International Journal of GEOMATE, May, 2022, Vol.22, Issue 93, pp.44-51
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2022.93.2506
Geotechnique, Construction Materials and Environment

AN *IN SITU* VOLCANIC GASEOUS EMISSIONS CONCENTRATION MEASUREMENT SYSTEM: A CASE STUDY FOR WELIRANG VOLCANO, MALANG, INDONESIA

*Arinto Yudi Ponco Wardoyo[1], Hari Arief Dharmawan[1], Muhammad Nurhuda[1], Arif Budianto[1,2], and Azarine Aisyah Widhowati[1]

[1]Faculty of Mathematics and Natural Sciences, Brawijaya University, Indonesia; [2]Faculty of Mathematics and Natural Sciences, Mataram University, Indonesia

*Corresponding Author, received: 02 June 2021, Revised: 24 Feb. 2022, Accepted: 27 March 2022

ABSTRACT: Gaseous emissions and particulate matter in different aerodynamic diameters can be derived from many sources, such as volcanic activities. According to previous studies, gaseous emissions, such as sulfur dioxide, carbon monoxide, and carbon dioxide, may affect human health. Furthermore, there is a significant correlation between exposure to gaseous emissions and cell deformation, indicating the organ system's abnormalities. Therefore, there is a need to mitigate and identify volcanic gaseous emissions as an identification system. Thus, this study conducted an *in situ* volcanic gaseous emissions concentration measurement system collected directly from areas near the plume of Welirang volcano, Malang, East Java Province, Indonesia (7º43'59" S 112º34'29" E). The measurement system consisted of several gases and particulate matter sensors. The measurements were conducted on ten areas surrounding the Welirang volcano's plume to identify the highest volcanic emission dispersion. The emission concentrations were measured for five minutes every 30 seconds as the interval time. The results show that emission consisted of several gases and particulate matters in different concentrations, such as carbon monoxide, carbon dioxide, methane, and toluene. In addition, the concentrations were influenced by the distance of the measurement sites to the plume. Therefore, the system works well with a response time of fewer than two seconds and the sensitivity of 0.56 Volt/ppm and 0.63 Volt/ppm, respectively, for methane and toluene. The range of the system measurement is 0-100 ppm (carbon monoxide), 400-1,000 ppm (carbon dioxide), 0-100 ppm (methane), and 0-100 ppm (toluene).

Keywords: Gaseous emission, In situ measurement, Volcanic gaseous emission, Welirang volcano

1. INTRODUCTION

Volcanic activities are natural sources of air pollutant emissions in the form of gaseous and particulate emissions. They may release gaseous emissions consisting of carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), mercury (Hg), and hydrogen sulfide (H_2S). Metals, including As (arsenic), Pb (lead), Sb (antimony), Se (selenium), and Tl (thallium), can also be found in the mixture substances [1, 2]. This activity also generates volcanogenic particulate matter that varies in composition, shape, and size. Both internal and external factors influence the composition's variety. The internal factor is related to the magmatic activity, while the external one is associated with the deposited dust in the magma pathway's surface [3]. Both volcanogenic gaseous and particulate emissions are formed from crustal rocks, fluid, and magma originating from the earth's mantle.

Carbon monoxide is considered an indirect greenhouse gas and contributes to the chemical reaction that produces other greenhouse gases, such as carbon dioxide and methane. Both are the two most important greenhouse gases, resulting in the acceleration of the global warming process [4, 5]. However, besides global warming, volcanism can cause the exact opposite of it. Volcanism has a cooling effect when there is a major eruption. The particles of the materials from the eruption float to the earth's atmosphere and block the solar radiation. This case happened in 1815 when Mt. Tambora (Indonesia) massively erupted, which caused prolonged winter that led to famine [6].

Besides impacting the environment, volcanic emissions can also bring adverse impacts on humans. The impact of particulate emissions for humans ranges from respiratory to cardiovascular disease, cognitive decline, and stroke [3, 7]. These adverse impacts are then classified based on their diameter, determining their deposition efficiency in the human body. Large particles (> 2.5 μm in diameter, as known as coarse particles) are deposited in the trachea, bronchi, and bronchioles. At the same time, small particles (<2.5 μm in diameter, as known as fine particles) are deposited in the lung area that can penetrate deeper into the

respiratory system to the blood circulation and the heart and kidneys [8]. The deposited particulate matter in the respiratory tract will directly impact the inhalation capacity of the lungs and may cause many negative cell deformations [9, 10]. In contrast, it can induce changes in skin morphology and oxidative stress that lead to inflammatory cytokines on the skin. The greater the surface area of a particulate matter that enters the body causes a higher ability to produce oxidative stress. Moreover, research in the Azores area (Portugal) found a severe increase in chronic bronchitis from volcanic emissions. Furthermore, volcanic emissions exposure can lead to cancers of the mouth and larynx [11].

Air quality measurement systems consisting of gas and PM are always in constant development to produce the nearest value to the actual value, especially volcanic emission measurement systems. Previous research has developed a portable DOAS (Differential Optical Absorption Spectroscopy) system for scanning SO_2 (sulphur dioxide) concentrations. This instrument measures the solar radiation that reaches the CCD (Charge-Coupled Device) detector to generate a spectral signal from the spectrometer then uses the DOAS algorithm [12, 13]. Using satellites or atmospheric chemistry experience (ACE), gas measurement has a similar principle to DOAS using solar radiation. It is done by measuring the composition of pollutants in the atmosphere, one of which is volcanic emissions using the solar occultation method. An occultation occurs when another object covers an object as it passes through between the observed object and the observer. Measurements are taken when the sun rises and sets. The center of solar radiation will be tracked, and the decrease in light intensity (I) is measured using a near-sight infrared spectrophotometer [14]. PM and gas measurement systems can also be carried out using a satellite-based sensor system. The sensors are mounted on the satellite to measure various pollutant gases. Near real-time air pollutant measurement can detect PM (particulate matter), CO, SO_2, NH_4 (ammonium), CO_2, and others. Sensors such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIPSO) provide 3D information regarding air pollution [15, 16].

2. RESEARCH SIGNIFICANCE

This study designed a measurement system for volcanic emissions. This research combined many sensors to examine some gaseous emissions, such as toluene, carbon dioxide, methane, and carbon monoxide. This system becomes an alternative method to mitigate volcanic emission impact. Besides impacting the environment, these emissions can bring adverse impacts on humans.

3. MATERIALS AND METHODS

3.1 System Circuit

The minimum system circuit had a step-down switching regulator integrated circuit (IC) LM2596. This circuit converted the DC (direct current) input voltage (12 V) to 5 V output voltage (V_{cc}) up to 3A (maximum current, maximum voltage input = 3 to 40 Volt, maximum voltage output = 35 Volt) of continuous current I. The input voltage was used to power up the microcontroller board, suction pump, and cooling fan. The output voltage was connected to the sensor's V_{cc} (common voltage collector) and G (ground) pins. This circuit was added with a safety switch to cut off the current (Fig.1). The study used an Arduino UNO microcontroller board (ATMEGA 328P type) and four different sensors for sensing and signal processing purposes. In contrast, a Sensirion SHT-31D (I2C – Inter-Integrated Circuit - pins were connected to SDA and SCL pins of the microcontroller) was used to monitor the temperature (T) and relative humidity (RH). SHT-31D was a factory-calibrated sensor, so it did not need to be calibrated anymore.

The toluene (C_7H_8) concentration was detected using an analog Figaro TGS2600 (connected to the analog pin A0 of the microcontroller). In addition, a metal oxide CCS811 sensor was installed on the system to measure equivalent carbon dioxide (eCO_2) (equivalent carbon dioxide) concentrations (connected to SDA (serial data) and SCL (serial clock) pins of the microcontroller). This sensor had digital and calibrated outputs that could be used directly for data processing without any signal conversion technique.

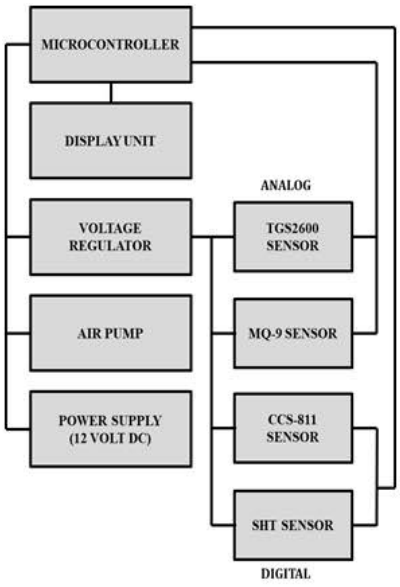

Fig.1 The schematic diagram of the system

Another analog sensor, the MQ-9 sensor, was

connected to the A1 pin of the microcontroller to measure methane gas (CH_4) and carbon monoxide (CO) gas concentrations. The measured concentrations were displayed on a 20 x 4 I2C LCD (liquid crystal display). This display had four bars and twenty columns to display all characters obtained from the measurement processes.

2.2 System Calibration and Measurement

The system was calibrated using a TSI Q-Trak model 7575x (CO, eCO_2, T, and RH) and a TVOCs meter (Total of Volatile Organic Compounds) inside an experimental chamber with a volume of 12,000 cm^3 (20 cm (height) x 20 cm (width) x 30 cm (length)).

Q-Trak, an indoor air quality monitor (TSI, model 7575), provided accurate and quick CO_2 and CO gaseous emissions concentrations. This device also displayed other parameters, such as temperature and relative humidity. Besides, the TVOCs meter measured total HCHO (formaldehyde) and volatile organic compounds.

This procedure was repeated three times (n = 3) for an hour. At the same time, the resulting resistance (R_s) and voltage output signals (V) were compared to the provided datasheet and the comparator devices (Fig.2).

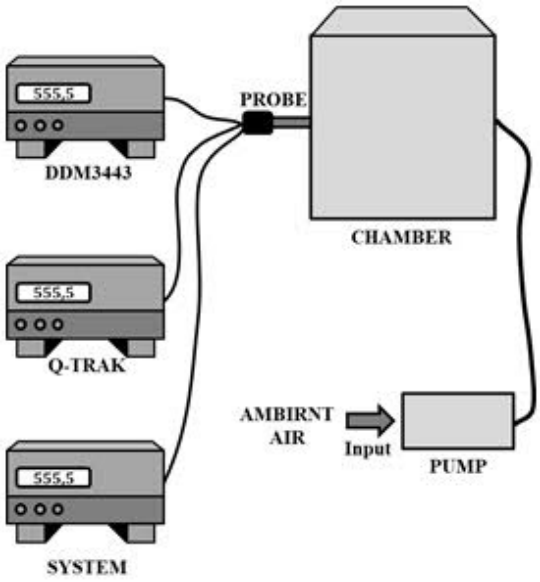

Fig.2 The procedure of the system calibration inside an experimental chamber

The resulted values were analyzed to obtain the sensitivity (S), the response time (t_r), and the range (r) [17]. Response time was calculated by repeating the measurement in eight sampling points. The difference duration (Δt) between the initial time (t_0) and the processing time of the microcontroller (t_e) was considered as the response time [17]. Sensitivity was obtained from the system output values, C_n, whose concentrations were increased stepwise from C_0 to C_{max} related to the datasheet (S), representing the effect of offset parameter (Eq. 1) [18]:

$$S = \frac{\Delta V}{\Delta C} \quad (1)$$

2.3 Sampling Sites

This research was conducted at the Welirang volcano's plume areas, Malang, East Java, Indonesia (7º43'58" S 112º34'29" E, elongation = 3,070 m a.s.l.). The measurement areas were divided into 12 sampling sites (A1 to A12 sites) to identify the dispersion of the volcanic emissions (Fig.3). These site variations were varied based on the plume's distance (s) from the measurement areas [1, 12]. These sites are located 4 to 5 km away from the plume (measurement radius) with an elongation of 1,542 to 1,730 m a. s. l. (above the sea level) (Table 1).

Table 1 Sampling sites at the Welirang volcano areas with different radius and elongation (n = 12)

Site	Radius (m)	Elongation (m a. s. l.)
A1	5,090	1,690
A2	4,310	1,730
A3	4,440	1,624
A4	4,230	1,590
A5	5,200	1,542
A6	4,190	1,590
A7	3,830	1,653
A8	3,770	1,650
A9	3,710	1,660
A10	5,330	1,600
A11	4,640	1,640
A12	5,630	1,727

2.1 Statistical Analysis

All data were written as the mean values ± standard error of the mean (SEM). A linear function regression was used to identify the measurement system performance to the filtered ambient air, including sensitivity, response time, and accuracy. At the end, R^2 (regression coefficients) > 0.75 was considered statistically significant [19]. The emission dispersion parameter was approximated using a correlation between measurement radius and the measured concentrations (interpreted as the dispersion graph).

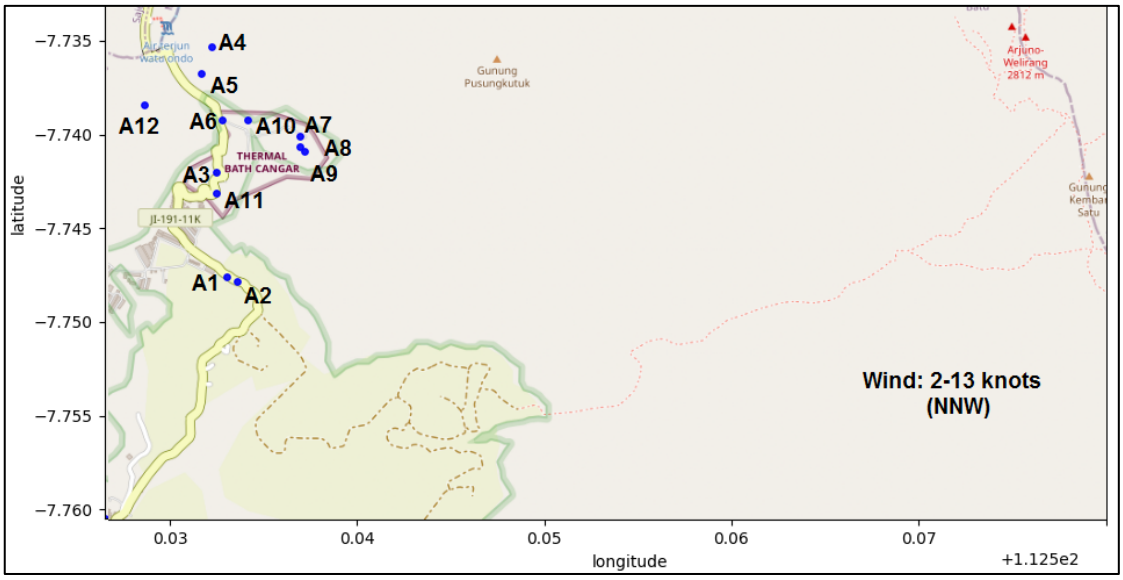

Fig.3 The sampling sites (red dots) in the Welirang volcano areas. The red circle in the downside figure shows the Malang city position

4. RESULTS AND DISCUSSION

3.1 Carbon Monoxide (CO) and Carbon Dioxide (CO_2)

The measured CO and CO_2 concentrations are presented in Fig.4. There is no significant difference between CO concentrations from A1 to A12 ($p < 0.05$). The concentrations are in the range of 2 to 3 ppm. In contrast, there is a fluctuation in CO_2 concentrations related to the distance from the plume (the concentrations are 400.4 to 401.4 ppm). A nonconstant wind speed may influence the fluctuation, where the wind direction and speed have changed compared to the initial sampling time. Other parameters, such as temperature and relative humidity, might influence these results.

The inactive status of the plume may influence these insignificant differences. CO_2 shall be found as the volcanic activity output as major gas species [20-21], even in a volcanic lake as the diffuse CO_2 [22]. Edwards et al. [1] reviewed that this gas's existence may serve as more tracer gas for other emissions, such as Hg.

This gas also indicates the possibility of the geothermal prospect and other volcanic parameters [23]. Considering that there was no significant volcanic activity during the measurement time, it is possible to determine that the influencing factor of these gases is the distance (x). The secondary data support the resulted measurement values. According to the secondary data obtained from the meteorology station, there is no significant difference in the wind speed (2-13 knots).

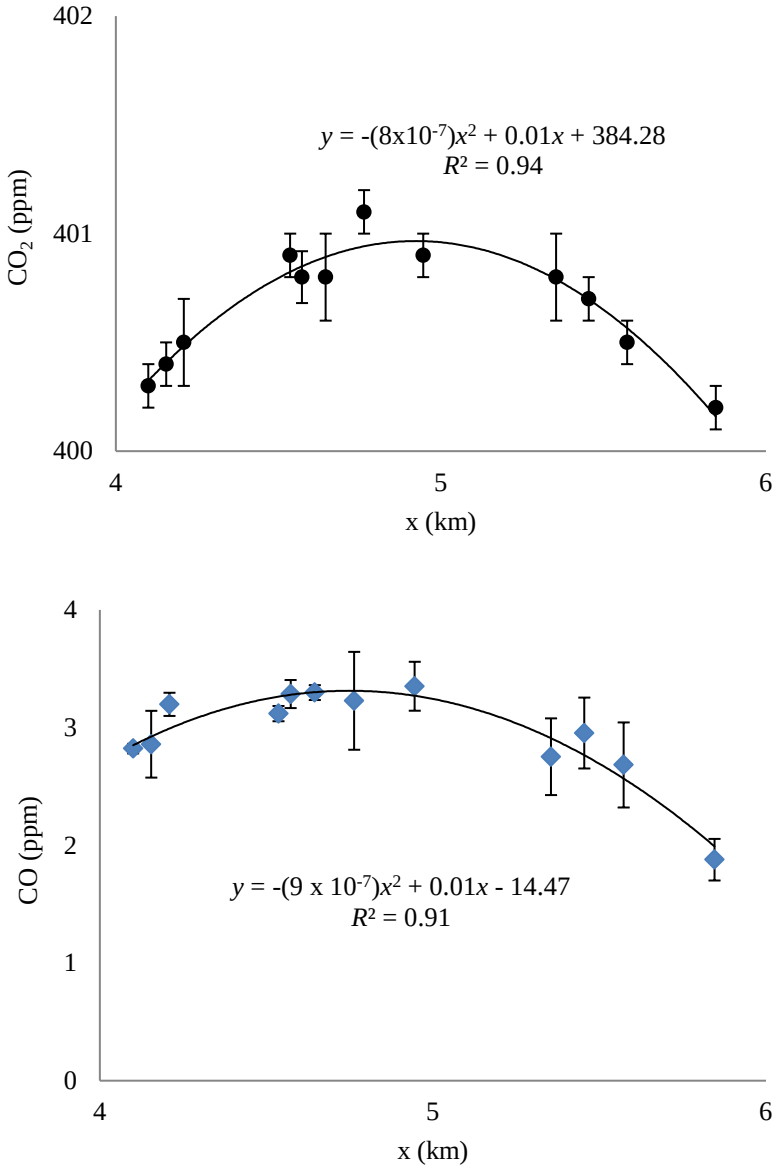

Fig.4 Measured CO_2 and CO concentrations from different measurement radius

3.2 Toluene (C_7H_8)

Toluene concentrations are in the range of 1 ppm to 6 ppm. These results show that volcanic activity may generate VOCs or volatile organic compounds, such as toluene or C_7H_8 (Fig.5). The developed system works well in measuring this gas, with a sensitivity of 0.63 Volt/ppm (0 to 100 ppm of the system range). The system needs <2 s to detect the toluene gas, as defined as the response time. As stated in a previous study, many organic compounds from volcanic gases (more than 200 types) [26].

They are indeed derived from abiogenic gas-phase radical reactions, specifically at a high temperature [26]. However, there is limited information about the volatile compounds related to volcanic activity. As reported in a previous study, only bromine (either in volatile forms of condensed gas) was identified as the volatile compound emissions associated with the complex eruption in Puyehue-Cordon Caulle, 2011 [27].

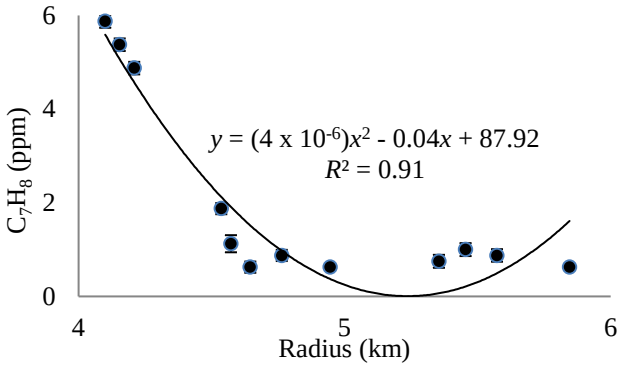

Fig.5 Measured C_7H_8 concentrations from different measurement radius

3.3 Methane (CH_4)

Methane gas (CH_4) concentrations are interpreted in Fig.6-7. The results show that the volcanic emission measurement has a range value of 0 ppm to 4 ppm, with a sensitivity of 0.56 Volt/ppm. These results show that the system works well in sensing low levels of methane gas from volcanic activity emissions with a fair sensitivity (S) level result (R^2 = 0.99).

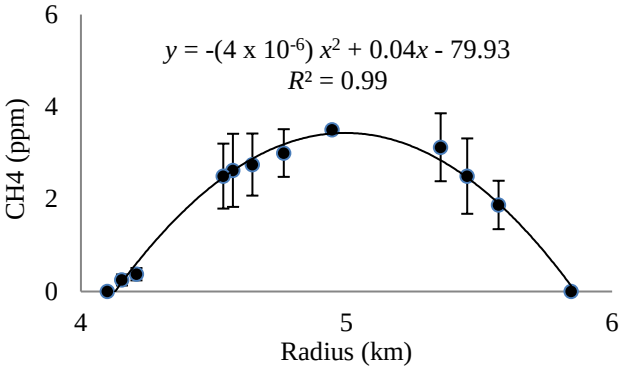

Fig.6 Measured CH_4 concentrations from different measurement radius

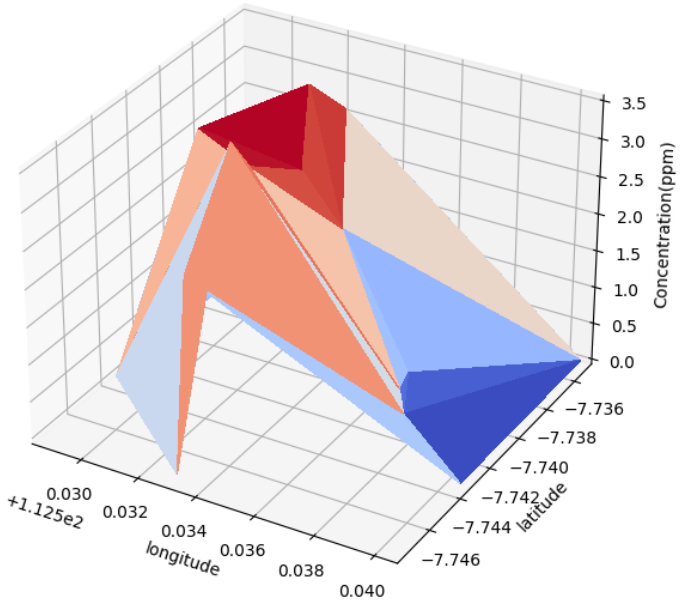

Fig.7 Measured CH_4 concentrations from different measurement radius in a 3D interpretation

5. CONCLUSION

According to the results, it can be concluded that the system works well in measuring volcanic gas emissions. The system can measure methane, toluene, carbon monoxide, and carbon dioxide gasses in 0 to 100 ppm. The developed system needs a response time of fewer than two seconds and a sensitivity of 0.56 Volt/ppm and 0.63 Volt/ppm, respectively, for methane and toluene. The resulted data are influenced by the distance of the measurement sites to the plume.

6. ACKNOWLEDGMENTS

The authors wish to acknowledge assistance or encouragement from colleagues Eko T.P. Adi, Moch. Agung P. N., Rizqi Amalia, and Maria Pramundhitya W. W. All authors thank the "Ministry of Research and Technology/ National Research and Innovation Agency Republic of Indonesia" for their financial contribution (with contract number: 1270.19/UN10.C10/TU/2021 – March 13th, 2021 and 023/E4.1/AK.04.PT/2021, July 12th, 2021).

7. AUTHOR'S CONTRIBUTIONS

Arinto Yudi Ponco Wardoyo and Muhammad Nurhuda made the conception and design of the system and measurement processes. They also wrote the manuscript draft. Hari Arief Dharmawan did the acquisition and analysis. Arif Budianto and Azarine Aisyah Widhowati did the data interpretation.

8. REFERENCES

[1] Edwards B. A., Kushner D. S., Outridge P. M., and Wang F., Fifty Years of Volcanic Mercury Emission Research: Knowledge Gaps and Future Directions, Sci. Total Environ., Vol. 757, 2021, pp. 143800.

[2] Zelenski M., Chaplygin I., Babadi M. F., Taran Y., Campion R., Mehrabi B., Shakeri A., Delavari M., Nekrylov N., Pokrovsky B., Sevastyanov V., and Kuznetsova O., Volcanic Gas Emissions From Taftan and Damavand, the Iranian Volcanoes, J. Volcanol. Geotherm. Res., Vol. 397, 2020, pp. 106880.

[3] Trejos E. M., Silva L. F. O., Hower J. C., Flores E. M. M., Gonzáles C. M., Pachón J. E., and Aristizábal B. H., Volcanic Emissions and Atmospheric Pollution: A study of Nanoparticles, Geosci. Front., Vol. 12, 2021, pp. 746–755.

[4] Dimitriou K., Bougiatioti A., Ramonet M., Pierros F., Michalopoulus P., Liakakou E., Solomos S., Quehe P. –Y., Delmotte M., Gerasopoulos E., Kanakidou M., and Mihalopoulos N., Greenhouse Gases (CO_2 and CH_4) at an Urban Background Site in Athens, Greece: Levels, Sources and Impact of Atmospheric Circulation, Atmos. Environ., Vol. 253, 2021, pp. 118372.

[5] Liu S., Fang S., Liang M., Sun W., and Feng Z., Temporal Patterns and Source Regions of Atmospheric Carbon Monoxide at Two Background Stations in China, Atmos. Res., Vol. 220, 2019, pp. 169–180.

[6] Fell H. G., Baldini J. U. L., Dodds B., and Sharples G. J., Volcanism and Global Plague Pandemics: Towards an Interdisciplinary Synthesis, J. Hist. Geogr., Vol. 70, 2020, pp. 36–46.

[7] Ramírez O., Sánchez de la Campa A. M., Amato F., Moreno T., Silva L. F., and de la Rosa J. D., Physicochemical Characterization and Sources of the Thoracic Fraction of Rroad Dust in a Latin American Megacity, Sci. Total Environ., Vol. 652, 2019, pp. 434–446.

[8] Mazuryk O., Gajda-Morszewski P., Flejszar M., Labuz P., Eldik R. V. Stochel G., and Brindell M., Influence of Aqueous Extracts of Urban Airborne Particulate Matter on the Structure and Function of Human Serum Albumin, Environ. Pollut., Vol. 263, 2020, pp. 114667.

[9] Wardoyo A. Y. P., Juswono U. P., and Noor J. A. E., The Association Between the Diesel Exhaust Particle Exposure From Bus Emission and the Tubular Epithelial Cell Deformation of Rats, Environ. Sci. Pollut. Res., Vol. 27, 2020, pp. 23073–23080.

[10] Wardoyo A. Y. P., Juswono U. P., and Noor J. A. E., How Exposure to Ultrafine and Fine Particles of Car Smoke Can Alter Erythrocyte Forms of Male Mice, Polish Journal of Environmental Studies, Vol. 28, 2019, pp. 2901–2910.

[11] Heaviside C., Witham C., and Vardoulakis S., Potential Health Impacts From Sulphur Dioxide and Sulphate Exposure in the UK Resulting From an Icelandic Effusive Volcanic Eruption, Science of The Total Environment, Vol. 774, 2021, pp. 145549.

[12] Raponi M., Vilar O., Arboleas H., García S., Otero L., Pereyra A., Martorella E., and Gómez M., First Portable Scanning-DOAS System Developed in Latin America For Volcanic SO_2 Monitoring, Journal of South American Earth Sciences, Vol. 108, 2021, pp. 103177.

[13] Li X., Xie P., Li A., Xu J., Ren H., Ren B., Li

Y., and Li J., Study of Aerosol Characteristics and Sources Using MAX-DOAS Measurement During Haze at an Urban Site in the Fenwei Plain, Journal of Environmental Sciences (China), Vol. 107, 2021, pp. 1–13.

[14] Bernath P. F., Crouse J., Hughes R. C., and Boone C. D., The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) Version 4.1 Retrievals: Trends and Seasonal Distributions, J. Quant. Spectrosc. Radiat. Transf., Vol. 259, 2021, pp. 107409.

[15] Tang Y., Tong D. Q., Yang K., Lee P., Baker B., Crawford A., Luke W., Stein A., Campbell P. C., Ring A., Flynn J., Wang Y., McQueen J., Pan L., Huang J., and Stajner I., Air Quality Impacts of the 2018 Mt. Kilauea Volcano Eruption in Hawaii: A Regional Chemical Transport Model Study With Satellite-Constrained Emissions, Atmos. Environ., Vol. 237, 2020, pp. 117648.

[16] Singh D., Dahiya M., Kumar R., and Nanda C., Sensors and Systems For Air Quality Assessment Monitoring and Management : A Review, J. Environ. Manage., Vol. 289, 2021, pp. 112510.

[17] Jin H., Tao X., Feng B., Yu L., Wang D., Dong S., and Luo J., A Humidity Sensor Based on Quartz Crystal Microbalance Using Graphene Oxide as a Sensitive Layer, Vacuum, Vol. 140, 2017, pp. 101–105.

[18] Pongsuttiyakorn T., Sooraksa P., and Pornchalermpong P., Simple Effective and Robust Weight Sensor For Measuring Moisture Content in Food Drying Process, Sensors Mater., Vol. 31, 2019, pp. 2393–2404.

[19] Alfano B., Barretta L., Giudice A. D., Vito S. D., Francia G. D., Esposito E., Formisano F., Massera E., Miglietta M. L., and Polichetti T., A Review of Low-Cost Particulate Matter Sensors From the Developers' Perspectives, Sensors (Switzerland), Vol. 20, 2020, pp. 1–56.

[20] Yang X., Yan D., Zhang B., Zhang L., Wei X., Li T., Zhang J., and She X., The Impact of Volcanic Activity on the Deposition of Organic-Rich Shales: Evidence From Carbon Isotope and Geochemical Compositions, Mar. Pet. Geol., Vol. 128, 2021, pp. 105010.

[21] Zelenski M., Simakin A., Taran Y., Kamenetsky V. S., and Malik N., Partitioning of Elements Between High-Temperature, Low-Density Aqueous Fluid and Silicate Melt as Derived From Volcanic Gas Geochemistry, Geochim. Cosmochim. Acta, Vol. 295, 2021. pp. 112–134.

[22] Andrade C., Cruz J. V., Viveiros F., and Coutinho R., Diffuse CO_2 Emissions From Sete Cidades Volcanic Lake (São Miguel Island, Azores): Influence of Eutrophication Processes, Environ. Pollut., Vol. 268, 2021.

[23] Taussi M., Nisi B., Vaselli O., Maza S., Morata D., and Renzulli A., Soil CO_2 Flux and Temperature From a New Geothermal Area in the Cordón De Inacaliri Volcanic Complex (Northern Chile), Geothermics, Vol. 89, 2021, pp. 101961.

[24] Aroskay A., Martin E., Bekki S., Montana G., Randazzo L., Cartigny P., Chabas A., and Verney-Carron A., Multi O- and S-isotopes As Tracers of Black Crusts Formation Under volcanic and Non-Volcanic Atmospheric Conditions in Sicily (Italy), Sci. Total Environ., Vol. 750, 2021. pp. 142283.

[25] Henley R. W. and Fischer T. P., Sulfur Sequestration and Redox Equilibria in Volcanic Gases, J. Volcanol. Geotherm. Res., Vol. 414, 2021, pp. 107181-107202.

[26] Schwandner F. M., Seward T. M., Gize A. P., Hall K., and Dietrich V. J., Halocarbons and Other Trace Heteroatomic Organic Compounds in Volcanic Gases From Vulcano (Aeolian Islands, Italy), Geochim. Cosmochim. Acta, Vol. 101, 2013, pp. 191–221.

[27] Bubach D., Pérez Catán S., Arribére M., and Guevara S. R., Bioindication of Volatile Elements Emission by the Puyehue-Cordón Caulle (North Patagonia) Volcanic Event in 2011, Chemosphere, Vol. 88, 2012, pp. 584–590.