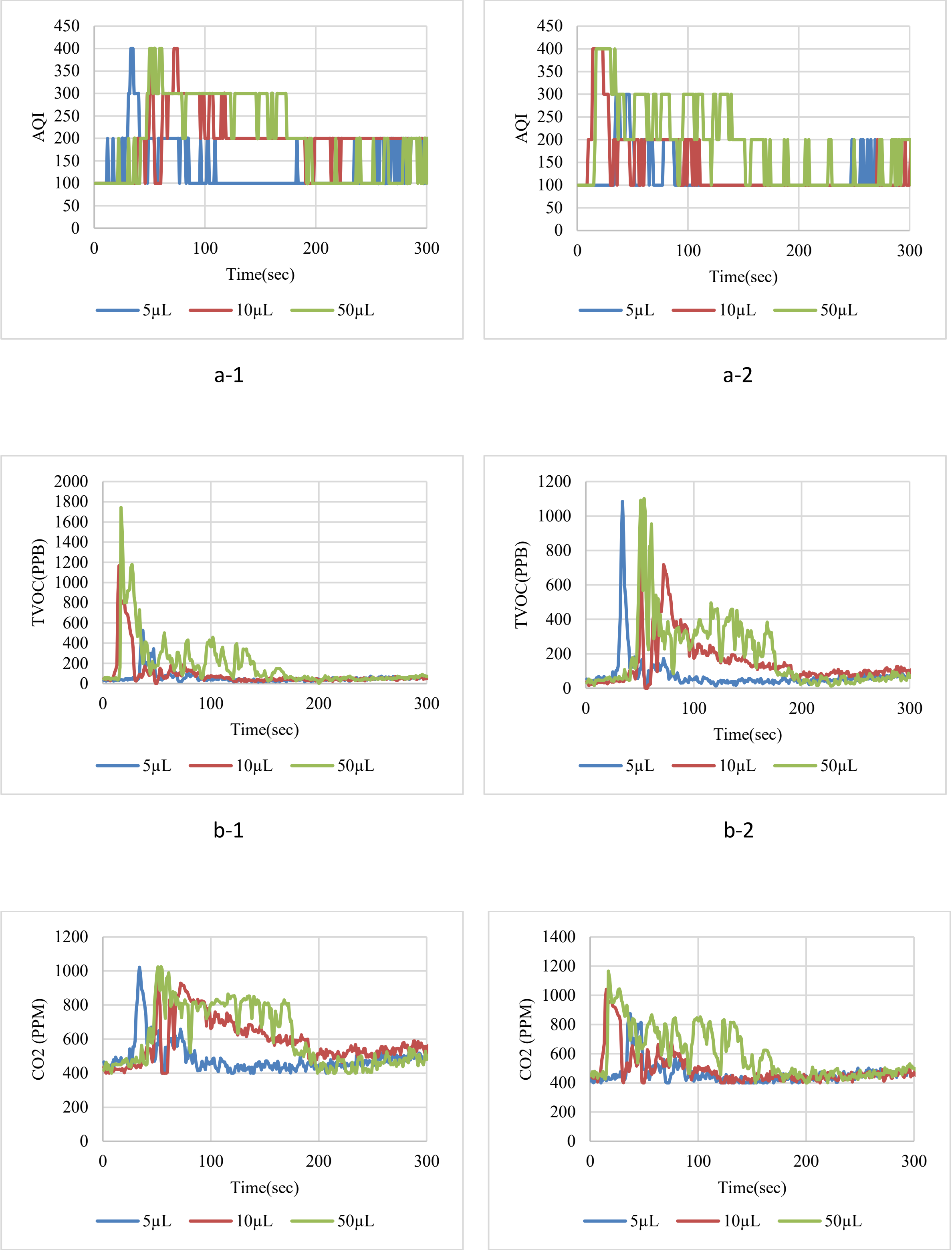


a-1 a-2

b-1 b-2

c-1 c-2

Fig. 8: Acetonitrile ($C_2H_3N$) response for ENS160 (a, b, c) at 40 cm (1) and 100 cm (2).

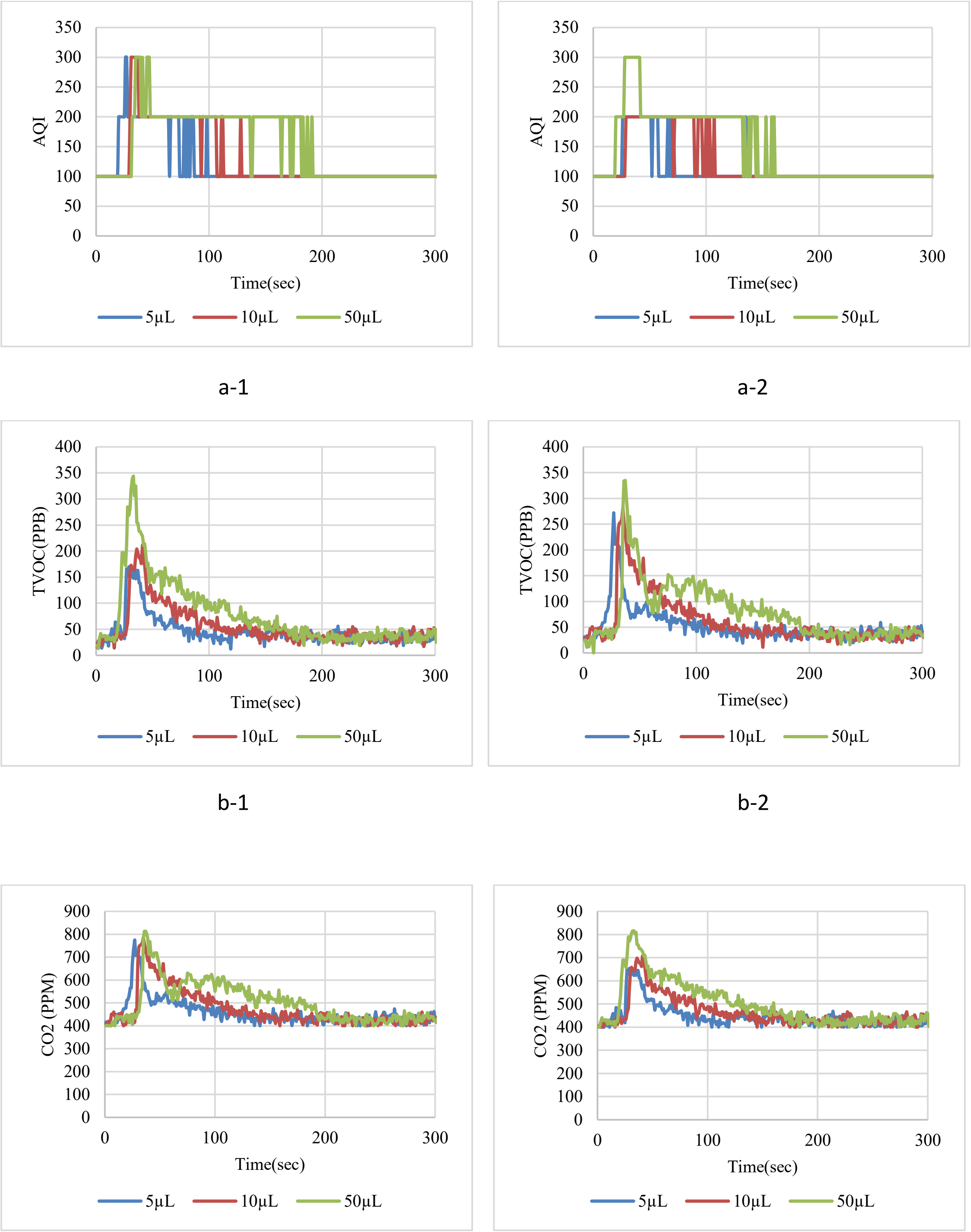


a-1 a-2

b-1 b-2

c-1 c-2

Fig. 9: Benzene ($C_6H_6$) response for ENS160 at 40 cm (1) and 100 cm (2)

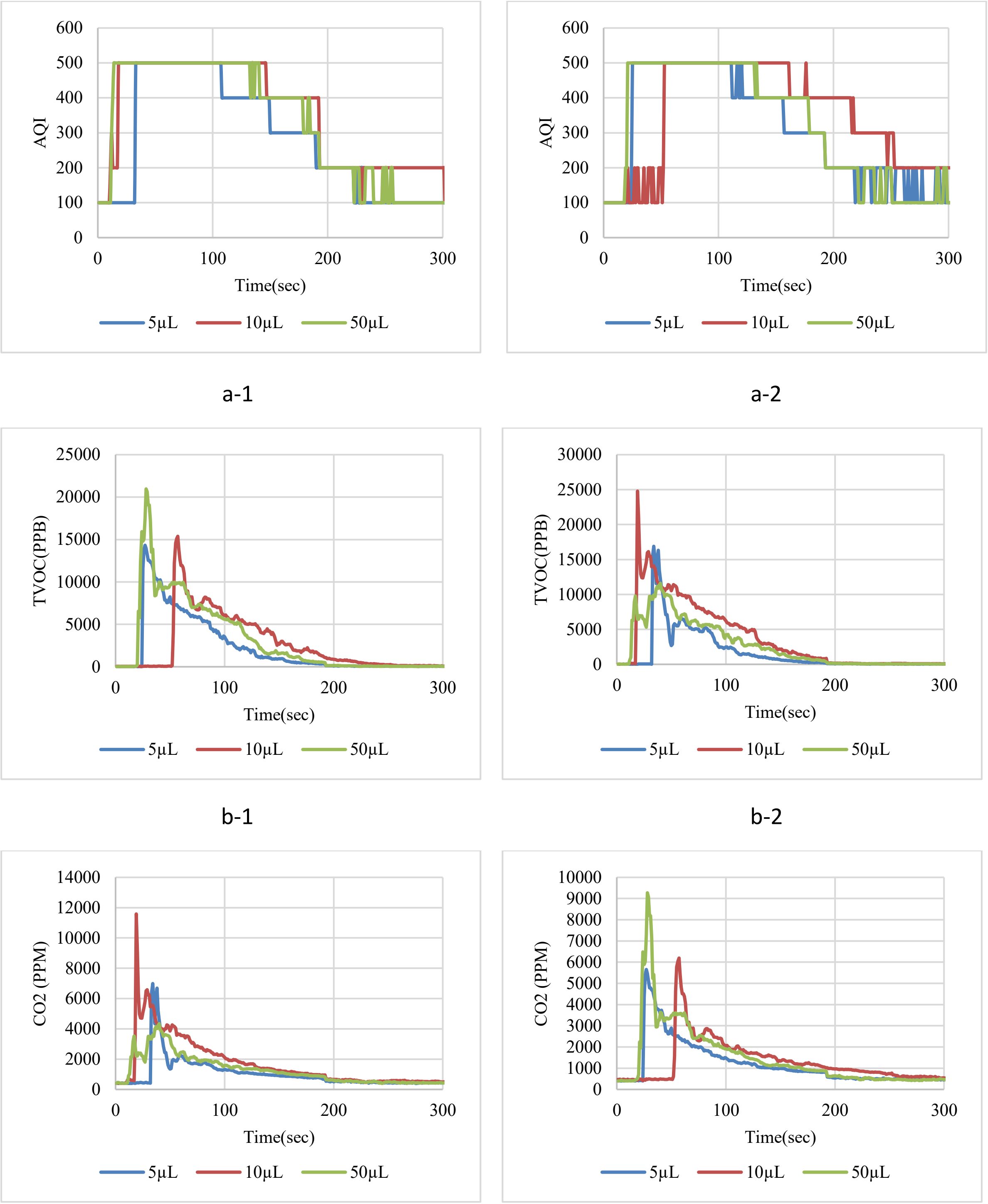


a-1 a-2

b-1 b-2

c-1 c-2

Fig. 10: Dichloromethane ($CH_2Cl_2$) response for ENS160 (a, b, c) at 40 cm (1) and 100 cm (2)



a-1 a-2

b-1 b-2

c-1 c-2

Fig. 11: Diethyl Ether ($C_4H_{10}O$) response for ENS160 (a, b, c) at 40 cm (a) and 100 cm (b),

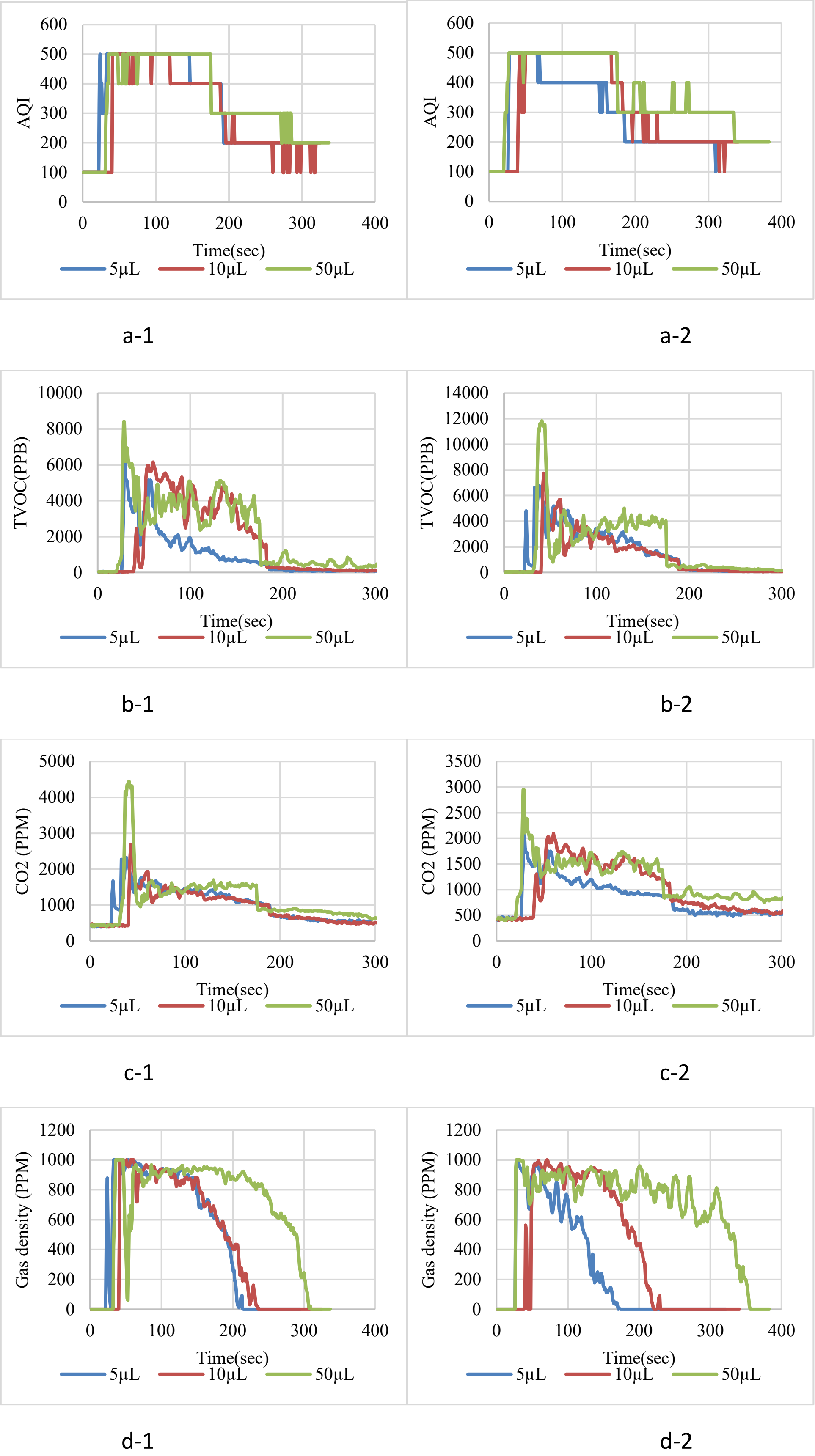
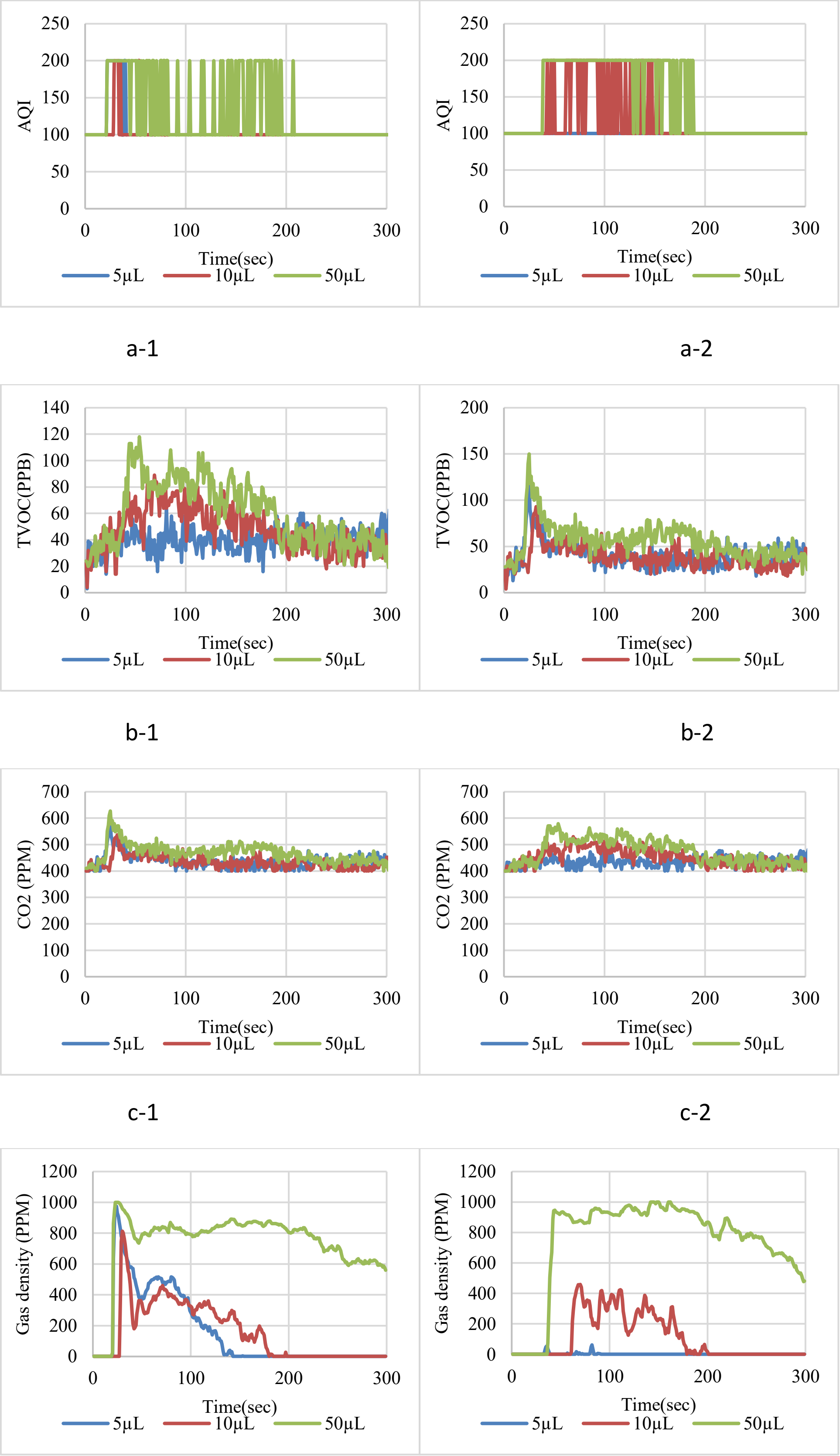


Fig. 12: Ethanol ($C_2H_6O$) response for ENS160 (a, b, c) and TED110 (d) at 40 cm (1) and 100 cm (2)



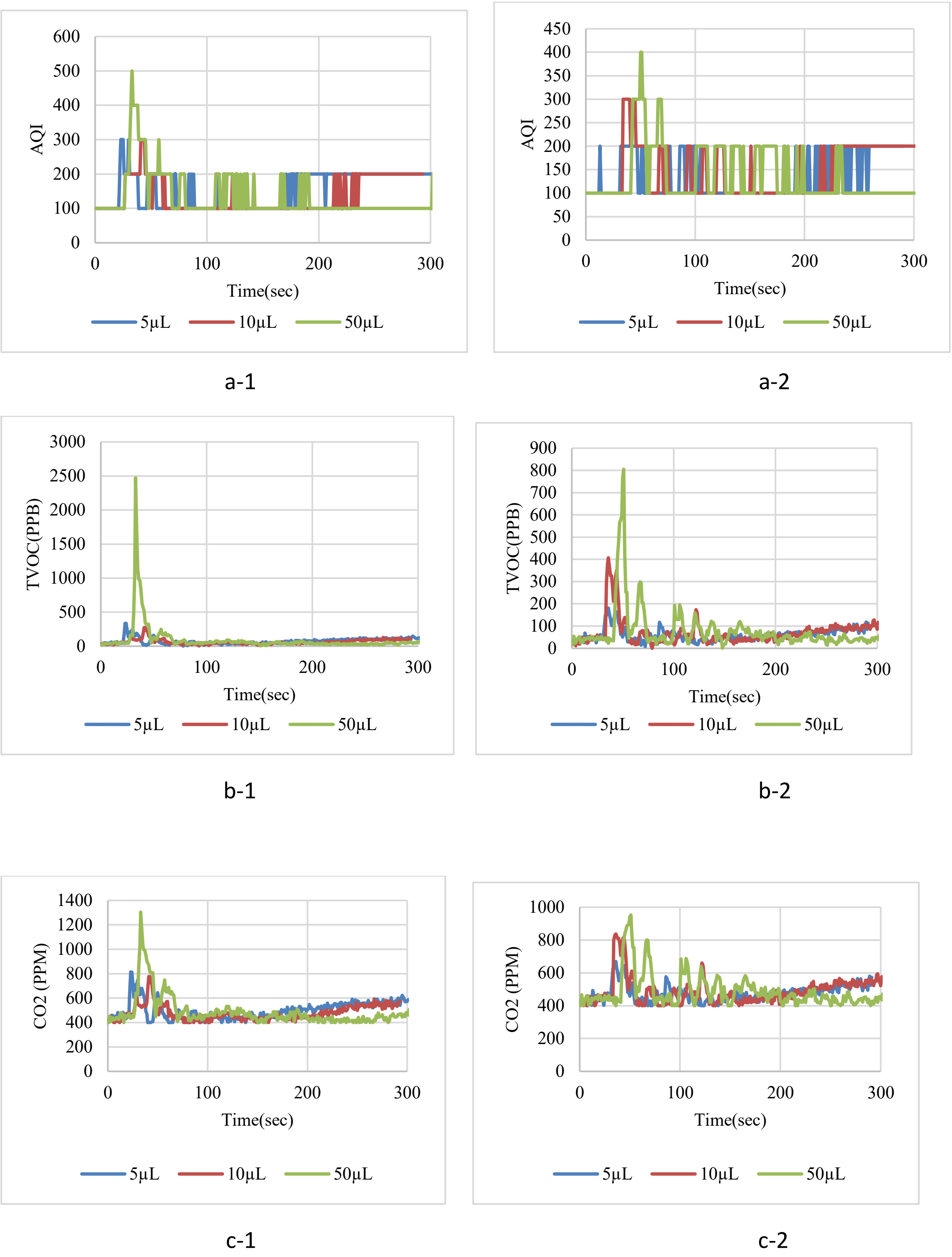
a-1 a-2

b-1 b-2

c-1 c-2

d-1 d-2

Fig. 13: Formic Acid ($CH_2O_2$) response for ENS160 (a, b, c) and TED110 (d) at 40 cm (1) and 100 cm (2)



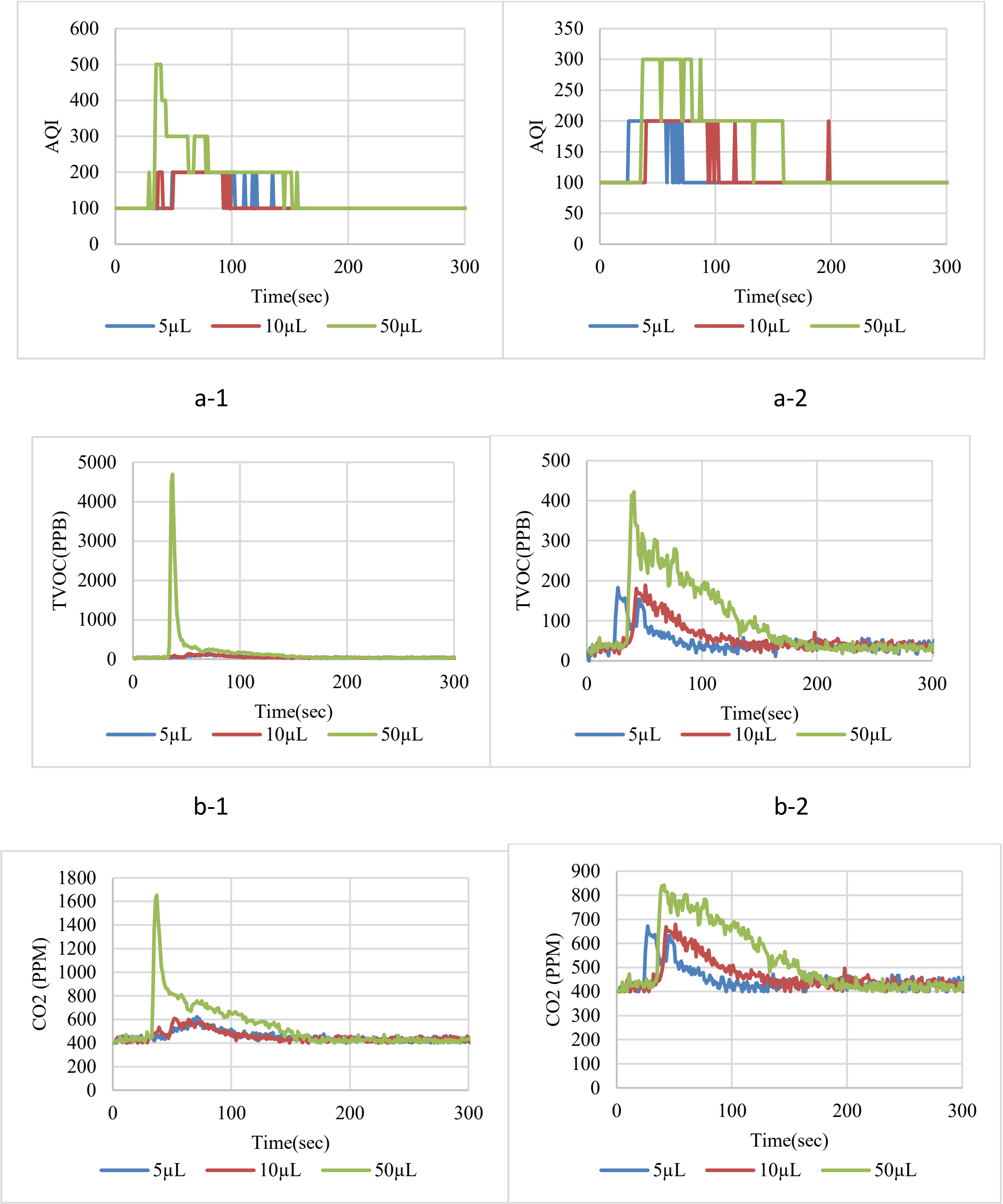
a-1 a-2

b-1 b-2

c-1 c-2

Fig. 14: Heptane ($C_7H_{16}$) response for ENS160 (a, b, c) at 40 cm (1) and 100 cm (2)

ENS160 hexane ($C_6H_{14}$) has an excellent response from >50µL for 40 cm for all the required parameters. The AQI, TVOC, and $CO_2$ responded well with >50µL at 40 cm with a low response at 100 cm. In contrast to the MOX sensor principle, ENS160 can detect hexane but shows low sensitivity, effectiveness, and detection level. Fig. 15 depicts the hexane responses for ENS160. The TED110 gas sensor (gas density) hexane has not responded in any amount.



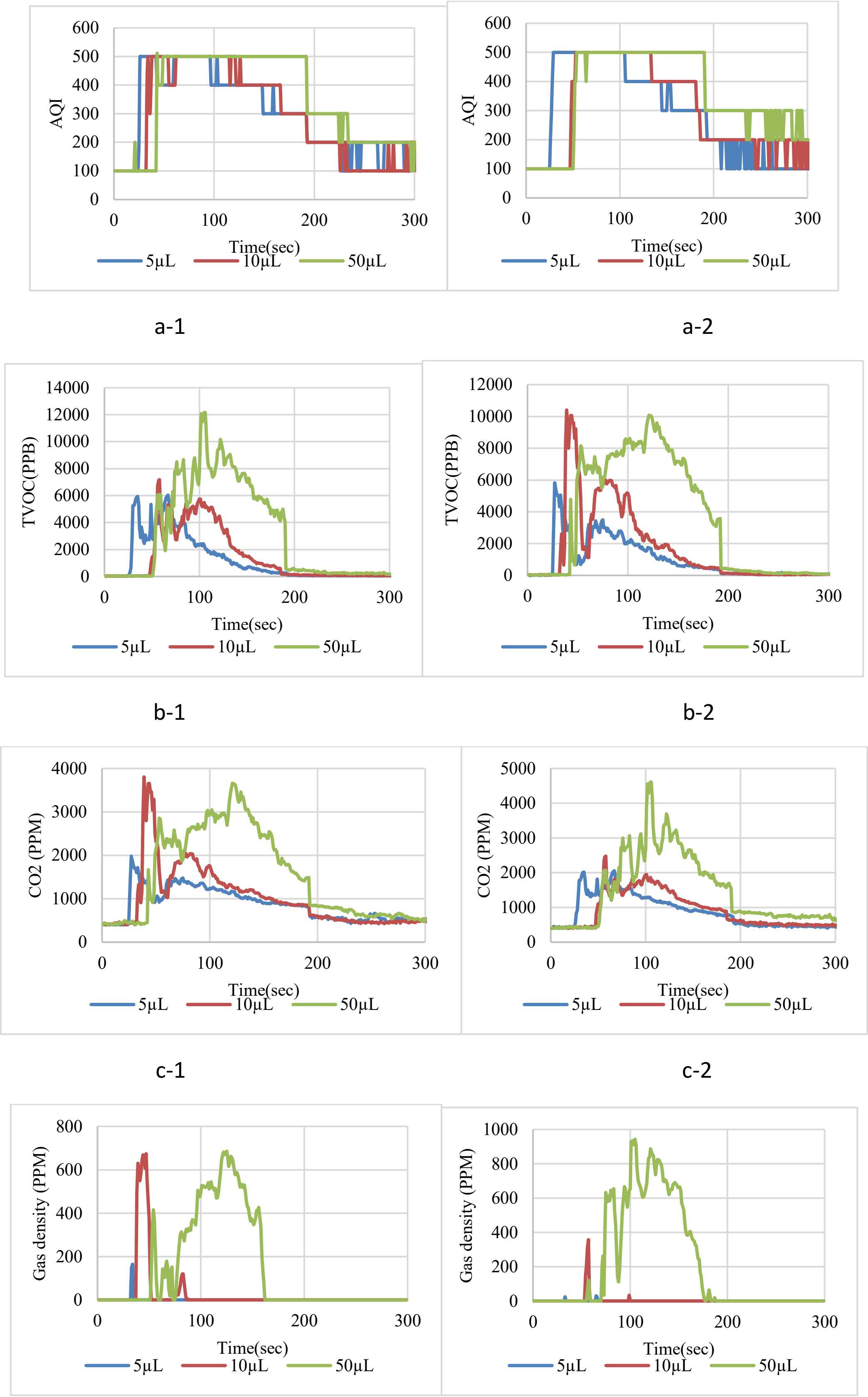
a-1 a-2

b-1 b-2

c-1 c-2

Fig. 15: Hexane ($C_6H_{14}$) response for ENS160 (a, b, c) at 40 cm (1) & 100 cm (2).

For all the required parameters, isopropanol ($C_3H_8O$) shows an excellent response with the ENS 160 gas sensor from the sample amounts at >5μL. The TED110 gas sensor (gas density) at a 40 cm distance has an excellent response with isopropanol from >10μL. Based on the MOX gas sensor concepts, the ENS160 and TED110 gas sensors effectively detect isopropanol under varying sample amounts and distances. Further investigations specifically for TED110 are essential to optimize sensor performance and understand the extent of their accuracy and reliability in real-world environments. Fig. 16 displays the isopropanol sensor responses for both sensors.



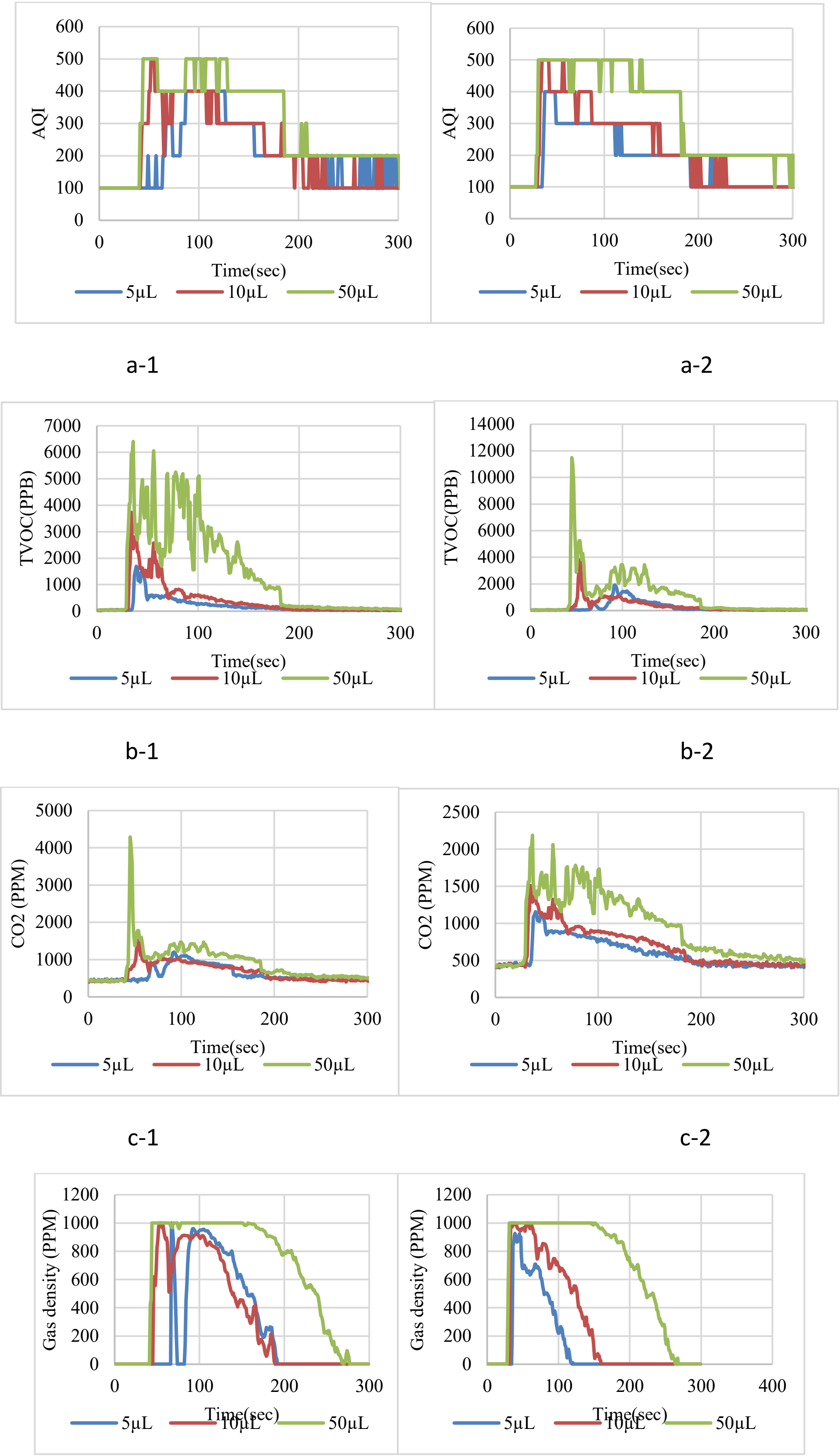
a-1 a-2

b-1 b-2

c-1 c-2

d-1 d-2

Fig. 16: Isopropanol ($C_3H_8O$) for ENS160 (a, b, c) and TED110 (Gas density) (d) at 40 cm (1) and 100 cm (2)



a-1

a-2

b-1

b-2

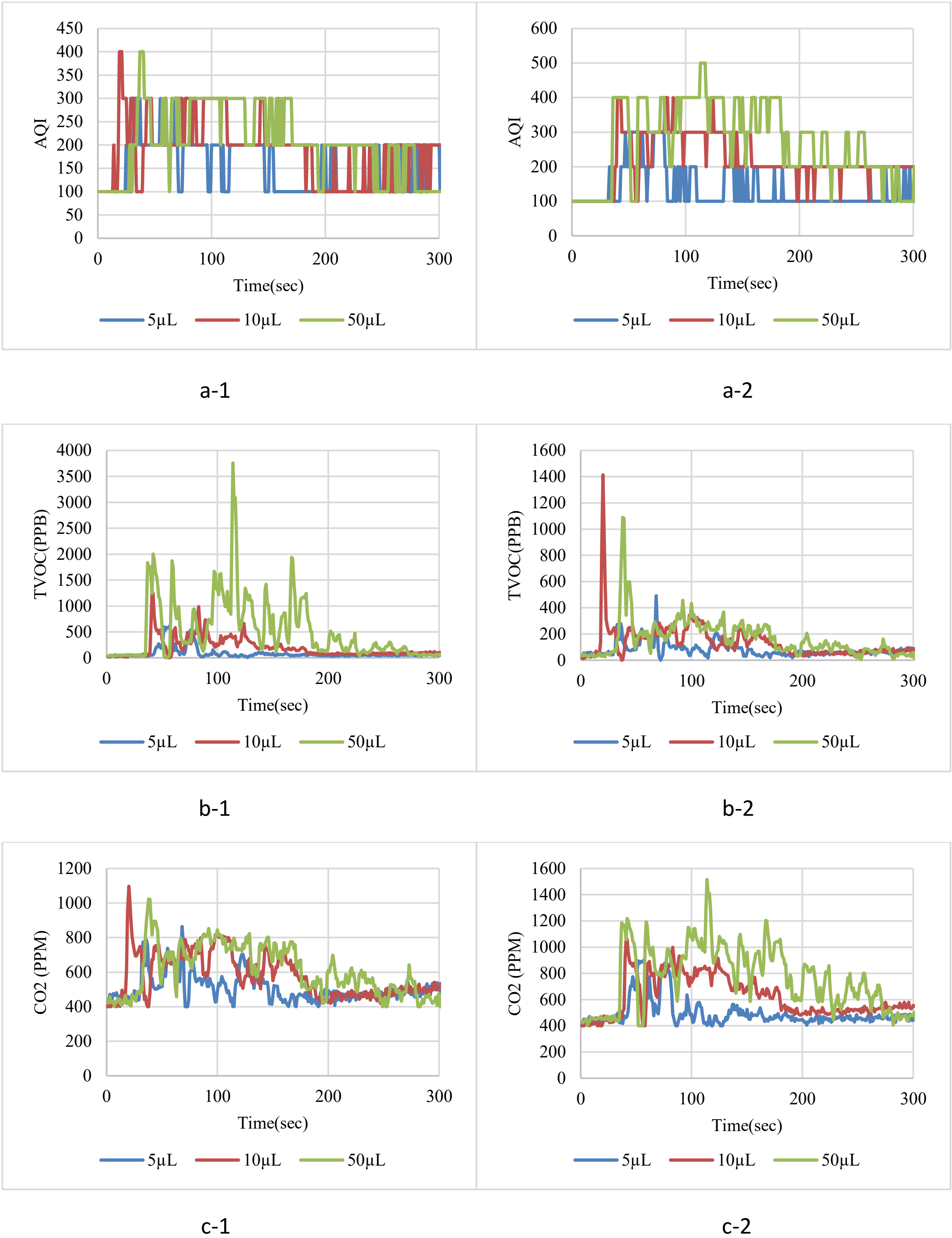
c-1

c-2

d-1

d-2

Fig. 17: Methanol ($CH_3OH$) response for ENS160 (a, b, c) and TED110 (d) at 40 cm (1) & 100 cm (2)

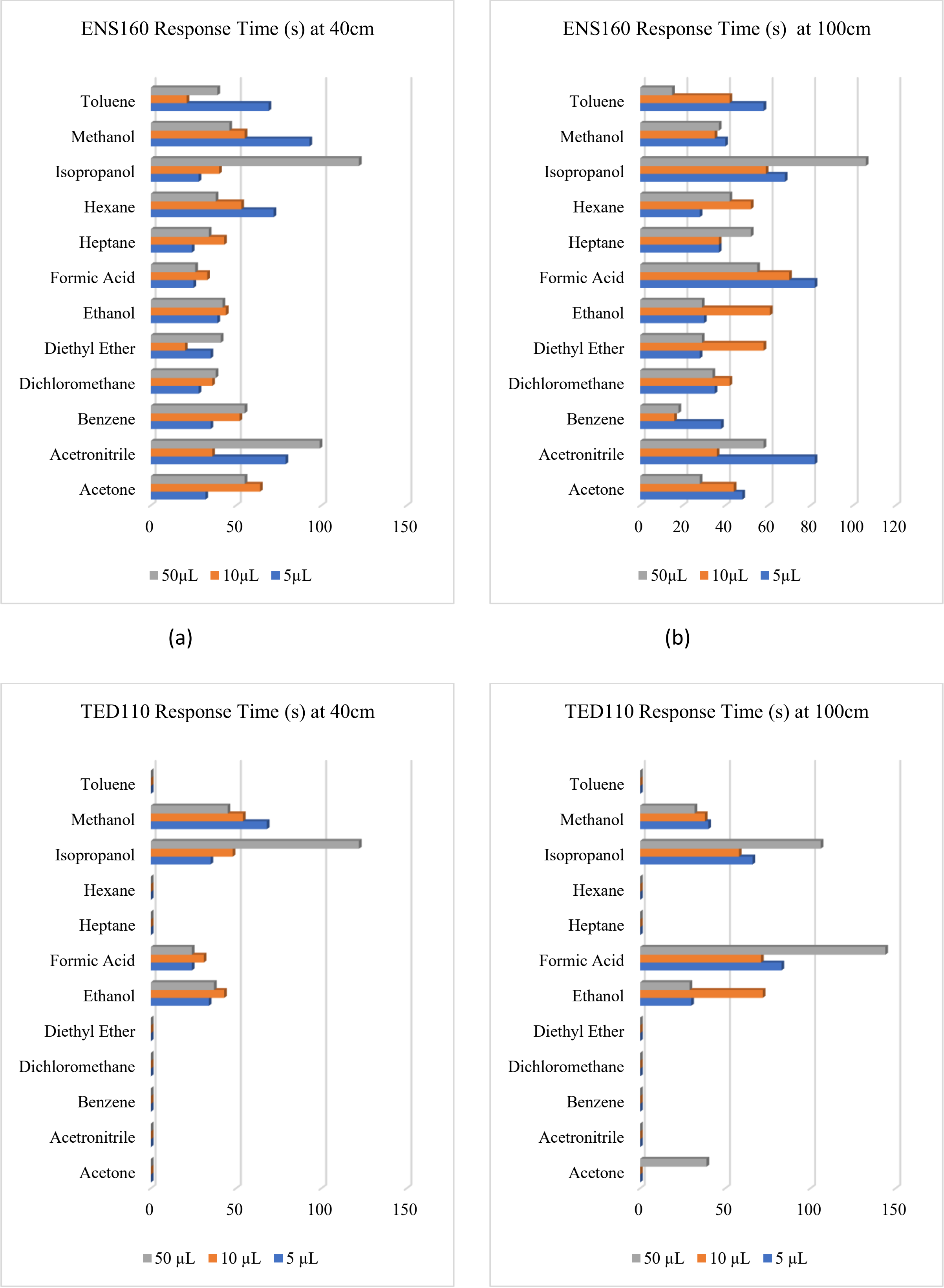


a-1 a-2

b-1 b-2

c-1 c-2

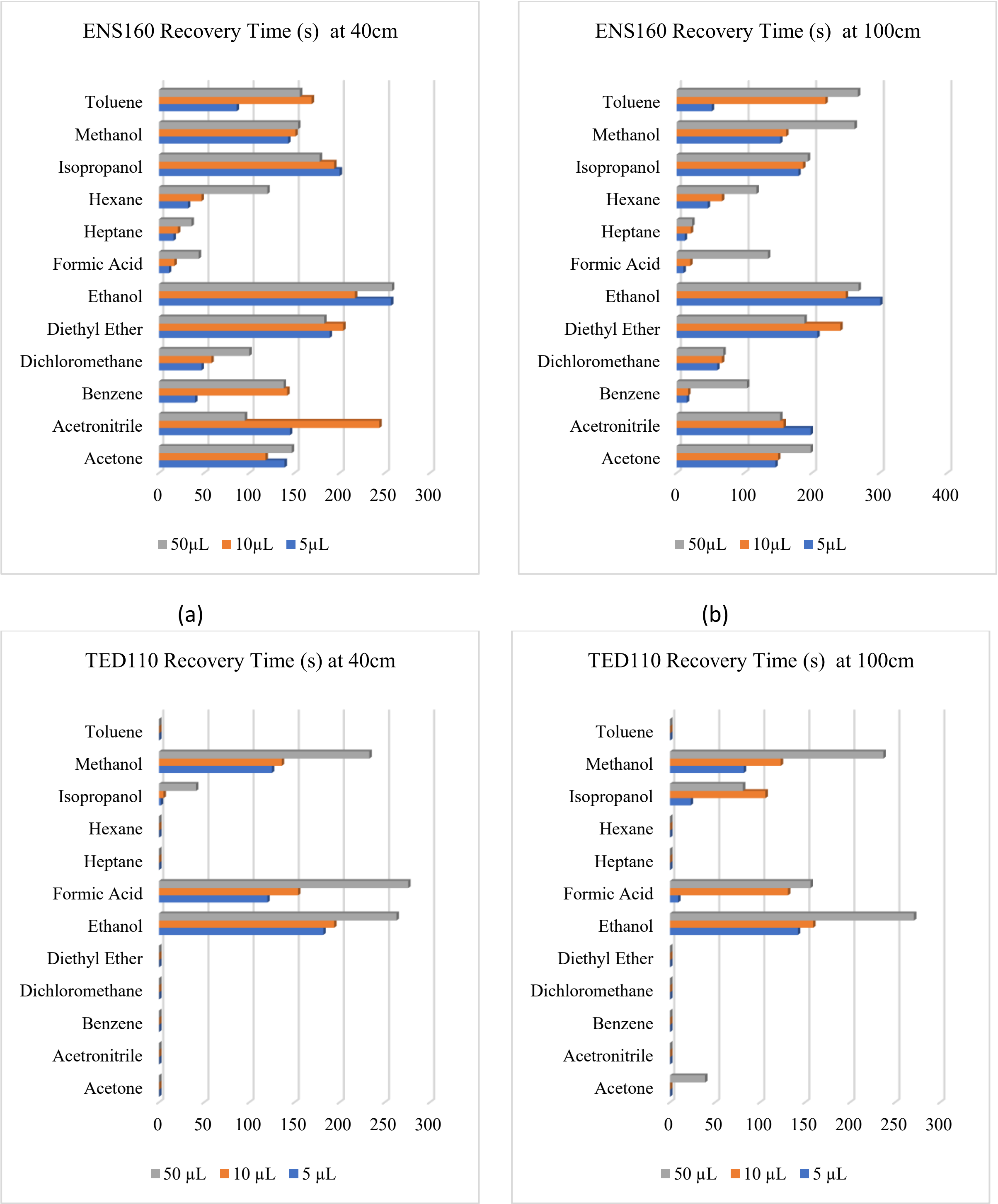
Fig. 18: Toluene ($C_7H_8$) response for ENS160 (a, b, c) at 40 cm (1) & 100 cm (2)



(a) (b)

(c) (d)

Fig. 19: ENS160 maximum Response time (s) at 40 cm (a) and 100 cm (b), TED110 maximum Gas Density Response Time(s) at 40 cm (c) and 100 cm (d).



(a) (b)

(c) (d)

Fig. 20: ENS160 maximum Recovery time (s) at 40 cm (a) and 100 cm (b); TED110 maximum Gas Density Recovery Time(s) at 40 cm (c) and 100 cm (d).

The ENS160 shows an excellent response for methanol ($CH_3OH$) with gas samples amounting to>5μL. All sample compounds, such as AQI, TVOC, and $CO_2$, show the highest response in the desired parameters. The TED110 gas sensor (gas density) for ethanol ($C_2H_6O$) at 40 cm and 100 cm for amounts at >5μL has a response. Both sensors' excellent response to methanol based on the MOX sensor concept and significant performance among all sample compounds make them valuable for gas detection applications. Fig. 17 depicts both sensor responses for methanol.

Toluene ($C_7H_8$) exhibits an excellent response with a sample amount of 10µL for all necessary parameters for ENS160, as illustrated in Fig. 18. With a quantity of >10µL, the AQI shows an excellent response at 40 cm sensor node distances. The reaction rate of TVOC and $CO_2$ increases the high volumes of gases. Above all, ENS160 has a low detection level for toluene due to no oxygen compounds, which need further investigation to improve the accuracy. The TED110 gas sensor (Gas density) does not react to amounts of toluene at 40 cm and 100 cm.

The response time (s) is the time it takes for the sensor output signal to reach 90% of its highest measured value from its initial settled condition; some strong gas with more sensitivity has quick response time, e.g., ethanol, methanol. Both sensors require a long response time (s) for isopropanol to reach its maximum point compared to other samples' response times (s); ethanol shows a rapid response (it requires less time to get its maximum response point). This indicates ENS160 has high sensitivity and efficiency in detecting most vapors; has a quick response for most of the strong gases. Improving response times can enhance gas sensors' effectiveness and accuracy to provide real-time and accurate measurements in environments. Fig. 19 presents both sensor's response times (s) for the different distances and specific amounts of the samples.

Correspondingly, the recovery time (s) is when the sensor response signal returns to its initial condition from its maximum measured value. Compared to other experimental gas samples' recovery time (s), the ENS160 gas sensing of ethanol needs longer to recover to its initial state. In contrast, methanol causes the longest recovery for the TED110 sensor. Gas sensors can exhibit varying response and recovery times based on the sensitivity to the gases. Some gases have rapid responses and longer recovery times based on their characteristics. By improving recovery times, gas sensors can become more responsive and reliable, making them better suited for safety monitoring in laboratory infrastructure. Fig. 20 displays both sensor's recovery times (s) for the different distances and specific amounts of the samples.

The data overview for all tested materials that was acquired from the two sensors and their response graphical presentation is listed below-

- ☐ ENS 160 successfully detects the AQI, TVOCs, and $CO_2$ 60 test out of 72 Tests.
- ☐ ENS 160 AQI, TVOCs, and $CO_2$ detection rate is around 83%.
- ☐ TED110 successfully detects the Gas Density 24 test out of 72 Tests.
- ☐ TED110 overall detection rate is 33%.

The concentration of the exposed analytes directly relates to the change in sensor resistance. On the surface of MOX, oxygen is adsorbed at high temperatures. The charge carrier concentration changes due to the adsorbed oxygen capturing electrons from the conduction band, which impacts the resistance of the MOX sensing Sensor layer. So, the ENS160 gas sensor strongly reacts to oxygen containing compounds such as acetone ($C_3H_6O$), diethyl ether ($C_4H_{10}O$), isopropanol ($C_3H_8O$), methanol ($CH_3OH$), and ethanol ($C_2H_6O$): Only formic acid ($CH_2O_2$) has no response. Its response is excellent in specific amounts and sensor node distances; it maintains a good sensitivity, selectivity, and detection limit. The ENS 160 reaction for the other compounds depends on the specific amounts of gas samples and sensor node distances. The reaction changes as the sample concentration or sensor node distances vary; a higher sample rate and a lower sensor node distance achieve a good response. The TED110 responds with the strongest gases, such as isopropanol ($C_3H_8O$), methanol ($CH_3OH$), ethanol ($C_2H_6O$), and formic acid ($CH_2O_2$), where all the gases contain oxygen. According to the datasheet [34], the TED110 can detect methene and toluene. However, these gases don't contain oxygen. However, in this experiment, the sensor failed to detect these gases. The reason for this lack of detection was likely sensor contamination during the electronics assembly or incorrect sensor purchase, e.g., some aging effect.

Table 5: Comparison of BME88, SGP 40, SGP 30, ENS 160, TED 110

| **Samples** | **BME88** | **SGP 40** | **SGP 30** | **ENS 160** | **TED 110** |
|---|---|---|---|---|---|
| Acetone | — | Good response ≥ 10μL | Good response ≥ 10μL | Strong response ≥ 5μL | No response |
| Diethyl ether | — | Good response ≥ 50μL | Weak response < 100μL | Strong response ≥ 5μL | No response |
| Isopropanol | — | Good response ≥ 10μL | Weak response < 100μL | Strong response ≥ 5μL | Strong response ≥ 5μL |
| Methanol | — | Good response ≥ 2μL | Good response ≥ 100μL | Strong response≥ 5μL | Strong response ≥ 5μL |
| Toluene | — | Good response ≥ 100μL | Good response ≥ 100μL | Strong response ≥ 50μL | No response |
| Ethanol | Strong response≥ 10μL | Good response ≥ 2μL | Good response ≥ 5μL | Strong response ≥ 5μL | Strong response ≥ 5μL |
| Hexane | Weak response | Weak response < 100μL | Weak response < 100μL | Strong response ≥ 10μL | No response |
| Acetonitrile | Weak response | Weak response < 100μL | Good response ≥ 10μL | Good response ≥ 5μL | No response |
| Benzene | - | Good response ≥ 100μL | Good response ≥ 100μL | Good response > 5μL | No response |
| Dichloromethane | Weak response | Good response ≥ 100μL | Good response ≥ 100μL | Weak response < 50μL | No response |
| Formic Acid | Strong response≥ 10μL | Good response ≥ 2μL | Good response ≥ 2μL | Weak response < 50μL | Strong response ≥ 5μL |
| Heptane | - | Good response ≥ 5μL | Weak response < 100μL | Weak response < 50μL | No response |

In [20], Neubert et al. used the BME 688 and SPG30 gas sensors in their project. Those sensors were tested with various TVOCs (ethanol, formic acid, acetonitrile, dichloromethane, and hexane). The studies employed two distinct heights, 25 and 40 cm, and four different quantities of each component. Dichloromethane, acetonitrile, and hexane were chosen in quantities of 1, 5, 10, and 20mL, respectively, while ethanol and formic acid were selected in quantities of 10, 100, 500, and 1000µL. Both sensors produced excellent results with ethanol and formic acid but had insufficient responses to acetonitrile, dichloromethane, and hexane.

Furthermore, in [7], Al-Okby et al. tested SPG40 and SPG30 with 12 samples of VOC. This experiment tested VOC in two locations, one directly 1 m below the sensor. The sensor node was moved one meter horizontally from the bottom for the second position. The volume was raised according to the sensor's reaction. The quantities used were 2µL, 5µL, 10µL, 50µL, and 100µL. The test volume was not increased once the lowest detectable volume for a particular position and distance was determined to avoid sensory overload. The evolution of the sensor based on TVOC (ppm) and AQI is the SPG30 that has an inadequate response for diethyl ether, isopropanol, hexane, and heptane. All other VOCs have a good reaction with the SPG30 gas sensor. Besides, the SPG 40 has a weak hexane and acetonitrile response among the 12 VOC samples. This project used the ENS 160 sensor, showing a weak response signal in dichloromethane and formic acid. All other gas samples with this sensor have good responses. Finally, the TED110 had an excellent reaction for isopropanol, ethanol, methanol, and formic acid. Almost all other eight gas samples did not respond. The gas sensor comparison table from the previous project and the current experiment are shown in Table 5.

The comparison results with other sensors (BME688, SGP 40, and SGP 30) show that the ENS 160 has an excellent response, making it suitable for laboratory gas detection. On the other hand, the TED110 shows inadequate response compared to all other gas sensors, possibly due to contamination or incorrect sensor selection. Without additional testing and improvement, this sensor may not be appropriate for the project's extension. Since this experiment was conducted in a real laboratory, measures were taken to avoid destructive factors such as traditional chemical hood air drafts, air conditioning, opening doors, and human presence, which can impact measurements due to cosmetics and human body exudation. Above all, for further accuracy improvement and avoiding external factors, different calibration methods can be utilized, for instance, reference measurements, and dynamic calibration, to adapt to changing conditions and minimize the impact of external factors like air drafts and human presence. Additionally, implementing signal processing techniques, such as noise filtering and pattern recognition algorithms, can improve the system's performance by accurately isolating gas-specific signals from background noise. Regular maintenance and sensor calibration is crucial to maintaining optimal performance and sensitivity. Lastly, incorporating machine learning algorithms and sensor fusion techniques can enhance the system's effectiveness and gas detectable limit by intelligently analyzing and combining data from multiple sensors to improve accuracy and reliability.

## 4. CONCLUSION

This project aims to implement a mobile gas sensing system to detect hazardous and toxic gases/chemical vapors. We investigated the performance of two novel gas sensors, ENS160 and TED110, using multiple parameters (AQI, TVOC, CO2, and Gas Density). In the future, the plan is to extend this project into gas detection with alarming systems; for that reason, it also helps to find efficient parameters among all parameters (AQI, TVOC, $CO_2$, and Gas Density). Overall, from the data visualization and the data analysis, both sensors have shown that they are generally suitable for detecting VOC leakages in laboratories. The ENS 160 sensor has a low sensing rate for dichloromethane and formic acid. All other experimented samples responded very well; it has a detection rate of 60 out of 72 samples; in the three parameters, such as AQI, TVOCs, and $CO_2$, it has an 83% response rate. In contrast, the TED110 has an excellent reaction for isopropanol, ethanol, methanol, and formic acid (the other eight experimental samples have no response), responded to 24 out of 72 tests, and the detection rate was 33%. Therefore, both sensors must do more tests with higher sample amounts. This system can be adapted to a flexible IoT platform; the required modules, such as IoT wireless communication modules and portable power supplies, can be connected and used independently by connecting to a computer. The drawback of this developed system is that the sensor node is comparably bigger than the divided processing units, resulting in the system consuming more energy. In terms of measured parameters and functional qualities, this mobile gas sensing system can be adapted to various application scenarios, for example, moving objects such as robots and trolleys. The TED110 gas sensor requires more investigation to improve its accuracy, sensor data calibration, and more accurate data conversion. Furthermore, machine learning applications can distinguish different VOCs to precisely identify the natural hazard and sensor calibration, as well as real-time data analysis and visualization. This mobile sensing can be used in laboratory robots or moveable equipment so that in the future, the indoor localization sensor can be implemented to record the position of detection of the robots or movable objects, for example, roller carriages with laboratory equipment, which need to be monitored for gases and location.

## ACKNOWLEDGEMENT

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Table 6: Table of nomenclature

| **Symbol/Abbreviation** | **Description** |
|---|---|
| MOX | metal oxide semiconductor |
| VOC | volatile organic compounds |
| TVOC | total volatile organic compounds |
| AQI | air quality index |
| PPM | Parts per Million |
| PPB | Parts per billion |
| MEMS | Micro-Electro-Mechanical System |
| MCU | Microcontroller unit |
| PCB | Printed circuit board. |
| I2C | Inter-Integrated Circuit |
| IDE | Integrated Development Environment |