

Metal Corrosion Indicators for Sulfur Exposure Assessment in Urban and Volcanic Areas of East Java

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Manuscript received: 8 February 2026; Received in revised form: 28 May 2026; Accepted: 1 June 2026

Abstract

This study investigates the relationship between sulfur content in commercial fuels and metal corrosion behavior as an environmental indicator of sulfur exposure in urban and volcanic areas of East Java. The research aims to evaluate corrosion characteristics of iron materials immersed in various commercial fuels and to examine their potential relevance to regional sulfur-related atmospheric conditions. Corrosion experiments were conducted using iron spheres immersed for 21 days in several fuel types, including diesel, gasoline, Pertamina, Pertalite, and Pertasol variants. Sulfur characterization was performed using an Oil Sulfur Analyzer based on X-ray Fluorescence (XRF) principles, while corrosion rates were determined using the weight-loss method. The results indicate that fuels with higher sulfur content generally produced higher corrosion rates. Diesel fuel exhibited the highest corrosion rate (1.0300 mpy), while low-sulfur fuels such as Pertamina showed significantly lower corrosion behavior (0.4120 mpy). Spatial interpretation of sulfur-related environmental conditions in East Java suggests contrasting characteristics between urban regions dominated by anthropogenic fuel combustion and volcanic areas influenced by natural sulfur degassing. Estimated sulfur dioxide emissions and their associated radiative forcing values demonstrate that sulfur-rich fuels potentially contribute to greater atmospheric sulfur loading and sulfate aerosol formation. Overall, the findings suggest that metal corrosion indicators have potential applicability as supporting proxies for sulfur-related environmental assessment.

Keywords: Environmental assessment; Fuel sulfur; Metal corrosion indicators; Sulfur dioxide; Urban and volcanic environments.

Citation: Ramadhan, Y. D., Rahmawan, M. T., Haq, A., Maulidiyah, N. R., Noorlaksono, D. A., Realita, A., Madlazim, M., Fahmi, M. N., Situmeang, A. D., & Ardiansyah, Z. F. (2026). Metal Corrosion Indicators for Sulfur Exposure Assessment in Urban and Volcanic Areas of East Java. *Jurnal Geoelebes*, 10(2): 160–176, doi: 10.70561/geoelebes.v10i2.49863

Introduction

Sulfur dioxide (SO₂) is one of the major atmospheric pollutants generated from anthropogenic and geogenic activities and plays an important role in atmospheric chemistry, aerosol formation, environmental degradation, and climate-related processes (IPCC, 2021; Bond et al., 2013). Anthropogenic SO₂ emissions are

primarily produced by fossil fuel combustion, industrial operations, and transportation sectors, whereas geogenic sulfur emissions mainly originate from volcanic degassing processes (Carn et al., 2017). Geological and geotechnical characteristics also influence environmental instability processes because weathering and erosion mechanisms may accelerate material

degradation and increase susceptibility to environmental disturbances under reactive surface conditions (Firoozi et al., 2024). In rapidly urbanizing tropical regions characterized by active volcanic systems, sulfur-related environmental dynamics become increasingly complex because urban-industrial emissions coexist with natural volcanic sulfur sources (Henley & Fischer, 2021). Sulfur dioxide oxidation processes in the atmosphere contribute to sulfate aerosol formation and atmospheric acidity under humid environmental conditions (Burns et al., 2016).

East Java represents one of the most environmentally dynamic regions in Indonesia because it combines densely populated urban-industrial corridors with active volcanic systems within the same regional environment (Ibrahim et al., 2025). Urban areas such as Surabaya, Sidoarjo, and Gresik are characterized by intensive transportation activity, industrial fuel consumption, and increasing population density, all of which contribute to anthropogenic sulfur emissions (Crippa et al., 2020; World Bank, 2023). At the same time, southern and eastern parts of East Java are strongly influenced by active volcanic systems associated with the Sunda volcanic arc, including Mount Semeru, Bromo, Ijen, and the Lamongan volcanic field (Ibrahim et al., 2025). These volcanic systems are characterized by continuous volcanic activity, degassing processes, and sulfur-bearing gas emissions that contribute significantly to regional sulfur loading and atmospheric environmental dynamics in East Java (Carn et al., 2017; Moktikanana et al., 2024). The coexistence of anthropogenic sulfur emissions from urban-industrial activities and geogenic sulfur emissions from volcanic systems creates a mixed sulfur environment that potentially influences regional atmospheric conditions and environmental quality (Moktikanana et al., 2024).

Recent studies have widely investigated sulfur emissions, sulfate aerosol formation, atmospheric pollution, and urban environmental degradation (IPCC, 2021). Other studies have demonstrated that sulfur-containing compounds accelerate electrochemical degradation processes on metallic materials by destabilizing protective oxide layers and enhancing acidic oxidation mechanisms (Gao et al., 2022). Sulfur-bearing fuels may therefore create more aggressive corrosive environments and increase sulfur-related environmental exposure. In addition, atmospheric oxidation of sulfur dioxide contributes to sulfate aerosol formation, which influences atmospheric radiation scattering and environmental conditions (Kusumaningtyas et al., 2022).

Although sulfur emissions, corrosion mechanisms, and atmospheric sulfur dynamics have been studied separately, integrated studies combining fuel sulfur characterization, laboratory corrosion indicators, and sulfur related spatial environmental interpretation remain limited, particularly in tropical urban volcanic systems such as East Java (Granados-Bolaños et al., 2021). Previous studies have mainly focused on atmospheric monitoring, industrial emissions, volcanic degassing, or material corrosion independently, while comparative environmental interpretation integrating anthropogenic and geogenic sulfur systems has received less attention (Wang et al., 2024).

Metal corrosion behavior has potential applicability as a supporting physicochemical proxy for evaluating sulfur-related environmental characteristics because sulfur compounds intensify electrochemical oxidation processes on iron surfaces (Gao et al., 2022). Consequently, understanding the relationship between sulfur content, corrosion behavior, and sulfur-related environmental patterns is important for evaluating sulfur-related

environmental conditions in mixed urban–volcanic regions.

This study aims to evaluate the corrosion characteristics of iron materials exposed to different commercial fuels, analyze the relationship between fuel sulfur content and corrosion behavior, and examine sulfur-related environmental characteristics in urban and volcanic regions of East Java. Corrosion experiments were conducted using iron sphere immersion methods combined with sulfur characterization using an Oil Sulfur Analyzer based on X-ray Fluorescence (XRF) principles. The findings are expected to provide additional insights into the environmental implications of sulfur-containing fuels and the potential use of metal corrosion indicators as supporting proxies for sulfur-related environmental assessment.

Materials and Methods

Study Area

This study was conducted in urban and volcanic regions of East Java, Indonesia, representing environmental systems influenced by both anthropogenic and geogenic sulfur sources. Urban areas include Surabaya, Sidoarjo, Gresik, and Mojokerto, which are characterized by high population density, industrial activities, transportation intensity, and commercial fuel consumption. Volcanic regions include Malang Regency, Batu City, Pasuruan, and surrounding areas influenced by volcanic systems such as Mount Semeru, Bromo–Tengger, and Arjuno–Welirang. These volcanic systems continuously release sulfur-bearing gases through degassing processes and therefore contribute to regional atmospheric sulfur loading (Carn et al., 2017).

The selection of East Java was based on its environmental complexity, where urban–industrial emissions coexist with active volcanic sulfur emissions. This environmental setting provides an

appropriate regional framework for evaluating sulfur-related environmental characteristics from an environmental geophysics’ perspective (IPCC, 2021).

Fuel Sample Preparation

Seven commercial fuel samples were analyzed in this study, consisting of diesel fuel, gasoline, Pertamina, Peralite, and Pertasol variants (CA, CB, and CC). All fuel samples were obtained from commercial distributors in East Java and stored in sealed laboratory containers to minimize contamination and evaporation prior to analysis.

Each fuel sample was prepared under identical laboratory conditions to ensure consistency during corrosion testing and sulfur characterization. Fuel samples were maintained at room temperature during the experimental period following laboratory fuel handling recommendations described in fuel chemistry studies (Gao et al., 2022).

Corrosion Rate Measurement

Corrosion experiments were conducted using spherical iron specimens with a diameter of 6.35 mm. Each iron sphere was immersed separately in individual fuel samples for 21 days under sealed conditions at room temperature to minimize external environmental influences such as humidity fluctuations and airborne contamination. Sulfur-bearing environments may accelerate oxidation behavior and metallic degradation processes under reactive conditions (Han et al., 2019).

Daily visual observations were performed to identify changes in surface appearance, oxidation intensity, and deposit formation. After the immersion period, the iron specimens were removed, cleaned using distilled water and ethanol, dried under controlled laboratory conditions, and weighed using a digital analytical balance. Corrosion processes on metallic materials are strongly influenced by acidic sulfur-

bearing environments that accelerate electrochemical oxidation reactions.

The corrosion rate was determined using the weight-loss method based on ASTM G31 standard principles for laboratory immersion corrosion testing. The corrosion rate equation is expressed as (ASTM G31-21, 2021):

$$CR (Corrosion Rate) = \frac{K \cdot W}{\rho \cdot A \cdot t} \quad (1)$$

where:

- CR : corrosion rate (mm.year⁻¹)
 K : conversion constant (8.76 × 10⁴ for mm.year⁻¹ when *W* is expressed in grams)
 W : mass loss of the metal due to corrosion (g)
 ρ : metal density (g.cm⁻³)
 A : exposed surface area of the metal (cm²)
 t : exposure time (h)

The corrosion rate values were used as physicochemical indicators representing the relative influence of sulfur-containing fuel environments on metallic degradation processes (Gao et al., 2022; ASTM G31-21, 2021).

Sulfur Characterization using Oil Sulfur Analyzer

Sulfur characterization of fuel samples was conducted using an Oil Sulfur Analyzer based on X-ray fluorescence (XRF) spectroscopy principles. This method enables qualitative to semi-quantitative identification of sulfur concentrations within liquid hydrocarbon matrices.

The XRF method operates through excitation of sulfur atoms by primary X-rays, producing secondary characteristic fluorescence emissions whose intensities are proportional to sulfur concentration (Skoog et al., 2017). The obtained sulfur concentration values were used to compare sulfur characteristics among different fuel types and to support interpretation of corrosion behavior.

The sulfur measurements in this study were intended for comparative environmental assessment rather than absolute atmospheric sulfur quantification.

Sulfur Emission Estimation

Potential sulfur dioxide (SO₂) emissions were estimated theoretically based on sulfur concentrations measured in fuel samples. The estimation assumes complete oxidation of sulfur during combustion processes according to stoichiometric sulfur oxidation principles described in atmospheric chemistry studies. The SO₂ emission estimation is expressed as (Seinfeld & Pandis, 2016):

$$SO_2 Emissions = Sulfur Content \times 2 \cdot 10^{-3} \quad (2)$$

The total mass of sulfur dioxide emitted (M_{SO2}) was subsequently estimated by multiplying the calculated SO₂ emission value by the volume of the fuel sample used in the experiment. This simplified sulfur emission estimation approach follows sulfur mass balance concepts commonly applied in atmospheric environmental assessments, expressed as (IPCC, 2021):

$$Total emissions of SO_2 (M_{SO_2}) = SO_2 Emissions \times sample volume = \dots g \quad (3)$$

The estimated sulfur dioxide emissions were then converted into simplified sulfur-related radiative forcing indicators using sulfur aerosol forcing coefficients adapted from atmospheric aerosol forcing studies. The simplified radiative forcing relationship is expressed as (Haywood & Boucher, 2021):

$$RF = \frac{M_{SO_2}}{1 \times 10^9 g} \times (-0.3) W/m^2 \quad (4)$$

where:

- M_{SO2} : mass of SO₂ released (grams)
 -0.3 W/m² : approximate global mean negative radiative forcing coefficient associated with anthropogenic sulfate aerosols derived from SO₂

emissions (IPCC, 2021)

The negative radiative forcing coefficient reflects the cooling effect produced by sulfate aerosols formed through atmospheric oxidation of sulfur dioxide, which increases shortwave radiation scattering in the atmosphere (Seinfeld & Pandis, 2016). The resulting values therefore represent simplified relative sulfur-related atmospheric indicators rather than direct atmospheric SO₂ measurements or comprehensive climate-scale radiative transfer calculations (Loveridge et al., 2025).

This estimation approach was adapted from simplified sulfur emission relationships commonly used in atmospheric environmental assessments and aerosol forcing interpretation studies (IPCC, 2021).

Spatial Environmental Interpretation

Spatial interpretation of sulfur-related environmental conditions was conducted using regional sulfur distribution maps, population density information, and volcanic distribution data in East Java.

The sulfur distribution maps were interpreted as supporting environmental datasets to qualitatively compare sulfur characteristics between urban-industrial regions and volcanic regions. Population density data used in this study were obtained from the Ministry of Home Affairs of the Republic of Indonesia to support urban spatial interpretation and regional demographic analysis (Ministry of Home Affairs of the Republic of Indonesia, 2022). Volcanic distribution data were interpreted based on regional geological and volcanic frameworks of Java Island (van Bemmelen, 1949).

The spatial interpretation in this study was performed qualitatively and semi-quantitatively to distinguish anthropogenic sulfur signatures in urban regions from geogenic sulfur influences in volcanic regions. This approach emphasizes

comparative environmental interpretation based on sulfur-related spatial patterns rather than applying complex atmospheric dispersion simulations, which generally require detailed meteorological parameters, advection–diffusion modeling, and computational atmospheric transport analysis (Leelössy et al., 2018; Erfani & Mitchell, 2026). Therefore, the spatial assessment presented in this study was intended to support environmental characterization of sulfur-related conditions in East Java rather than conduct comprehensive atmospheric dispersion modeling (Granados-Bolaños et al., 2021).

Results and Discussion

At a regional scale, population density dynamics play a crucial role in shaping the interaction between anthropogenic activities, energy consumption, and atmospheric geophysical processes. Uneven population growth intensifies the demand for transportation, industrial operations, and commercial fuel usage, particularly in densely populated areas, thereby increasing the potential release of sulfur dioxide (SO₂) into the atmosphere. From a geophysical environmental perspective, population distribution functions as an important indicator of anthropogenic pressure on atmospheric composition, as high-density regions generally correspond to elevated emission intensities and altered atmospheric chemical processes. Consequently, population density mapping provides a critical demographic framework for interpreting SO₂ spatial distribution and proxies for assessing regional sulfur dynamics in East Java (Gao et al., 2022).

Based on the 2022 population density distribution map of Java Island shown in Figure 1, population concentration forms a continuous west–east urban corridor extending from the Jakarta metropolitan region in West Java to Surabaya and its surrounding industrial belt in East Java.

The highest density clusters are visible in the Jakarta–Bekasi–Karawang area, Bandung Basin, Semarang, and the Surabaya – Gresik – Sidoarjo corridor, reflecting strong metropolitan expansion, industrial agglomeration, and transportation network intensity. Recent demographic and urban assessments indicate that rapid urban concentration in Southeast Asia, including Indonesia, significantly increases energy demand and

fossil fuel consumption, thereby intensifying anthropogenic air pollutant emissions (United Nations, 2022; World Bank, 2023). The strong coupling between urban density and emission intensity has also been emphasized in recent emission inventory studies showing that densely populated megacities contribute disproportionately to regional sulfur dioxide (SO₂) loading (Crippa et al., 2020).

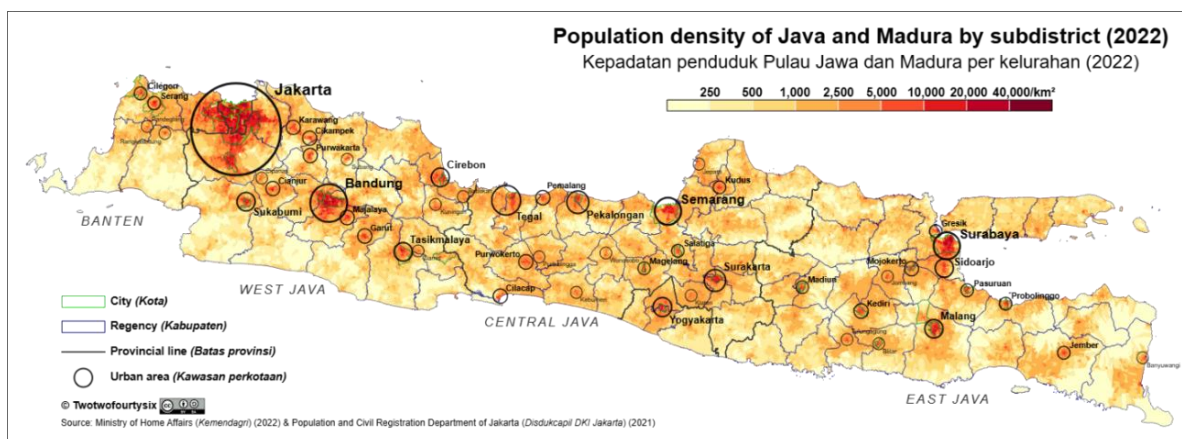


Figure 1. Distribution of population density in Java Island 2022 (Ministry of Home Affairs of the Republic of Indonesia, 2022).

In East Java specifically, the Surabaya metropolitan region exhibits high-density clustering consistent with industrial and port-centered development, which is closely linked to transportation-related fuel combustion. Contemporary air quality evaluations in Indonesian urban regions confirm that transportation and industrial fuel use remain dominant contributors to SO₂ variability in major cities (World Health Organization, 2021). In contrast, areas such as Malang and Pasuruan display moderate to high population densities but are situated along active volcanic corridors associated with Mount Semeru, Bromo, and Arjuno–Welirang. In these regions, atmospheric sulfur dynamics are influenced not only by anthropogenic combustion but also by persistent volcanic degassing, which has been identified as a major natural contributor to regional SO₂ emissions in Indonesia (Bani et al., 2022).

The coexistence of dense urban populations and active volcanic systems therefore

creates a dual-source sulfur environment in East Java (Figure 2). Recent atmospheric chemistry assessments emphasize that interactions between anthropogenic emissions and natural volcanic inputs can amplify localized sulfate aerosol formation and alter regional radiative balance (IPCC, 2021). Consequently, the 2022 population density pattern across Java Island provides an essential demographic framework for interpreting spatial SO₂ variability, particularly when distinguishing purely urban emission signatures from mixed urban–volcanic atmospheric systems.

The distribution of volcanoes in East Java and Central Java Provinces follows a well-defined east–west alignment that corresponds to the active Sunda volcanic arc formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Wandono et al., 2025). This tectonic setting results in a high concentration of Quaternary volcanoes extending from Central Java (e.g., Merapi–Merbabu

volcanic complex) through East Java, including major volcanic systems such as Semeru, Bromo–Tengger, Kelud, Ijen, and Raung. These volcanoes are predominantly located along structural zones such as the Kendeng Zone and the Southern Mountains, where magmatic ascent is facilitated by crustal weaknesses (Berghuis et al., 2022). The spatial clustering of active and potentially active volcanoes in these regions makes them significant natural sources of sulfur dioxide (SO_2), continuously contributing to the regional atmospheric sulfur background through volcanic degassing. This geological configuration provides a critical geophysical context for interpreting sulfur anomalies observed in East Java, as illustrated by the elevated SO_2 concentrations mapped in the volcanic sector shown in Figure 3, where the correspondence between volcanic locations and high sulfur intensity highlights the strong influence of geogenic emissions on atmospheric sulfur distribution (Blessing et al., 2025).

The sulfur distribution patterns illustrated in Figure 3 reveal a clear spatial differentiation between urban areas and regions influenced by volcanic activity in East Java, which is closely related to

variations in emission sources and fuel characteristics. As shown in Figure 1, urban centers such as Surabaya and Sidoarjo are characterized by relatively low SO_2 column densities, indicated by cooler color gradients. This pattern suggests that sulfur accumulation in these areas remains comparatively controlled despite high levels of industrial and transportation activity, reflecting the influence of low-sulfur fuel standards and improved combustion efficiency in urban environments (Anastasopoulos et al., 2023).

A more detailed spatial representation in Figure 3 highlights localized increases in sulfur concentrations within several suburban and peri-urban industrial zones, indicating mixed contributions from local anthropogenic emissions and regional atmospheric transport. In contrast, the southern and highland regions associated with volcanic systems particularly around Malang, Malang City, and Batu City consistently exhibit elevated sulfur levels. The dominance of warmer color tones in these areas signifies substantial sulfur loading driven primarily by continuous volcanic degassing processes, which contribute significantly to the regional atmospheric sulfur background.



Figure 2. Distribution of Volcanoes in East Java and Central Java Provinces (modified from van Bemmelen, 1949).

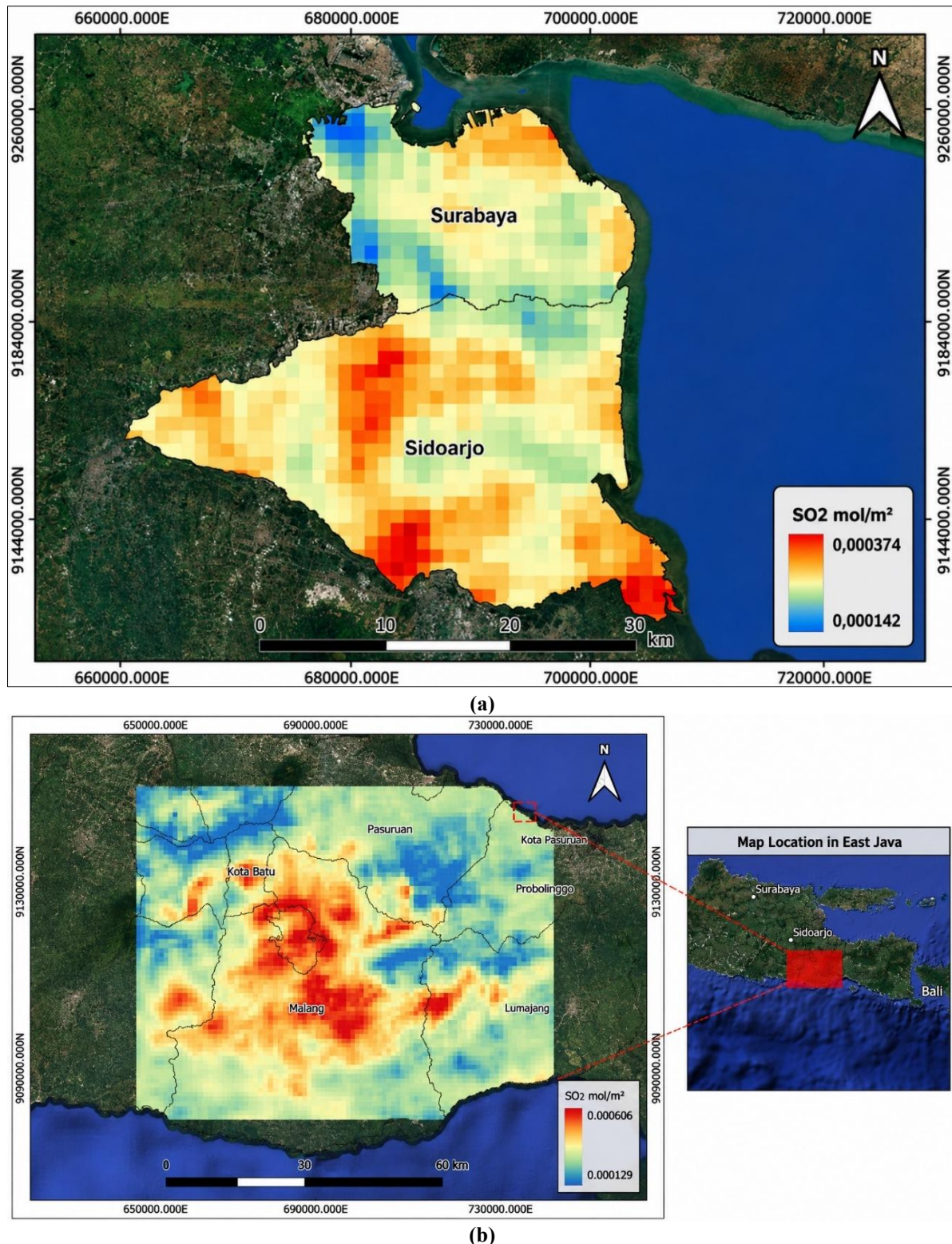


Figure 3. Sulfur Dioxide (SO_2) distribution map (a) Urban areas (b) Volcanic areas of East Java.

The experimental data presented in Table 1 and Figure 4 reveal distinct variations in corrosion rates among the tested fuel types, underscoring their differing impacts on iron degradation and their relevance as supporting indicators of sulfur-related

environmental exposure. The measured corrosion rates (CR) range from 0.4120 to 1.0300 mpy, with diesel fuel exhibiting the highest value (1.0300 mpy), followed by Pertasol CC (0.8930 mpy) and Pertasol CA and CB (0.8240 mpy). Figure 4 clearly

illustrates this trend, showing a progressive increase in corrosion intensity from low-sulfur fuels toward sulfur-rich fuels. The graphical distribution highlights diesel fuel as the dominant corrosive medium, while Pertamina exhibits the lowest corrosion behavior among all tested samples. These

differences reflect variations in sulfur concentration among commercial fuels and support the interpretation that corrosion behavior may provide physicochemical information regarding sulfur-related environmental conditions (Cao et al, 2023).

Table 1. Corrosion rate values for each fuel sample.

Type of Material	Diameter (cm)	Areas (cm ²)	T (Hour) (21 Days)	Initial Mass (gr)	Final Mass (gr)	Δm (gr)	Cr (mpy)
Pertasol CA	0.635	1.266	504	1.0311	1.0299	0.0012	0.8240
Pertasol CB	0.635	1.266	504	1.0311	1.0305	0.0012	0.8240
Pertasol CC	0.635	1.266	504	1.0311	1.0298	0.0013	0.8930
Diesel	0.635	1.266	504	1.0311	1.0301	0.0015	1.0300
Gasoline	0.635	1.266	504	1.0311	1.0210	0.0010	0.6870
Pertamax	0.635	1.266	504	1.0311	1.0305	0.0006	0.4120
Pertalite	0.635	1.266	504	1.0311	1.0301	0.0010	0.6870

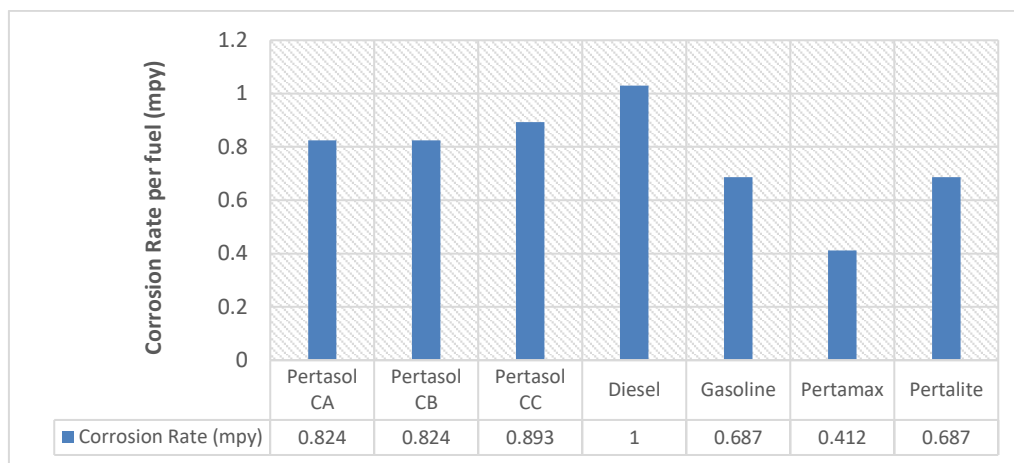


Figure 4. Graph of corrosion rate per fuel (mpy).

Diesel fuel demonstrates the most pronounced corrosive effect, consistent with its highest mass loss ($\Delta m = 0.0015$ g), indicating a more aggressive sulfur-bearing chemical environment (Nguyen & Vu, 2019). The sharp increase in corrosion rate observed in Figure 4 for diesel fuel suggests stronger electrochemical degradation processes compared to gasoline-based fuels. This behavior is associated with elevated sulfur fractions that may undergo oxidation to form sulfur dioxide (SO_2) and sulfur-derived acidic compounds under oxidizing and humid conditions, thereby accelerating electrochemical reactions at the metal surface (Schmitz & Linderholm, 2018). Sulfate ions may enhance electrochemical activity by increasing ionic

conductivity and accelerating interfacial charge transfer kinetics on metallic surfaces under reactive conditions (Reddy et al., 2025). These electrochemical processes intensify metallic degradation behavior and indicate a potential relationship between sulfur-containing fuels, corrosion mechanisms, and sulfur-related environmental loading.

Similarly, Pertasol CA, CB, and CC exhibit intermediate to high corrosion rates (0.8240–0.8930 mpy), consistent with their relatively higher sulfur characteristics compared to gasoline-based fuels. Figure 4 demonstrates that the Pertasol fuels form a clustered corrosion pattern below diesel but substantially above Pertamina and gasoline

fuels, indicating moderate-to-high corrosive characteristics. Although Pertasol CA and CB present identical mass losses ($\Delta m = 0.0012$ g), the slightly greater mass reduction in Pertasol CC ($\Delta m = 0.0013$ g) produces a measurable increase in corrosion rate, emphasizing the sensitivity of metallic corrosion processes to subtle sulfur–metal chemical interactions. This trend is consistent with corrosion studies showing that sulfur-containing environments accelerate oxidation kinetics and electrochemical degradation processes on iron surfaces (Gao et al., 2022).

In contrast, low-sulfur fuels such as Pertamina and Peralite display substantially lower corrosion rates, 0.4120 mpy and 0.6870 mpy respectively, accompanied by minimal mass loss ($\Delta m = 0.0006$ – 0.0010 g). Figure 4 further emphasizes the distinct reduction in corrosion intensity for Pertamina, which appears significantly lower than all other fuel samples. These findings indicate relatively improved chemical stability toward metallic materials and correspond to stricter sulfur regulation standards applied to modern fuel products. Low-sulfur fuels such as Pertamina and Peralite exhibited lower corrosion rates, indicating improved chemical stability toward metallic materials and reduced sulfur-related degradation potential (Gao et al., 2022). Previous studies have demonstrated that sulfur-containing compounds promote anodic dissolution and destabilize protective oxide films on iron surfaces (Ottosson et al., 2018). Sulfur-derived ionic species may enhance electrochemical reaction kinetics by increasing interfacial charge transfer activity and ionic conductivity at the metal–fuel interface under reactive conditions (Reddy et al., 2025). Prolonged exposure to sulfur-bearing fuels may therefore intensify localized metallic degradation processes, including pitting corrosion and micro-galvanic interactions on iron surfaces.

The corrosion characteristics identified experimentally in Table 1 and visualized comparatively in Figure 4 can be qualitatively associated with the sulfur-related spatial patterns shown in Figure 3. Urban-industrial regions such as Surabaya and Sidoarjo display moderate sulfur-related anomalies associated with transportation activity, industrial combustion, and intensive commercial fuel utilization. In contrast, volcanic regions surrounding Malang, Pasuruan, and the Bromo–Semeru volcanic corridor exhibit relatively stronger sulfur-related spatial anomalies, which are interpreted as environmental indications of additional geogenic sulfur influence from volcanic degassing systems (Bani et al., 2022).

From an environmental geophysics' perspective, the coexistence of anthropogenic sulfur emissions from fuel combustion and natural volcanic sulfur emissions creates spatially variable sulfur exposure conditions across East Java. The laboratory corrosion results therefore provide supporting physicochemical evidence that fuels characterized by higher sulfur content possess greater potential to contribute to sulfur-related environmental loading under both urban and volcanic atmospheric systems (Cao et al., 2023). Figure 4 particularly supports this interpretation by demonstrating a consistent relationship between fuel type and corrosion intensity, where sulfur-rich fuels systematically produce greater metallic degradation compared to low-sulfur fuels.

However, it is important to emphasize that the corrosion experiment conducted in this study represents a laboratory-scale physicochemical assessment and does not directly measure atmospheric SO_2 concentration or atmospheric sulfur dispersion. Consequently, the sulfur-related spatial interpretation presented in Figure 3 should be regarded as supporting environmental context rather than direct validation of corrosion measurements.

The simplified sulfur-related atmospheric indicators calculated in this study show a consistent dependence on sulfur concentration, indicating that fuels with higher sulfur content possess greater potential to contribute to sulfur-related atmospheric loading through sulfate aerosol formation. Diesel fuel (950 ppm sulfur) produced the highest estimated sulfur

dioxide emission potential ($0.0009500 \text{ mol/m}^2$) and the largest relative sulfur-related atmospheric indicator ($-5.7 \times 10^{-10} \text{ W/m}^2$), whereas low-sulfur fuels such as Pertamina (18.6 ppm) generated substantially lower estimated sulfur emissions ($0.0000186 \text{ mol/m}^2$) and weaker atmospheric indicator values ($-1.1 \times 10^{-11} \text{ W/m}^2$), as presented in Table 2.

Table 2. Radiative forcing value of each fuel sample (W/m^2)

Material Type	Sulfur Content (ppm)	Emissions SO_2 (mol/m^2)	Total SO_2 Emissions (mol/m^2)	Radiative Forcing (W/m^2)
Pertasol CA	182.2	0.3644	0.0001822	-1.093×10^{-10}
Pertasol CB	259.9	0.5198	0.0002599	-1.559×10^{-10}
Pertasol CC	306.3	0.6126	0.0003063	-1.837×10^{-10}
Diesel	950.0	1.9000	0.0009500	-5.700×10^{-10}
Gasoline	176.6	0.3532	0.0001766	-1.059×10^{-10}
Pertamax	18.6	0.0372	0.0000186	-1.116×10^{-11}
Pertalite	56.6	0.1132	0.0000566	-3.396×10^{-11}

This trend is consistent with atmospheric chemistry principles indicating that sulfur dioxide may undergo oxidation processes to form sulfate aerosols, which can increase shortwave radiation scattering and contribute to atmospheric cooling effects (Seinfeld & Pandis, 2016). At the global scale, sulfate aerosol forcing associated with anthropogenic sulfur emissions has been estimated to produce net negative radiative forcing on the order of -0.3 W/m^2 (IPCC, 2021), demonstrating that sulfur-derived aerosols influence atmospheric radiative balance.

However, the forcing-related values calculated in this study should not be interpreted as direct atmospheric radiative forcing measurements or comprehensive climate-scale forcing simulations. Atmospheric dispersion and radiative processes generally require complex advection–diffusion modeling, meteorological parameter integration, and large-scale atmospheric transport analysis to produce quantitative predictions (Alrammah et al., 2022; Leelóssy et al., 2018). Therefore, the obtained values in this study represent simplified relative environmental indicators derived from theoretical sulfur emission estimations

based on fuel sulfur content and are intended only for comparative interpretation among fuel types rather than quantitative climate prediction (Darwish et al., 2025).

From a regional environmental perspective, fuels characterized by lower sulfur concentrations demonstrate relatively smaller sulfur-related atmospheric influence compared to sulfur-rich fuels (Dudziak et al., 2023). Reduced sulfur content may decrease sulfur dioxide emission potential and limit sulfate aerosol formation, thereby minimizing possible atmospheric and material degradation impacts under sulfur-related environmental exposure conditions (Liu et al., 2025).

When compared with the sulfur-related spatial patterns presented in Figure 3, the relative atmospheric indicator results demonstrate qualitative consistency with observed sulfur anomaly distributions in East Java. The volcanic sector shown in Figure 3(b) exhibits relatively stronger sulfur-related anomalies, particularly within the Malang–Pasuruan and Bromo–Semeru volcanic corridor, which is spatially associated with active volcanic sulfur degassing systems (Carn et al., 2017; Ibrahim et al., 2025). These volcanic

emissions contribute natural geogenic sulfur input capable of increasing regional sulfur background conditions independently of anthropogenic fuel combustion.

In contrast, the urban-industrial sector shown in Figure 3(a) demonstrates relatively moderate and spatially fragmented sulfur-related patterns across Surabaya and Sidoarjo. These spatial sulfur characteristics are interpreted as being associated with anthropogenic emission intensity driven by transportation density, industrial activities, and fuel consumption patterns in urban environments. Similar spatiotemporal emission studies have shown that urban atmospheric pollutant distributions are strongly influenced by human activities, industrial development, traffic density, and emission variability across metropolitan regions (Lou et al., 2025).

The comparison between urban and volcanic regions therefore illustrates a dual-source sulfur system in East Java, where anthropogenic fuel combustion and volcanic degassing jointly contribute to regional sulfur-related environmental characteristics. Sulfur-rich fuels potentially increase localized sulfur-related atmospheric influence, while volcanic systems contribute persistent natural sulfur background conditions that may enhance sulfate aerosol formation processes (Nwankwo & David, 2025).

From an environmental geophysics' perspective, the integration of corrosion behavior, sulfur characterization, simplified atmospheric indicators, and sulfur-related spatial interpretation provides a comparative framework for understanding sulfur-related environmental dynamics in East Java (Granados-Bolaños et al., 2021; Li et al., 2024). Nevertheless, it should be emphasized that the relationship established in this study is qualitative to semi-quantitative and does

not represent direct atmospheric sulfur dispersion modeling or comprehensive radiative transfer simulation. Consequently, the interpretation presented here should be regarded as a supporting environmental assessment approach rather than a direct climate-scale atmospheric evaluation (Nisticò et al., 2025).

Conclusion

This study demonstrates that sulfur content in commercial fuels influences metallic corrosion behavior and contributes to sulfur-related environmental characteristics in East Java. Experimental results show that fuels with higher sulfur concentrations generally produced greater corrosion rates, with diesel fuel exhibiting the highest corrosion intensity ($CR = 1.0300$ mpy), while low-sulfur fuels such as Pertamina and Peralite displayed substantially lower corrosion behavior. These findings support the interpretation that sulfur-bearing compounds contribute to electrochemical degradation processes on iron surfaces under sulfur-containing fuel environments.

The integration of sulfur characterization, corrosion measurements, simplified sulfur-related atmospheric indicators, and spatial environmental interpretation suggests that East Java represents a mixed sulfur system influenced by both anthropogenic fuel combustion and geogenic volcanic emissions (Ibrahim et al., 2025). Urban-industrial regions such as Surabaya and Sidoarjo are primarily associated with transportation and industrial sulfur emissions, whereas volcanic regions surrounding Malang and Pasuruan demonstrate additional sulfur influence related to volcanic degassing activity. The qualitative consistency between laboratory corrosion behavior and sulfur-related spatial patterns indicates that corrosion indicators may have potential applicability as supporting physicochemical proxies for comparative sulfur-related environmental assessment (Gao et al., 2022). In addition,

fuels characterized by lower sulfur concentrations demonstrated relatively smaller sulfur-related atmospheric implications, suggesting the importance of fuel sulfur reduction for minimizing environmental and material degradation effects. Nevertheless, this study represents a qualitative to semi-quantitative environmental assessment approach and does not constitute direct atmospheric sulfur dispersion modeling or comprehensive radiative transfer analysis (Haywood & Boucher, 2021). Future studies integrating direct atmospheric SO₂ observations, satellite-based monitoring, and atmospheric transport modeling are recommended to improve understanding of sulfur-related environmental dynamics in mixed urban–volcanic systems.

Acknowledgements

The authors would like to express their sincere gratitude to the lecturers of Physics Departmen, laboratory assistants, and technical staff of the Oil and Gas Laboratory (Laboratorium Migas) Cepu for their valuable support in fuel characterization, laboratory measurements, and data acquisition that significantly contributed to this research. The authors also gratefully acknowledge all supporting institutions, colleagues, and field assistants whose guidance, technical assistance, and encouragement contributed to the successful completion of this study. Special appreciation is extended to the reviewers and editors for their constructive comments, valuable suggestions, and insightful feedback, which significantly improved the scientific quality and clarity of this manuscript.

Author Contribution

Yuansyah Dhaniar Ramadhan: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing original draft. Muhammad Tegar Rahmawan: Investigation, Data curation, Validation.

Ayunita Haq: Methodology, Investigation, Formal analysis. Nayla Rohmatul Maulidiyah: Investigation, Data curation. Daryll Alfaraby Noorlaksono: Software, Data curation, Visualization. Arie Realita: Conceptualization, Supervision, Writing, Review & Editing, Project administration. Madlazim: Methodology, Formal analysis, Writing, Review & Editing, Supervision. Muhammad Nurul Fahmi: Conceptualization methodology, Supervision. Adedio Daniel Situmeang: Spatial analysis, Sulfur distribution map interpretation, Visualization. Zunan Faruq Ardiansyah: Mapping visualization, Spatial imaging assistance, GIS support. All authors have read and approved the final version of the manuscript and agree to be accountable for the content of the work.

Conflict of Interest

The authors declare no conflict of interest

References

- Alrammah, I., Saeed, I. M. M., Mhareb, M. H. A., & Alotiby, M. (2022). Atmospheric dispersion modeling and radiological environmental impact assessment for normal operation of a proposed pressurized water reactor in the eastern coast of Saudi Arabia. *Progress in Nuclear Energy*, 145, 104121. <https://doi.org/10.1016/j.pnucene.2022.104121>
- Anastasopoulos, A. T., Hopke, P. K., Sofowote, U. M., Mooibroek, D., Zhang, J. J. Y., Rouleau, M., Peng, H., & Sundar, N. (2023). Evaluating the effectiveness of low-sulphur marine fuel regulations at improving urban ambient PM_{2.5} air quality: Source apportionment of PM_{2.5} at Canadian Atlantic and Pacific coast cities with implementation of the North American Emissions Control Area. *Science of The Total Environment*, 904, 166965. <https://doi.org/10.1016/j.scitotenv.2023.166965>

- 23.166965
- ASTM International. (2021). *ASTM G31-21: Standard Guide for Laboratory Immersion Corrosion Testing of Metals*. ASTM International. <https://doi.org/10.1520/G0031-21>
- Bani, P., Oppenheimer, C., Tsanev, V., Scaillet, B., Primulayana, S., Saiing, U. B., Alfianti, H., & Marlia, M. (2022). Modest volcanic SO₂ emissions from the Indonesian archipelago. *Nature Communications*, 13, 3366. <https://doi.org/10.1038/s41467-022-31043-7>
- Berghuis, H. W. K., van Kolfschoten, T., Adhityatama, S., Troelstra, S. R., Noerwidi, S., Suriyanto, R. A., Wibowo, U. P., Pop, E., Kurniawan, I., Hilgen, S. L., Veldkamp, A., & Joordens, J. C. A. (2022). The eastern Kendeng Hills (Java, Indonesia) and the hominin-bearing beds of Mojokerto, a re-interpretation. *Quaternary Science Reviews*, 294, 107716. <https://doi.org/10.1016/j.quascirev.2022.107692>
- Blessing, M., Lerouge, C., Gal, F., Lahfid, A., Fléhoc, C., & Kloppmann, W. (2025). Geogenic greenhouse gas emissions and shale weathering: lessons learned from an alpine “eternal flame”. *Science of The Total Environment*, 987, 179799. <https://doi.org/10.1016/j.scitotenv.2025.179799>
- Burns, D. A., Aherne, J., Gay, D. A., & Lehmann, C. M. B. (2016). Acid rain and its environmental effects: Recent scientific advances. *Atmospheric Environment*, 146, 1–4. <https://doi.org/10.1016/j.atmosenv.2016.10.019>
- Cao, X., Nan, F., Zhang, J., Chen, L., Gao, H., & He, W. (2023). Effect of sulfuric residual acid on the physicochemical properties, thermal behavior, and decomposition kinetics of nitrocellulose. *Thermochimica Acta*, 729, 179605. <https://doi.org/10.1016/j.tca.2023.179605>
- Carn, S. A., Fioletov, V. E., McLinden, C. A., Li, C., & Krotkov, N. A. (2017). A decade of global volcanic SO₂ emissions measured from space. *Scientific Reports*, 7, 44095. <https://doi.org/10.1038/srep44095>
- Crippa, M., Solazzo, E., Huang, G., Guizzardi, D., Koffi, E., Muntean, M., Schieberle, C., Friedrich, R., & Janssens-Maenhout, G. (2020). High-resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Scientific Data*, 7, 121. <https://doi.org/10.1038/s41597-020-0462-2>
- Darwish, H., AlHmoud, I. W., Turlapaty, A. C., & Gokaraju, B. (2025). Predicting the future climate: Integrating renewable energy and machine learning to address temperature and GHG emissions. *Energy Reports*, 14, 2399–2419. <https://doi.org/10.1016/j.egyr.2025.09.004>
- Dudziak, T., Rząd, E., Morgiel, J., Kirchner, A., Polczyk, T., Moskal, G., Klöden, B., Weißgärber, T., Toboła, D., & Wójcicki, M. (2023). Influence of a rich sulphur atmosphere on the phase development and kinetic behaviour of differentially processed RNT650 γ-TiAl alloys. *Journal of Materials Research and Technology*, 23, 1753–1760. <https://doi.org/10.1016/j.jmrt.2023.01.120>
- Erfani, E., & Mitchell, D. L. (2026). Constraining a Radiative Transfer Model with Satellite Retrievals: Contrasts between cirrus formed via homogeneous and heterogeneous freezing and their implications for cirrus cloud thinning. *Atmospheric Chemistry and Physics*, 26(1), 523–546. <https://doi.org/10.5194/acp-26-523-2026>

- Firoozi, A. A., & Firoozi, A. A. (2024). Water erosion processes: Mechanisms, impact, and management strategies. *Results in Engineering*, 24, 103237. <https://doi.org/10.1016/j.rineng.2024.103237>
- Gao, J., Jia, S., Xu, Q., Wu, S., & Sui, H. (2022). Spontaneous combustion mechanism and influencing factors of sulfur corrosion products in petroleum refining equipment. *American Journal of Applied and Industrial Chemistry*, 6(2), 29–37. <https://www.sciencepublishinggroup.com/article/10.11648/j.ajaic.20220602.12>
- Granados-Bolaños, S., Quesada-Román, A., & Alvarado, G. E. (2021). Low-cost UAV applications in dynamic tropical volcanic landforms. *Journal of Volcanology and Geothermal Research*, 410, 107143. <https://doi.org/10.1016/j.jvolgeores.2020.107143>
- Han, X., Wang, Y., Peng, S., & Zhang, H. (2019). Oxidation behavior of FeCrAl-coated Zry-4 under high-temperature steam environment. *Corrosion Science*, 149, 45–53. <https://doi.org/10.1016/j.corsci.2019.01.004>
- Haywood, J., & Boucher, O. (2000). Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. *Reviews of Geophysics*, 38(4), 513–543. <https://doi.org/10.1029/1999RG000078>
- Henley, R. W., & Fischer, T. P. (2021). Sulfur sequestration and redox equilibria in volcanic gases. *Journal of Volcanology and Geothermal Research*, 414, 107181. <https://doi.org/10.1016/j.jvolgeores.2021.107181>
- Ibrahim, K., Bijaksana, S., Abdurrachman, M., Sahara, D. P., Suryanata, P. B., Zulaikah, S., Wirawan, R., Harlianti, U., Widagdo, T. A. M., Fajar, S. J., Noya, Y., & Suandayani, N. K. T. (2025). Contrasting magmatic structures and tectonic controls from integrated gravity and magnetic data in the Bromo–Tengger–Semeru complex and the Lamongan Volcanic Field, East Java, Indonesia. *Journal of Volcanology and Geothermal Research*, 468, 108455. <https://doi.org/10.1016/j.jvolgeores.2025.108455>
- IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- Kusumaningtyas, S. D. A., Tonokura, K., Aldrian, E., Giles, D. M., Holben, B. N., Gunawan, D., Lestari, P., & Iriana, W. (2022). Aerosols optical and radiative properties in Indonesia based on AERONET version 3. *Atmospheric Environment*, 282, 119174. <https://doi.org/10.1016/j.atmosenv.2022.119174>
- Leelössy, Á., Lagzi, I., Kovács, A., & Mészáros, R. (2018). A review of numerical models to predict the atmospheric dispersion of radionuclides. *Journal of Environmental Radioactivity*, 182, 20–33. <https://doi.org/10.1016/j.jenvrad.2017.11.009>
- Li, X., Jia, J., Liu, C., Xu, Q., & Fan, X. (2024). Characterization of corrosion products formed on Q235 carbon steel and T2 copper in the Antarctic atmosphere. *Journal of Materials Research and Technology*, 29, 364–375. <https://doi.org/10.1016/j.jmrt.2024.01.063>
- Liu, Z., Dai, Z., Song, X., Yang, L., Yu, F., & Chen, S. (2025) Swelling and chemical degradation of sulfur-bearing fillers in high-speed railway subgrade: Effect of pH on ion release and material deterioration. *Transportation Geotechnics*, 51,

101546.
<https://doi.org/10.1016/j.trgeo.2025.101546>
- Lou, Y., Chen, Y., Chen, X., & Li, R. (2025). Spatiotemporal estimates of anthropogenic NO_x emissions across China during 2015–2022 using a deep learning model. *Journal of Hazardous Materials*, 487, 137308. <https://doi.org/10.1016/j.jhazmat.2025.137308>.
- Loveridge, J. R., Fu, D., & Di Girolamo, L. (2025). Validating machine learning retrievals of the cloud-top droplet effective radius over oceans that account for 3D radiative transfer effects. *Journal of Geophysical Research: Atmospheres*, 130(23), e2025JD044317. <https://doi.org/10.1029/2025JD044317>
- Ministry of Home Affairs & Population and Civil Registration Department of Jakarta (2022). *Population density map of Java and Madura by subdistrict (kelurahan) (2022)*.
- Moktikanana, M. L. A., Ohba, T., Harijoko, A., Wibowo, H. E., Gurusinga, M. A., & Cahyani, S. M. (2024). Geology, chronology, and temporal evolution of basaltic to dacitic magma system in Raung volcano, East Java, Indonesia. *Journal of Volcanology and Geothermal Research*, 452, 108126. <https://doi.org/10.1016/j.jvolgeores.2024.108126>
- Nguyen, X. P., & Vu, H. N. (2019). Corrosion of the metal parts of diesel engines in biodiesel-based fuels. *International Journal of Renewable Energy Development*, 8(2), 119-132. <https://doi.org/10.14710/ijred.8.2.119-132>
- Nisticò, F., Messina, G., Quercioli, C., Errico, S., Fanti, E., Frilli, E., Postiglione, M., De Luca, A., D'Urso, A., & Nante, N. (2025). Can “fine scale” data on air pollution be an evaluation tool for public health professionals? *Atmospheric Pollution Research*, 16(6), 102487. <https://doi.org/10.1016/j.apr.2025.102487>
- Nwankwo, N. E., & David, J. C. (2025). A review of sulfur-containing compounds of natural origin with insights into their pharmacological and toxicological impacts. *Discover Chemistry*, 2, 207. <https://doi.org/10.1007/s44371-025-00286-w>
- Ottosson, M., Boman, M., Berastegui, P., Andersson, Y., Hahlin, M., Korvela, M., & Berger, R. (2018). Response to the comments by P. Szakálos, T. Åkermark and C. Leygraf on the paper “Copper in ultrapure water, a scientific issue under debate”. *Corrosion Science*, 142, 308–311. <https://doi.org/10.1016/j.corsci.2018.02.003>
- Reddy, I. N., Veerla, S. C., Bhargav, A., Dhanasekar, M., Shim, J., & Bai, C. (2025). Investigating the impact of sulfate (SO₄²⁻) and hydroxide (OH⁻) ions on photocurrent density and reaction kinetics in WO₃/FeWO₄ pyramid structures under illumination for electrochemical applications. *Journal of Alloys and Compounds*, 1032, 181203. <https://doi.org/10.1016/j.jallcom.2025.181203>
- Schmitz, M., & Linderholm, C. (2018). Chemical looping combustion of biomass in 10- and 100-kW pilots – Analysis of conversion and lifetime using a sintered manganese ore. *Fuel*, 231, 73–84. <https://doi.org/10.1016/j.fuel.2018.05.071>
- Seinfeld, J. H., & Pandis, S. N. (2016). *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change* (3rd ed.). Wiley. <https://www.wiley.com/en-gb/Atmospheric+Chemistry+and+Physics%3A+From+Air+Pollution+to+Climate+Change%2C+3rd+Edition-p-9781118947401>

- Skoog, D. A., Holler, F. J., & Crouch, S. R. (2017). *Principles of Instrumental Analysis* (6th ed.). Cengage Learning.
- United Nations. (2022). *World Urbanization Prospects: The 2022 Revision*. Department of Economic and Social Affairs, Population Division. United Nations, New York.
- van Bemmelen, R. W. (1949). *The Geology of Indonesia*. Government Printing Office.
- Wandono, W., Ramdhan, M., Aulia, A. N., Pangestu, A. B., Hidayat, E., Syuhada, S., Widiyantoro, S., Rawlinson, N., Anggono, T., Pranata, B., Mukti, M. M., & Maulana, M. P. (2025). Seismic velocity structure beneath the western Java region, Indonesia, from local earthquake tomography. *Journal of Volcanology and Geothermal Research*, 468, 108472. <https://doi.org/10.1016/j.jvolgeores.2025.108472>
- Wang, C., Luo, A., Qu, S., Liang, X., Xiao, B., Mu, W., Wang, Y., & Yu, R. (2024). Anthropogenic processes drive spatiotemporal variability of sulfate in groundwater from a multi-aquifer system: Dilution caused by mine drainage. *Journal of Contaminant Hydrology*, 264, 104358. <https://doi.org/10.1016/j.jconhyd.2024.104358>
- World Bank. (2023). *Indonesia Economic Prospects: Urbanization and Infrastructure Development*. World Bank.
- World Health Organization. (2021). *WHO Global Air Quality Guidelines*. World Health Organization, Geneva.