Jurnal Penelitian Fisika dan Aplikasinya (JPFA)
Volume 15, Issue 1, 1-11 2025
https://journal.unesa.ac.id/index.php/jpfa/
p-ISSN: 2087-9946
e-ISSN: 2477-1775

A Preliminary Study of Exhaled Breath Profiling of GERD-Asthma using an E-nose and Carbon Dioxide Concentration as Biomarkers

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Received: 18 Desember 2024*; Revised:* 10 March 2025*; Accepted:* 20 March 2025

Abstract

Carbon dioxide plays a vital role in the human body. Many studies confirm that changes in carbon dioxide concentrations can serve as biomarkers for various health problems. This biomarker can be detected using several techniques, including an electronic nose (e-nose). However, there is a limitation in the e-nose's function and development in specific health cases, especially in respiratory or other systems. In line with this, this study aims to develop an economical, simple e-nose based on a CO_2 (carbon dioxide) gas sensor and to establish an exhaled breath profile related to asthma and GERD (gastroesophageal reflux disease), which are common daily health problems. For this purpose, 90 exhaled breath samples from three different health conditions were obtained as the primary breath profiling samples: healthy, GERD, and asthma. The samples were measured and analyzed using a simple e-nose based on a high-sensitivity carbon dioxide sensor. The e-nose was calibrated and tested under laboratory-scale procedures, including linearity, accuracy, and sensitivity examinations. Then, the collected samples were classified, analyzed, and interpreted to produce a profile prediction for those health problems. The results show that the e-nose system can measure CO_2 gas concentrations in the range of 400-9700 ppm. There are three selective profiles of the exhaled breath samples: healthy (450 to 899 ppm), GERD (3327 to 5381 ppm), and asthma (6612 to 9706 ppm). It can be concluded that the developed e-nose can classify different health conditions. There is a significant difference between healthy, GERD, and asthma samples ($p < 0.05$). These differences were interpreted as breath profiles with an accuracy level of 84%. This research may contribute to a preliminary investigation of breath profiles for specific health problems, with a rapid response time and high accuracy.

Keywords: *asthma; biomarker; carbon dioxide; electronic nose; GERD*

How to cite: Hadi KA, Anggriani NK, Budianto A, Nabilla DA, and Farahin DN. A preliminary study of exhaled breath profiling of GERD-asthma using an e-nose and carbon dioxide concentration as biomarkers. *Jurnal Penelitian Fisika dan Aplikasinya (JPFA)*. 2025; 15(1): 1-11. DOI: https://doi.org/10.26740/jpfa.v15n1.p1-11.

INTRODUCTION

CO_2 (carbon dioxide) is a gas consisting of one carbon atom and two oxygen atoms. CO_2 is classified as a natural part of the air and is also produced from various natural processes, such as human and animal breathing, as well as biomass burning, and many other combustion processes [1,2]. This gas plays an essential role in human respiration, especially in controlling the rate of respiration. [3,4]. This gas is produced by breathing and can trigger the brain to regulate the frequency and depth of breathing, ensuring the proper function of the respiratory and other essential body systems, such as oxygen and CO_2 exchange. However, exposure to high concentrations of CO_2 can be dangerous and lead to hypercapnia. [5]. Hypercapnia is a condition in which blood CO_2 levels are elevated, which can cause dizziness, headaches, and even loss of consciousness. [6–8]. In addition, this condition can cause respiratory acidosis, which may lead to damage to organs and body tissues. [9]. From a medical perspective, CO_2 is classified as a poisonous gas at high concentrations. CO_2 gas may cause suffocation due to a lack of oxygen. Other probable effects of excessive exposure to CO_2 gas are eye, nose, and throat irritation. [10,11].

Several previous studies show that CO_2 and other gases can be used as biomarkers for the development of an e-nose (electronic nose). [12–15]. An e-nose is widely used to analyze and predict biomarkers in human respiratory air residues. [16–19]. For example, a 2021 review shows that exhaled breath can serve as a biomarker for several diseases, based on chemical compounds analyzed using complex devices. This review confirms that lung diseases are associated with CO_2 concentration in exhaled breath. [20]. A previous study event shows that the existence of acetone, ethanol, methanol, toluene, butanol, and other gases in the exhaled breath (in a specific concentration) may be related to chronic obstructive pulmonary disease. [21]. These biomarkers and methods require complex statistical analysis, artificial neural networks, and other advanced instrumentation to achieve better performance. In contrast, there is a bias in exhaled breath profiling for asthma identification using a simple method based on e-nose technology. [22]. This study confirms that there is a significant difference between each classification in severe asthma cases. However, previous research does not clearly describe brief-breath profiling methods for specific health conditions, such as GERD (gastroesophageal reflux disease, a chronic condition in which stomach acid repeatedly flows back into the esophagus) and asthma.

As outlined above, there is a knowledge gap regarding the underdevelopment of e-nose technology to identify and predict diseases such as stomach acid, GERD, asthma, and other health problems in daily life. The developed e-noses are dominated at the molecular level by viruses, bacteria, and fungi. The developed e-noses for several health problems indeed show good results. However, other previous studies using gases as the selective biomarkers still lack breath profiles. In addition, e-noses are generally considered high-cost devices with specialized treatments and procedures. Several studies also used multiple gases for breath profiling and prediction. Hence, this study aims to develop an economical, simple e-nose based on a CO_2 gas sensor and to establish an exhaled breath profile related to asthma and GERD, which are common daily health problems. This research may contribute to a preliminary investigation of breath profiles for specific health problems, with a rapid response time and high accuracy. The development of an e-nose for breath profiling, especially for GERD and asthma, may lead to a rapid diagnostic tool from a medical perspective. These research aims can be achieved using a fully calibrated sensor and e-nose system, including the flow system, voltage stability, recovery time, gas filtration, and other instrumentation parameters.

METHOD

E-nose Development

The e-nose system was developed using an MG-811 sensor (susceptible to CO_2), a microcontroller, a power source, suction pumps, a display, tubes, and a sensor box. The sensor was chosen for its wide measurement range (350 ppm to 10000 ppm) and analog signal outputs. The sensor was connected to the microcontroller's analog pin and a 5.91 V voltage source. This voltage source was also connected to the microcontroller's input voltage pin (V_{in}). Then, the sensor was turned on for 7 consecutive days as a burn-in period. All of these kits were installed inside a sensor box, including the input and output tubes. The input tube was connected to an input suction pump (pump 1) with a constant velocity (v_1) of 0.9 m/s (for the breath air flow). The other tube (output tube) was also connected to an output suction pump (pump 2) to drain the gas from the sensor box with a velocity (v_2) of 1.8 m/s (Figure 1).

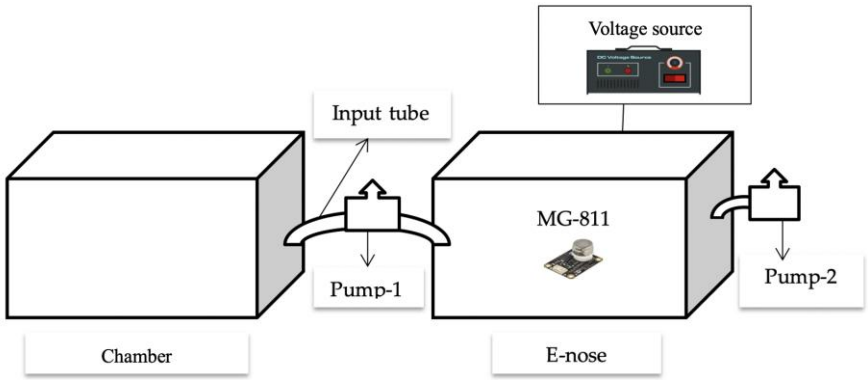

Figure 1. E-nose calibration and characterization processes using an exposure chamber

E-nose Calibration

The e-nose system was calibrated using filtered fresh air (Figure 1). For this purpose, the ambient air was filtered using a particulate air filter before being exposed to the exposure chamber (area of input tube $A = 50\text{x}10^{-6}$ m^2, volume $V = 0.0044$ m^3) [23]. At the same time, the e-nose's input tube was connected to the chamber. The sensor output voltages were recorded for 100 s of the calibration time t (sampling time $t_s = 5$ s). This period was chosen from the approximation using the Bernoulli principle:

$$t = \frac{V}{A \cdot v_1} \quad (1)$$

The output signals (analog value, A_o) were converted into voltage signals (V_s) using the equation:

$$V_s = \frac{A_o}{1023} \text{ x } 5{,}91 \quad (2)$$

The voltage values were converted to a calculated CO_2 concentration ($C_{calculated}$) using Equation 3. This equation was obtained from the sensor's datasheet under controlled room temperature and humidity level (temperature = 28 °C; humidity = 65%):

$$C_{calculated} = 1.3851 \text{ x } V_s^2 - (900.22 \text{ x } V_s) + 146671 \quad (3)$$

The sensitivity level was calculated using Equation 4 [24]:

$$sensitivity = \frac{V_s}{C_{measured}} \quad (4)$$

E-nose Characterization

The system's performance was evaluated by assessing linearity, accuracy, and sensitivity. For this purpose, the system was exposed to CO_2 gas concentrations ($C_{measured}$) of 5 levels: C_1 (400 ppm), C_2 (700 ppm), C_3 (1000 ppm), C_4 (3000 ppm), and C_5 (6000 ppm). These treatments were conducted using a standard CO_2 gas sample (dry gas) measured using a comparator device [25,26]. For the first concentration variation (C1), the gas sample was injected into the exposure chamber and acclimatized for 60 s. Then, this sample was carried to the sensor box by the flow rate from the input pump. The e-nose system's output signals were recorded for 100 s at a sampling rate of 5 s. This treatment was repeated three times for all concentrations.

Exhaled Breath Profiling

This study used 90 exhaled breath samples (Table 1) for profiling. This step was conducted using the breath samples with a similar procedure to the previous step (e-nose characterization). These samples were obtained using a selective sampling method with the following criteria: male/female, not a smoker, not menstruating, and not consuming any foods/ drinks with strong odors. The calculated gas concentrations from all breath samples were then plotted in a graph, with a specific interval corresponding to each health prediction (healthy, GERD, and asthma). All procedures were approved by the Health Research Ethics Commission of the Faculty of Medicine and Health Sciences, University of Mataram (Ethical Approval Decision Letter: No. 020/UN18.F8/ETIK/2025).

Table 1. The exhaled breath samples: healthy, GERD, and asthma

Healthy	GERD	Asthma
n = 30	n = 30	n = 30

The differences between classifications were analyzed using an ANOVA. The p-value evaluated the significance. In this step, a p-value < 0.05 was considered significant. [27].

RESULTS AND DISCUSSION

E-nose Calibration

Figure 2 interprets the calibration results of the e-nose system using filtered fresh air. The developed system produces an output voltage of 322 ± 1 mV (n = 3, black dots) when tested inside an exposure chamber under filtered, fresh air. This voltage signal was calculated from the sensor's analog value (55-56), with a 10-bit resolution and a 1-s response time. At the same time, the measured CO_2 concentration (from the comparator device) was about 400-405 ppm ($C_{measured}$). Based on the MG-811 sensor datasheet (red line), these values indicate that the e-nose system performs well at detecting ambient CO_2 gas. The datasheet indeed confirms that the output voltages of 324-325 mV refer to ~400 ppm of CO_2 gas concentration.

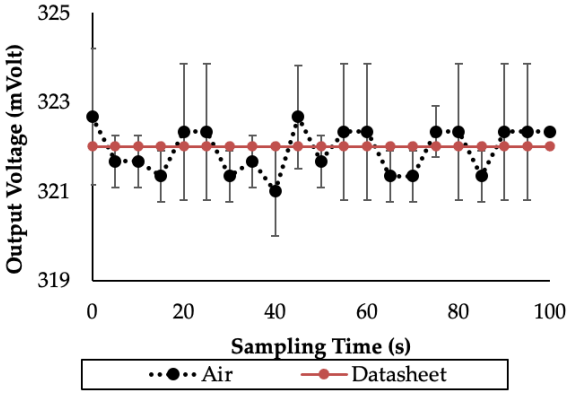

Figure 2. The calibration results of the e-nose system using filtered fresh air inside the chamber

E-nose Characterization

Figure 3 shows the results of the system characterization using five different gas concentrations: C_1 (400 ppm), C_2 (700 ppm), C_3 (1000 ppm), C_4 (3000 ppm), and C_5 (6000 ppm). These variations were used to assess the accuracy, linearity, and sensitivity.

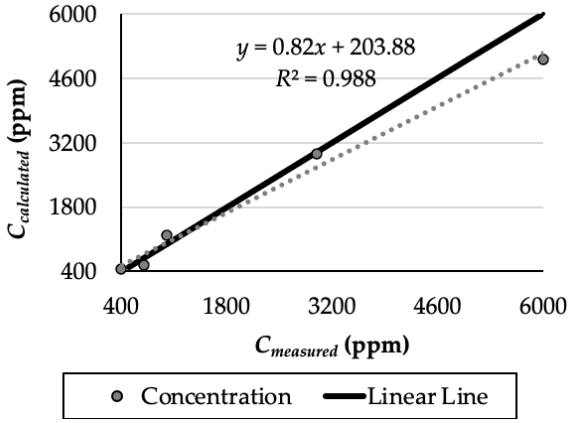

Figure 3. Comparison between the e-nose and the comparator in measuring CO_2 gas concentrations

Gas concentrations were determined from the e-nose system by calculating the sensor outputs using Equation 3. This equation converted the sensor's analog value (0-1023) to gas concentration (ppm). According to this conversion, the calculated concentrations are 463; 541; 1196; 2948; and 5014 ppm, respectively for C_1, C_2, C_3, C_4, and C_5. As shown in Figure 4, the developed e-nose exhibits good linearity, with an R^2 value of >0.98. This value was obtained from a linear function approximation, a straight line used to summarize the data. A linear trendline is a best-fit straight line in instrumentation science used to assess the linearity of a developed system. As obtained in this study, the linearity of the e-nose is 98.8%, with a linear function of:

$$C_{calculated} = 0.82 \times C_{measured} - 203.88 \quad (5)$$

This R^2 value confirms the 98.8% similarity of the developed system (e-nose) with the

comparator ($C_{measured}$). This R^2 value also confirms the function of the burn-in period, which increases the sensor's sensitivity by improving the performance of its sensitive material (semiconductor). In other words, the developed e-nose has characteristics similar to the comparator's, specifically in sensing only CO_2 gas, with an accuracy of 84%. This accuracy level indicates that the e-nose system works well as a CO_2 gas concentration measurement system, with a sensitivity of ~0.34 mV/ppm.

Exhaled Breath Profiling

Table 2 presents the mean CO_2 gas concentrations for healthy, GERD, and asthma conditions. As a control parameter, no sample suffers from both GERD and asthma. These values were obtained from the e-nose system and interpreted as exhaled breath profiling, with three distinct gas concentration classifications.

The healthy samples show varied CO_2 gas concentrations, ranging from 450 to 899 ppm. The mean concentration is about 611 ppm. In contrast, the GERD samples have concentrations of 3327 ppm to 5381 ppm. The mean value is 4367 ppm, showing a significant difference compared to the healthy samples ($p < 0.05$). Interestingly, the asthma samples show higher CO_2 concentrations. The lowest concentration is 6612 ppm, which is 1231 ppm higher than the highest concentration in the GERD sample. These results indicate that the highest CO_2 concentration is in the asthma samples (9706 ppm). There is also a significant difference between the healthy and asthma samples ($p < 0.05$). A similar pattern is also observed in the comparison between the GERD and asthma samples, showing a smaller difference than in other comparisons ($p < 0.05$). Hence, it can be seen that there are substantial differences among all sample classifications.

Table 2. The CO_2 gas concentrations of the exhaled breath samples under different health conditions: healthy, GERD, and asthma samples ($N = 90$)

Number	*Healthy*	GERD	Asthma
Mean	611	4367	9089

The e-nose system can generate exhaled breath profiles from three health conditions: healthy, GERD, and asthma, as interpreted in Figure 4. The asthma sample profile shows a CO_2 concentration between 6612 and 10000 ppm (green zone). The red zone (450-3327) shows the prediction concentration of the healthy profile. On the last point, the yellow zone corresponds to the GERD profile, with CO_2 concentrations ranging from 3327 ppm to 6612 ppm.

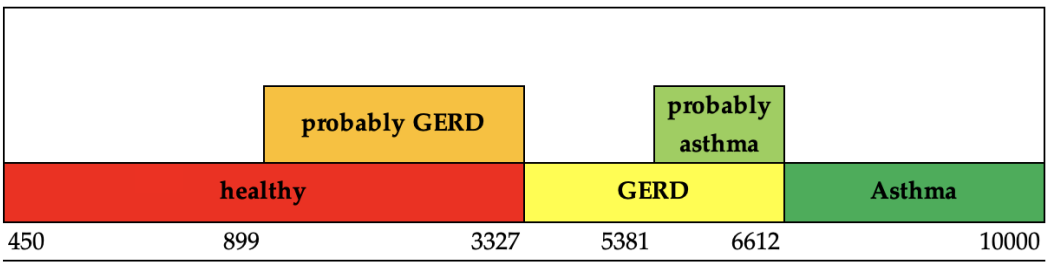

Figure 4. Exhaled breath profiling of the samples in different conditions for classification

The performance of an e-nose system depends on calibration and examination procedures,

especially when using semiconductor-based sensors (e.g., ZnO, TiO2, SnO2). [10]. As conducted in this study, the system was also calibrated to confirm the output signals or sensor responses. The best responses were the best values within tolerance when all parameters were controlled (as seen in the sensor datasheet), such as a constant flow rate, humidity, and temperature. That is why this developed e-nose has a low measurement error (±1 mV).

The accuracy, sensitivity, and linearity levels of the e-nose system were examined using the comparator device. As confirmed in the datasheet, the sensitivity of the MG-811 sensor is 0.025 mV/ppm. This means the MG-811 sensor has a measurement range of 350-10000 ppm for CO_2 gas concentration. As confirmed in a previous study by Viejo et al. (2020), the MG-811 sensor has a good sensitivity level of CO_2 gas in concentrations of 350-10000 ppm (0.025 mV/ppm) [28]. In contrast, another study shows that the effective range was only 400-5000 ppm. [24]. However, as a gain function, this sensitivity value may be influenced by the electronic circuit on the board and the setting time. [28]. Hence, the developed e-nose's accuracy cannot reach 100% compared to the comparator device. The best accuracy is>80%, with a sensitivity of 0.34 mV/V ppm.

After calibration and inspection, the e-nose system is ready for exhaled breath measurements. Based on this performance, we measured CO_2 gas concentration to generate a breath profile. As shown in the data collection, the developed e-nose performs well in generating exhaled breath profiles for asthma-GERD and healthy conditions. These patterns or profiles were obtained after verifying the sensor's reliability in detecting CO_2 at several concentrations. Using the MG-811 sensor and the developed system, we measured CO_2 concentrations in 30 exhaled breath samples. All results indicate that the detected or measured CO_2 concentrations are consistent with those reported in the datasheet (350-10000 ppm). The human respiratory system typically exhales 500-1500 ppm of CO_2 in a normal condition (2 seconds) [29,30]. Notably, in Table 2, it can be seen that the normal or healthy samples have concentrations of 450-899 ppm. These concentrations were generated from a standard or correct way to breathe and exhale. Not all samples were related to smoking, menstruation, drugs, or excessive food/drink consumption. These treatments indeed improved the e-nose's accuracy (>80%), since we obtained a good "gold reference" for exhaled breath profiling.

Abnormal CO_2 concentrations in human exhaled breath can be related to many factors. As confirmed by a previous study, the exhaled gas substances correlate with the variability in breathing techniques, patterns, and individual characteristics. [31]. This study also reveals that the sampling instrument and ambient volatile organic compound concentrations may influence gas concentrations. These parameters might then affect the generated breath profiles and, in turn, the final analysis's prediction accuracy. According to a previous study, breathing patterns may vary between different conditions or individuals. [32]. For example, a person breathes by taking shallower breaths than another person. This pattern may be influenced by the lung's tidal volume and by the volatile metabolite of a compound to which an individual has been exposed. In another case, the CO_2 gas concentration is also influenced by respiratory system conditions, such as asthma [33]. According to these results, it can be seen that the human body system may have different behaviors when suffering health problems, as found in this study.

Many factors, including physical activity, diet, health condition, and environmental gas concentrations, also influence e-nose performance. These parameters may lead to false positives or false negatives in the histogram's classification. However, the false-positive rate (e.g., a double conclusion in the developed e-nose between healthy-GERD and asthma-GERD) can be minimized

by using an anamnesis questionnaire.

CONCLUSION

An e-nose system has been developed as an exhaled breath profiler for asthma and GERD. This system was successfully calibrated and examined in accordance with laboratory procedures. Exhaled breath contains CO_2 gas with concentrations of 400 - 9700 ppm. There are three selective profiles of the exhaled breath samples: healthy (450 to 899 ppm), GERD (3327 to 5381 ppm), and asthma (6612 to 9706 ppm). The developed e-nose can classify different health conditions. There is a significant difference between healthy, GERD, and asthma samples ($p < 0.05$). These differences were interpreted as breath profiles with an accuracy level of 84%. For future work, this research may contribute to a preliminary investigation of breath profiles for specific health problems, with rapid response time and high accuracy (a clinical implication). The developed e-nose may also enable the identification of volatile CO_2 biomarkers using a non-invasive method. The implementation of an artificial neural network is highly recommended to improve system performance, including accuracy and linearity, for medical applications.

ACKNOWLEDGMENT

The authors wish to thank the Institute of Research and Community Service (LPPM) of the University of Mataram, Public Senior High School 2 (SMAN 2) Selong, Lombok Timur, and all members of the Laboratory of Instrumentation and Biophysics at the University of Mataram. We acknowledge the kind hands of Roviq Wijaya, Karina A. Fidya, Nanda M. Apriza, and Sabila Alhadawiah.

AUTHOR CONTRIBUTIONS

Kasnawi Al Hadi: Methodology, Writing - Original Draft; Ni Ketut Anggriani: Methodology, and Validation; Arif Budianto: Conceptualization, Formal Analysis, Resources; Dewi Alya Nabilla: Resources; and Dewi Nor Farahin: Writing - Review & Editing.

DECLARATION OF COMPETING INTEREST

All the authors declare that there is no conflict of interest.

REFERENCES

[1] Kim HH, Park GY, Lee JH, et al. Concentrations of particulate matter, carbon dioxide, VOCs, and risk assessment inside Korean taxis and ships. *Environmental Science and Pollution Research*. 2019; **26**: 9619–31. DOI: https://doi.org/10.1007/s11356-019-04361-5.

[2] Bierwirth P. Carbon Dioxide Toxicity and Climate Change: A significant unapprehended risk for human health. *Research Gate Working Paper*. 2021; 1–25. DOI: https://doi.org/10.13140/RG.2.2.16787.48168.

[3] Schenck EJ, Hoffman K, Goyal P, Choi J, Torres L, Rajwani K, et al. Respiratory mechanics and gas exchange in COVID-19–associated respiratory failure. *Ann Am Thorac Soc*. 2020; **17**:158–1161. DOI: https://doi.org/10.1513/AnnalsATS.202005-427RL.

[4] Scarlata S, Pennazza G, Santonico M, Pedone C, Antonelli Incalzi R. Exhaled breath analysis by electronic nose in respiratory diseases. *Expert Rev Mol Diagn*. 2015; **15**: 933–56. DOI: https://doi.org/10.1586/14737159.2015.1043895.

[5] Stanek LW, Brown JS, Stanek J, Gift J, Costa DL. Air pollution toxicology — a brief review of the role of the science in shaping the current understanding of air pollution health risks. *Toxicological Sciences*. 2011; **120**: 8–27. DOI: https://doi.org/10.1093/toxsci/kfq367.

[6] Mekontso Dessap A, Bagate F, Repesse X, Blayau C, Fartoukh M, Canoui-Poitrine F, et al. Low-flow ECCO$_2$R conjoined with a renal replacement therapy platform to manage pulmonary vascular dysfunction with refractory hypercapnia in ARDS. *Heliyon*. 2024; 10. DOI: https://doi.org/10.1016/j.heliyon.2023.e23878.

[7] Melberg MB, Flaa A, Andersen GØ, Sunde K, Bellomo R, Eastwood G, et al. Effects of mild hypercapnia on myocardial injury after out-of-hospital cardiac arrest. A sub-study of the TAME trial. *Resuscitation.* 2024; 201. DOI: https://doi.org/10.1016/j.resuscitation.2024.110295.

[8] Sharma P, Muthuchellappan R, Bharadwaj S, Chakrabarti D, Srijithesh PR, Raja P, et al. Carbon dioxide-induced cerebral vasomotor reactivity in moderate-to-severe cerebral venous thrombosis patients and its impact on prognosis: A transcranial doppler-based prospective exploratory study. *Journal of Clinical Neuroscience*. 2024; 128. DOI: https://doi.org/10.1016/j.jocn.2024.110779.

[9] Ziemann AE, Allen JE, Dahdaleh NS, Drebot II, Coryell MW, Wunsch AM, et al. The amygdala is a chemosensor that detects carbon dioxide and acidosis, thereby eliciting fear behavior. *Cell*. 2009; **139**: 1012–21. DOI: https://doi.org/10.1016/j.cell.2009.10.029.

[10] Chen F, Zhang W, Mfarrej MFB, Saleem MH, Khan KA, Ma J, et al. Breathing in danger: Understanding the multifaceted impact of air pollution on health impacts. *Ecotoxicol Environ Saf*. 2024; 280. DOI: https://doi.org/10.1016/j.ecoenv.2024.116532.

[11] Jaiswal S, Jalbert I, Schmid K, Tein N, Wang S, Golebiowski B. Smoke and the eyes: A review of the harmful effects of wildfire smoke and air pollution on the ocular surface. *Environmental Pollution*. 2022; 309. DOI: https://doi.org/10.1016/j.envpol.2022.119732.

[12] Vasilescu A, Hrinczenko B, Swain GM, Peteu SF. Exhaled breath biomarker sensing. *Biosens Bioelectron*. 2021; 182. DOI: https://doi.org/10.1016/j.bios.2021.113193.

[13] Shanmugasundaram A, V Manorama S, Kim DS, Jeong YJ, Weon Lee D. Toward point-of-care chronic disease management: Biomarker detection in exhaled breath using an e-nose sensor based on rgo/sno2 superstructures. *Chemical Engineering Journal*. 2022; 448. DOI: https://doi.org/10.1016/j.cej.2022.137736.

[14] Gaidamavichute V, Knyazeva M, Khozina E, Men'shchikov I, Safaev R, Shkolin A. A LA-BTC MOF as a sensor element of an electronic nose for selective adsorption of biomarkers of diseases: Molecular dynamics simulations of adsorption. *Mater Today Commun*. 2024; 38. DOI: https://doi.org/10.1016/j.mtcomm.2023.107787.

[15] Jeon JY, Park SJ, Ha TJ. Wearable nitrogen oxide gas sensors based on hydrophobic polymerized ionogels for the detection of biomarkers in exhaled breath. *Sens Actuators B Chem*. 2022; 360. DOI: https://doi.org/10.1016/j.snb.2022.131672.

[16] Beduk T, Durmus C, Hanoglu SB, Beduk D, Salama KN, Goksel T, et al. Breath, as the mirror of our body, is the answer really blowing in the wind? Recent technologies in exhaled breath analysis systems as non-invasive sensing platforms. *TrAC - Trends in Analytical Chemistry*. 2021; 143. DOI: https://doi.org/10.1016/j.trac.2021.116329.

[17] Mule NM, Patil DD, Kaur M. A comprehensive survey on investigation techniques of exhaled breath (EB) for diagnosis of diseases in human body. *Inform Med Unlocked*. 2021; 26. DIO: https://doi.org/10.1016/j.imu.2021.100715.

[18] Shetty SS, Jayarama A, Bhat S, Satyanarayan, Karunasagar I, Pinto R. A review on metal-oxide based trace ammonia sensor for detection of renal disease by exhaled breath analysis. *Mater Today Proc*. 2022; **55:** 113–7. DOI: https://doi.org/10.1016/j.matpr.2021.12.411.

[19] Zhu R, Gao J, Tian Q, Li M, Gao Q, Wu X, et al. Optical chemical gas sensor based on spectral autocorrelation: A method for online detection of nitric oxide and ammonia in exhaled breath. *Sens Actuators B Chem*. 2025; **422**: 136694. DOI: https://doi.org/10.1016/j.snb.2024.136694.

[20] Chen T, Liu T, Li T, Zhao H, Chen Q. Exhaled breath analysis in disease detection. *Clinica Chimica Acta*. 2021; **515**: 61–72. DOI: https://doi.org/10.1016/j.cca.2020.12.036.

[21] Zhang Z, Zheng Z, He X, Liu K, Debliquy M, Zhou Y, et al. Electronic nose based on metal oxide semiconductor sensors for medical diagnosis. *Progress in Natural Science: Materials International*. 2024; **34**: 74–88. DOI: https://doi.org/10.1016/j.pnsc.2024.01.018.

[22] Brinkman P, Wagener AH, Hekking PP, Bansal AT, Maitland-van der Zee AH, Wang Y, et al. Identification and prospective stability of electronic nose (eNose)–derived inflammatory phenotypes in patients with severe asthma. *Journal of Allergy and Clinical Immunology*. 2019; **143**: 1811-1820.e7. DOI: https://doi.org/10.1016/j.jaci.2018.10.058.

[23] Budianto A, Wardoyo AYP, Masruroh, Dharmawan HA, Nurhuda M. Performance test of an aerosol concentration measurement system based on quartz crystal microbalance. *IOP Conf Ser Earth Environ Sci*. 2021; 1811. DOI: https://doi.org/10.1088/1742-6596/1811/1/012033.

[24] Shwetha HR, Sharath SM, Guruprasad B, Rudraswamy SB. MEMS based metal oxide semiconductor carbon dioxide gas sensor. *Micro and Nano Engineering*. 2022; 16. DOI: https://doi.org/10.1016/j.mne.2022.100156.

[25] Budianto A. A propanol gas measurement system using a quartz crystal microbalance as a mass sensor. *Journal of Environmental Engineering and Sustainable Technology*. 2022; **9**: 70–4.

[26] Yani A, Wardoyo AYP, Anggraeni D, Budianto A. Development of a measurement system of ethanol gas based on TGS-2600, TGS-2603, and MQ-138 sensors. *AIP Conf Proc*. 2024; 3112. DOI: https://doi.org/10.1063/5.0211681.

[27] Eeftens M, Phuleria HC, Meier R, Aguilera I, Corradi E, Davey M, et al. Spatial and temporal variability of ultrafine particles, NO2, PM2.5, PM2.5 absorbance, PM10 and PMcoarse in Swiss study areas. *Atmos Environ*. 2015; **111**: 60–70. DOI: https://doi.org/10.1016/j.atmosenv.2015.03.031.

[28] Gonzalez Viejo C, Fuentes S, Godbole A, Widdicombe B, Unnithan RR. Development of a low-cost e-nose to assess aroma profiles: An artificial intelligence application to assess beer quality. *Sens Actuators B Chem*. 2020; 308. DOI: https://doi.org/10.1016/j.snb.2020.127688.

[29] Fleming L, Gibson D, Hutson D, Ahmadzadeh S, Waddell E, Song S, et al. Breath emulator for simulation and modelling of expired tidal breath carbon dioxide characteristics. *Comput Methods Programs Biomed*. 2021; 200. DOI: https://doi.org/10.1016/j.cmpb.2020.105826.

[30] Wu G, Du H, Pakravan K, Kim W, Cha YL, Chiang ST, et al. Polyaniline/Ti3C2Tx functionalized mask sensors for monitoring of CO2 and human respiration rate. *Chemical Engineering Journal*. 2023; 475. DOI: https://doi.org/10.1016/j.cej.2023.146228.

[31] Bakali U, Killawala C, Monteagudo E, Dikici E, Deo SK, Daunert S. Exhaled breath analysis applications for evaluating occupational and environmental exposures. *TrAC - Trends in Analytical Chemistry*. 2024; 177. DOI: https://doi.org/10.1016/j.trac.2024.117787.

[32] Mojumder S, Das T, Mondal T, Ghosh S, Saha D, Ghosh CK, et al. Improved ammonia sensing performance achieved through defect modulation by Li doping in cauliflower-like ZnO for

exhaled breath analysis towards renal diseases detection: An experimental venture supported by DFT calculation. *TrAC - Trends in Analytical Chemistry*. 2024; 180. DOI: https://doi.org/10.1016/j.trac.2024.117896.

[33] Langhan ML, Zonfrillo MR, Spiro DM. Quantitative end-tidal carbon dioxide in acute exacerbations of asthma. *Journal of Pediatrics*. 2008; **152**: 829–32. DOI: https://doi.org/10.1016/j.jpeds.2007.11.032.