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Toxic natural pollution at Ijen crater volcano: Environmental characteristics and health risk assessment

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ABSTRACT

The Ijen crater volcano (ICV) is one of the active volcanoes with unique environmental conditions; it is the largest lake in the world with the most extreme acidity and a blue fire phenomenon and releases toxic volcanic gases, including dangerous sulfur dioxide (SO_2). It has an impact on the environment and ecosystem. This research aimed to investigate the blue fire phenomena and toxic gas SO_2 and characterize the environmental conditions and health effects of the ICV. The method used in this research involved carrying out an SO_2 concentration using an impinger in 32-point sampling around the Inje crater volcano. The environment was characterized based on self-observation, station observation, interviews, and reliable literature data. The health effect was measured based on the threshold level value based on local and global regulations. This research shows that the characteristics of the ICV include a crater lake with a depth of up to 200 m and a diameter of ± 900 m with pH values less than 1. Then, the source of SO_2 comes from the reaction of magma with volcanic gas. the blue fire phenomenon, which occurs in certain situations, frequently adds to the natural wonder of the ICV. In addition, the distribution of SO_2 concentrations ranges from 480 to 6960 ppb. Next, almost the Hazard Quotion (HQ) > 1 every point sampling. This means that the SO_2 concentration and HQ exceed the threshold value affecting human activities.

1. Introduction

The Ijen crater volcano (ICV), located in East Java, Indonesia, is one of the volcanic sites that has received international recognition from UNESCO (United Nations Educational, Scientific, and Cultural Organization) as part of the "Ijen Biosphere Reserve" [1]. This recognition was given for the uniqueness of the ecosystem and biodiversity in this area. The ICV Biosphere Reserve covers a diverse geological area with unique water systems and wildlife [2]. This area is also famous for its extraordinary natural phenomenon, namely the "Crater Lake and Blue Fire."

The blue fire phenomenon in the Ijen Crater results from the combustion of sulfur gas (SO_2) that comes from volcanic cracks at high temperatures and reacts with oxygen in the air. The sulfur gas that comes out of the crater has a temperature that can reach more than 600°C. At this temperature, the sulfur gas that comes out will undergo oxidation when it comes into contact with oxygen in the atmosphere, and the chemical reaction produces bright blue light. This process can only occur in very specific environmental conditions, including high temperatures, sufficient concentrations of sulfur gas, and adequate oxygen levels in the air. This blue fire can only be observed at night because its dim light is not visible in direct sunlight. This phenomenon can only be found in two locations worldwide, namely the Ijen Crater in Indonesia and Iceland [3,4]. However, behind its beauty, sulfur dioxide (SO_2) gas emissions from volcanic activity in the Ijen Crater have serious environmental and human health risks.

Sulfur dioxide (SO_2) gas is produced from volcanic activity, continuously releasing large emissions from the active crater. The main source of SO_2 in ICV comes from magma activity below the surface that produces volcanic gas and is released through fumaroles around the crater. High concentrations of SO_2 in the air can adversely affect the environment and human health, especially in individuals who are exposed for a long time [5,6]. Short-term exposure to SO_2 can irritate the respiratory

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tract, eyes, and skin, while long-term exposure can increase the risk of chronic lung disease and cardiovascular disorders [7–9].

With significant SO_2 gas emissions and ongoing volcanic activity, a deeper understanding of the distribution of toxic gases, environmental characteristics, and health impacts is very important. This study aims to analyze the environmental characteristics of ICV, focusing on SO_2 emissions, their distribution in the air, and the health risks they pose. With this approach, it is hoped that the research can contribute to mitigating risks, protecting the environment, and improving safety and health in the ICV area.

2. Method

2.1. Area study and SO_2 sampling

This research was conducted at the crater of ICV, located on the border of the Banyuwangi and Bondowoso Regencies, East Java, Indonesia. The identification of SO_2 sources was carried out by making direct observations by identifying sources of sulfur and SO_2 gas release points. The SO_2 was carried out based on random sampling that covered the ICV with total 32-point sampling. The point sampling can be seen at Fig. 1.

The impinger instrument is used to capture SO_2 gas in the air through the principle of chemical absorption. Air containing SO_2 is sucked through a vacuum pump and flowed into an impinger bottle containing 1 mol of sulfuric acid (H_2SO_4) absorbent solution for 1 hour with an airflow rate of 1 liter per minute [10,11]. When the air passes through the absorbent solution, SO_2 reacts with the solution and is chemically bound to be further analyzed in the laboratory using a Spectrophotometer to determine its concentration. The distance of each point is around 100 – 500 m. The sampling points were in the ICV environment, where the sampling points were taken based on the paths commonly traveled by sulfur mine workers and tourists/tourists. Coordinates were recorded for each sampling point. In contrast, climate data on temperature, wind direction, and rainfall were taken from the climate measurement station during the sampling period. SO_2 sampling was carried out during the dry season, August 13–25, 2023 [12].

2.2. Characteristics of ICV

The comprehensive characterization of ICV was meticulously conducted, encompassing geological and historical aspects, geochemistry, caldera lake conditions, existing sulfur conditions, and the history of volcanic activity. These aspects were gathered through self-observation, observation station data, and a rigorous review of various literature sources, ensuring the reliability and depth of the information.

2.3. Analyze sulfur dioxide and distribution

The SO_2 emission distribution map was created using QGIS software with the Inverse Distance Weighted (IDW) interpolation method. This method was chosen because of its ability to estimate spatial distribution based on observation point data by considering the spatial proximity between data points. The interpolation results were then visualized in the form of a map to provide a clearer picture of the SO_2 emission distribution pattern in the ICV. The resulting spatial map allows for the identification of both high- and low-concentration areas, providing critical insights into the environmental distribution of SO_2, which is vital for further analysis [13].

The SO_2 distribution map, a key outcome of our research, was instrumental in assessing the extent of SO_2 exposure. It particularly highlighted areas of significant risk to sulfur miners and tourists, where elevated SO_2 levels may exceed occupational or environmental health standards. This map is not just a tool for safety guidelines and precautions, but a crucial resource for policymakers and site managers to manage the crater's accessibility and ensure adequate protection measures.

Verification and validation of the SO_2 distribution model in Ijen Crater were carried out to ensure the accuracy and reliability of the results displayed. The verification process begins by checking the input

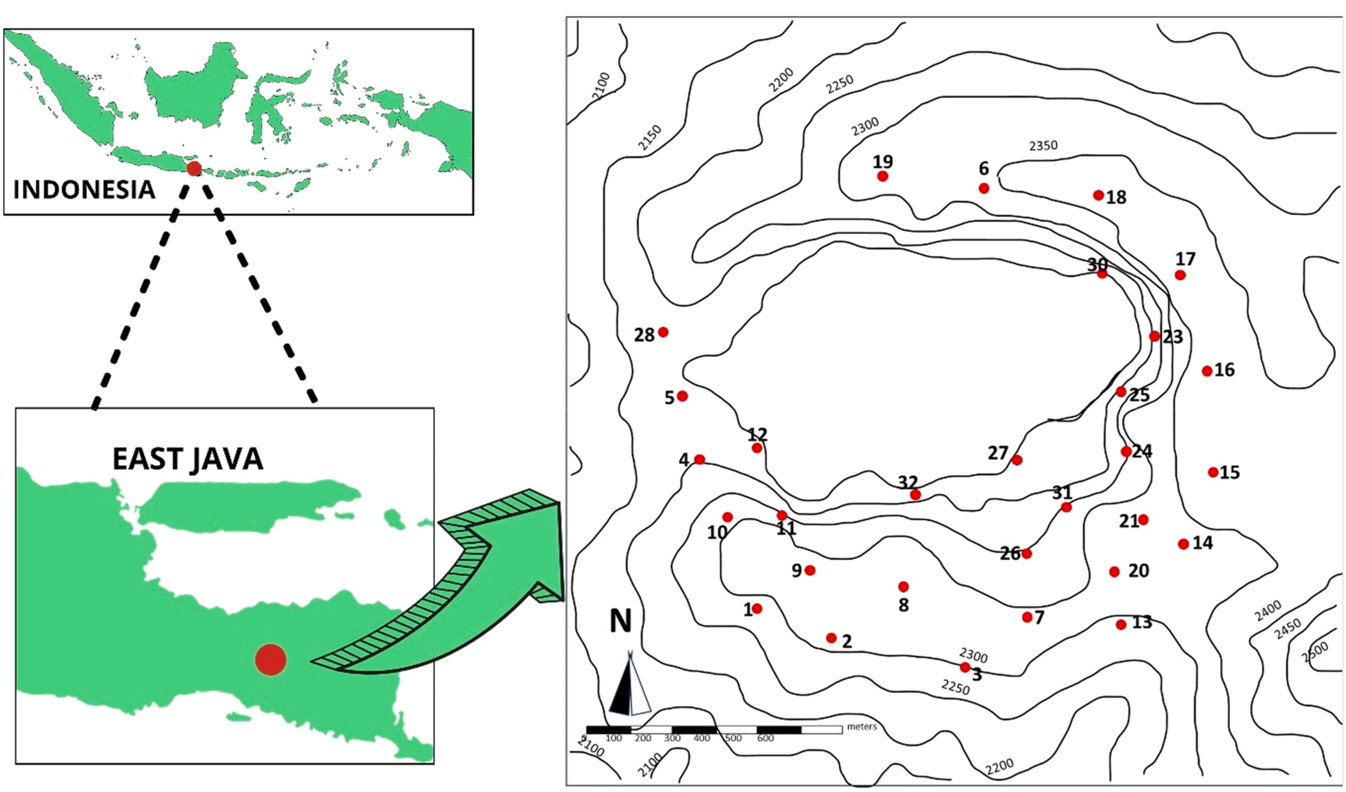

Fig. 1. Location of sampling point.

data used, such as the results of SO_2 concentration measurements at each observation point, and ensuring their compliance with geospatial parameters. Verification is carried out by checking the accuracy of the input data, including the consistency of SO_2 measurement results at each observation point and the interpolation method used in QGIS.

2.4. Health effects analyze

The health effects were carried out to measure the acute effect of SO_2 exposure on the tourist's activities. The health effects were enriched by evaluated SO_2 concentrations in the ICV area by comparing them with local and international threshold limit values (TLVs), including standards from the Occupational Safety and Health Administration (OSHA) [14], the Environmental Protection Agency (EPA) [15], American Conference of Governmental Industrial Hygienists (ACGIH) [16], local regulation of Indonesian [17] and World Health Organization (WHO) [18] the details of standard show in Table 1. These benchmarks helped assess the health risks for tourists and sulfur miners by considering their exposure levels and time spent in high-risk areas. This comprehensive analysis provided insights into the potential health impacts of SO_2 exposure and guided the development of protective measures to ensure environmental sustainability and human safety.

2.5. Health risk assessment

The health risk assessment is calculated based on chronic effects, which include potential long-term SO_2 exposure experienced by workers who have activities in the ICV. The workers that have potential exposure every day are tour guides, trolly porters, and sulfur mine workers. The calculation focuses on specific locations where these individuals carry out their main activities. The sites analyzed health risks with a total of 32 points (Fig. 1) but only focused discussion on points 7, 8, 13, and 20, which serve as resting areas for workers and checkpoints for climbing tourists. Additionally, points 15, 16, 17, and 18 are popular sunrise viewing spots for tourists, while points 27 and 32 are sulfur mining work areas. The health risk assessment uses [Eq. 1 and Eq. 2], evaluating the potential exposure risk over durations from one hour up to eight hours. This analysis helps determine the safe exposure time limits.

$$I_{inhalatin} = \frac{C.R.T_e.f_e.D_t}{W_b.T_{avg}} \quad (1)$$

Note:
$I_{inhalation}$ = Intake inhalation (I inh) (mg/kg/day)
C = Concentration (mg/m^3)
R = inhalation rate (0.83 m^3/hr)
e = time of exposure (hr/day)
Fe = Frequency of exposure (days/year)
W_b = Weight of body (kg)
D_t = Duration time, real time or 30 years projection
T_{avg} = Time average period (30 years, 365 days/year for noncarcinogenic substances)

Next, the hazard quotient from SO_2 exposure is calculated using Eq. 2.

$$HQ = \frac{I_{inhalation}}{Rfd\ or\ Rfc} \quad (2)$$

Table 1
Standard level value based on regulation.

Standard level value	Value	Unit	Ref
EPA: national ambient air quality standard (NAAQS)	75	ppb	[15]
Indonesia	900	ppb	[17]
ACGIH	250	ppb	[16]
OSHA	2000	ppb	[14]
WHO	40	µg/m^3	[18]

Note
HQ = Hazard Quotient
RfC = Reference concentration (mg/kg/day)
Rfd = Reference of dose (mg/kg/day)

The health risk assessment for SO_2 shows that an HQ value of less than 1 suggests no health impact, while an HQ value of 1 or greater indicates that the exposure may pose a health risk.

In addition to conducting health risk assessments, weather data collection was conducted for a full month to understand weather patterns and trends in the Ijen Crater area. This data includes parameters such as wind direction, wind speed, air temperature, humidity, and rainfall. Weather conditions play an important role in determining the distribution and spread of sulfur dioxide (SO_2) gas around the mining area and its surroundings.

3. Results and discussion

3.1. Environmental and geological conditions of ICV

ICV has the characteristics of young quartier rock soil that forms regosol soil, while the tyrosol type is formed from ash/sand rock, intermediate to sandy tuff, weak structure, yellow in color with steep topology. This indicates that the soil structure has yet to fully develop or is also called young volcanic soil. This is influenced by volcanic activity, rainfall, and dominant vegetation [19,20]. The vegetation seen on the mountain peak at an altitude of 3000 to 4000 m above sea level is only a little vegetation of shrubs and bushes. While at an altitude of 1000 to 2500 m above sea level in the form of pine forests and shrubs and bushes [21].

The ICV, an active volcano that grew after the formation of the Ijen Caldera, has an altitude of 2443 m above sea level. It is one of several volcanoes located in the Pleistocene Ijen caldera [21]. The ICV's location along the front of the Sunda volcanic arc and its relation to the subduction of the Indo-Australian and Eurasian plates [22] further highlight its geological importance. The cone formation process, characterized by strata of lava, lapilli, scoria, and ash with different compositions from basalt to andesite, adds to its geological significance. The lava flow descending northward toward the outside of the caldera, marked by the formation of a waterfall in the valley, is a testament to its geological importance [23].

According to Sitorus [24], the Ijen crater formed 70,000 years ago. The ancient ICV erupted with a powerful eruption that gave rise to a caldera with a diameter of more than 15 km, the largest caldera on Java (Fig. 2). A *caldera* is a vast volcanic depression formed by the roof collapse of a magma reservoir and increased in diameter by further eruptions [25].

After the caldera's formation, volcanism continued for approximately 50,000 years, creating 17 new volcanoes of varying sizes inside the Ijen and five outside the caldera. Of the 22 emerged volcanoes, 12 can be categorized as monogenetic volcanoes, while the others are polygenetic ones. The volcanic activity in the caldera section involved lava flows, pyroclastic deposits, and lahars. Despite the reduced volcanic activity, landslides from steep caldera walls produced lava deposits. These deposits then harden, preventing water from percolating. North of the caldera, Blawan lies close to the north wall and is the lowest point in the caldera, forming a lake known as Blawan Lake. However, erosion and sedimentation continue to occur within and around the caldera. It is influenced by the geological structure, particularly the Blawan fault, which moves from north to south. As a result, the northern caldera wall, especially in Blawan, is cut by the fault, causing the lake to dry up and water to flow through the Banyuputih River [5]. Currently, within the Ijen caldera, only seven mountains have been categorized: ICV, Mount Pawean, Mount Merapo, Mount Rante, Mount Jampit, Mount Suket, and Mount Raung. Currently, of the seven mountains, only two are active, namely,the ICV and Mount Raung.

The physiography of the Ijen caldera is generally circular (see Fig. 2),

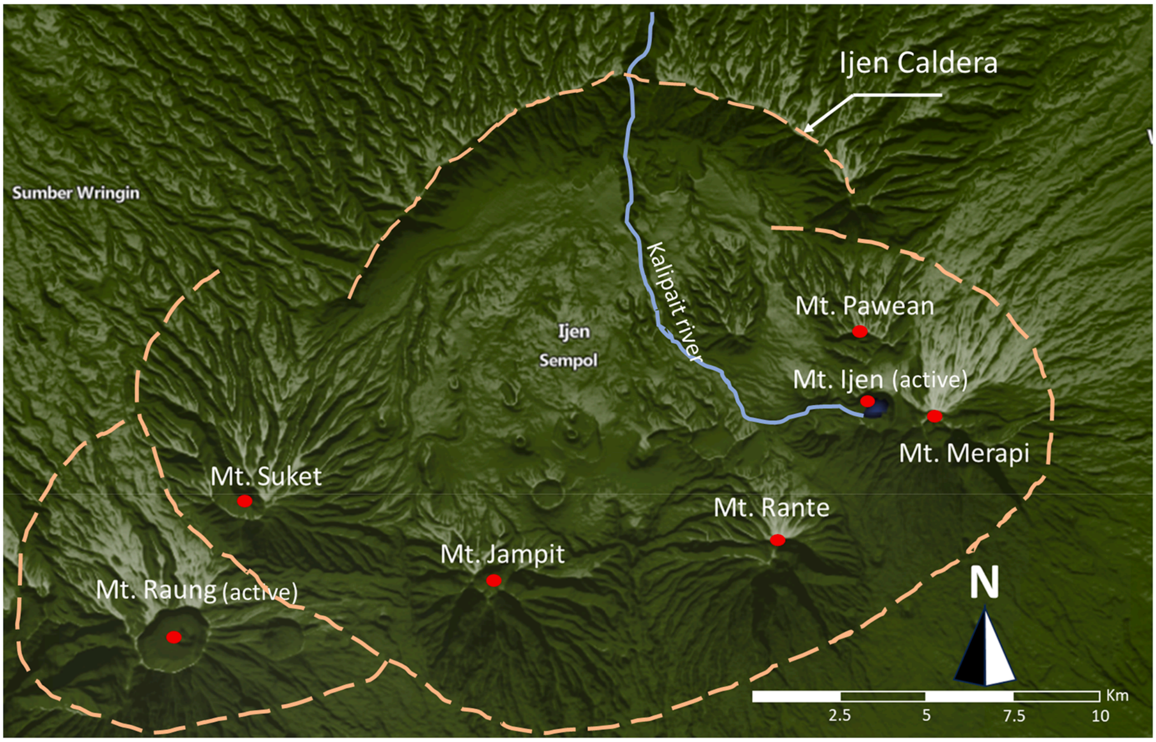

Fig. 2. The caldera of the ancient ICV.

which is an indication of collapse. In addition to collapse, the formation of circles, both intact and partially forming like a horseshoe, is also influenced by tectonic or volcano-tectonic factors, followed by a variety of accompanying lithologies and the emergence of new monogenetic eruption centres, the form of basaltic lavas, dacitic lavas, domes and pumice cones [26].

3.2. Crater lake Ijen volcano

Lake Ijen is an international destination unique for its natural beauty and blue crater, which contains highly acidic sulfuric acid (Fig. 3). The lake experienced some volcanic activity. Volcanic eruptions occur on a volcano where magma and rock material burst violently out of the earth [27]. Then, volcanic material, such as ash, rocks, and pyroclastic material, accumulated around the crater. This process results in the formation of steep crater walls. Rainwater that falls into a crater and is contaminated by volcanic gases such as sulfur in the atmosphere can produce acidic lakes [28]. Sulfur in the crater can oxidize and form sulfuric acid compounds, giving the lake its distinctive color. Continuous rainwater replenishes the lake in the crater through the hydrological cycle. Lakes are also thought to receive water from springs in or around mountains. Chemical reactions between volcanic gases and water in the crater may also play a role in the formation of the lake and the chemical properties of the water [29]; this lake flows upstream of the Kalipahit River, which has a length of approximately 8 km and empties into the Belawan waterfall, which is located in the northern direction of the ICV.

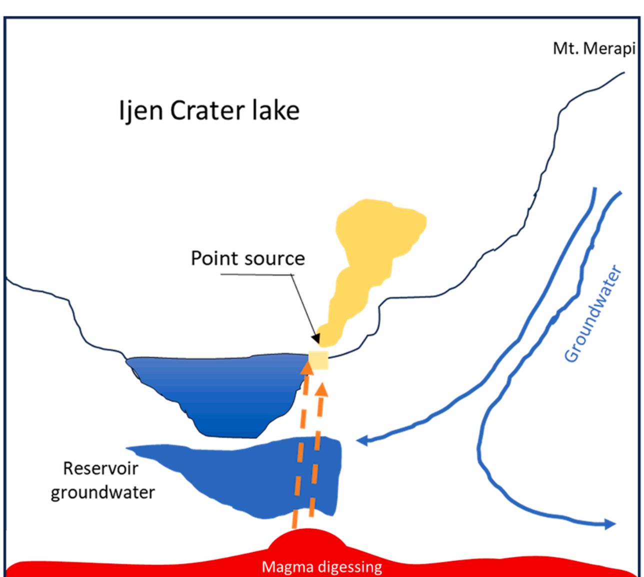

Fig. 3. The ICV underground schematic system.

The shape of Ijen Crater Lake is oblong, resembling an ellipse. The lake water discharge area is located west of the Kalipait River headwaters. Ijen Crater Lake has an area of 45 ha, a diameter of 950 m, and a depth of up to 200 m [30].

The lake's bathymetry is characterized by an inverted cone where the cross-section of the lake becomes deeper. To date, the depth profile of ICV Lake has been obtained only twice by researchers who have published the results. The first was conducted by Newmann Van Padang [31]. Takano et al. (2004) [32] used a chart strip recorder, and the results were generally similar. Delmelle (1995) reported that the ICV is different from other active crater lakes where the Ijen Crater Lake has been quiet; therefore, although it sometimes shows volcanic activity, the lake remains stable due to the dissipation of heat and gas from a stable magma [33].

Due to the uniqueness of Lake Ijen Volcano, several researchers have detected its chemical content. Ijen Volcano Crater Lake has a very acidic chemical composition with a pH < 0.5, while the heavy metal content and other chemical compositions can be found in Table 2. The highest to lowest elemental composition of Ijen Lake is Cl > Al > Fe > K > Na > Ca > Mg > Si > Mn > Sr > V > Ti > Pb > Zn > Rb > As > Sc > Y > Ga > Ba > Li > Co > Cu > Cd.

Heavy metal concentration data in Ijen Crater Lake show significant

Table 2
Water properties and composition of Lake Ijen.

Year	1990 (mg/l) [34]	1993 (mg/l) [27]	1996 (mg/l) [27]	1998 (mg/l) [32]	2000 (mg/l) [35]	2009 (mg/l) [23]	2014 (mg/l) [36]	2016 (mg/l) [30]
pH	0.18	0.02	-	-	0.17	0.45	0.75	-
Li	-	-	-	0.248	-	0.69	-	0.9
Na	585	-	-	1410	1025	1030	591	1141
Mg	-	-	-	787	-	682	317	686
Al	5490	-	5413	4600	5150	5596	3006	5792
Si	-	-	-	44.1	-	54	-	56
K	1702	-	-	1250	1113	1147	825	1312
Ca	1105	-	968	750	690	769	552	807
Cl	-	21218	22630	-	23380	22099	20934	-
Sc	-	-	-	1	-	-	-	1.2
Ti	-	-	-	10.1	-	7	-	8
V	-	-	-	12.3	-	8.1	-	11
Mn	-	-	-	54.9	-	40	-	45
Fe	1862	-	2063	2540	1977	2069	1495	2384
Co	-	-	-	395	-	0.49	-	-
Cu	0.4	-	-	0.299	0.19	0.35	-	-
Zn	4	-	-	0.74	4.8	5.1	-	5
Ga	-	-	-	1.007	-	-	-	0.9
As	-	-	-	1.51	-	1.6	-	-
Rb	-	-	-	3.84	-	3.8	-	3.8
Sr	-	-	-	15.8	-	15	-	16
Y	-	-	-	1.13	-	-	-	0.95
Cd	-	-	-	0.055	-	0.06	-	-
Ba	-	-	-	0.305	-	1.624	-	-
Pb	-	-	-	0.58	4.9	4.5	-	4.5

variations from year to year, reflecting the geochemical dynamics and volcanic activity in the area. Several elements such as sodium (Na), aluminum (Al), potassium (K), and iron (Fe) have relatively high concentrations, which can be attributed to the leaching process of volcanic rocks by acidic water and the release of materials from hydrothermal activity. For example, the concentration of aluminum (Al) ranged from 3006 mg/l (2014) to 5792 mg/l (2016), while sodium (Na) varied from 585 mg/l (1990) to 1410 mg/l (1998).

The increase in the concentration of these metals is generally influenced by changes in volcanic activity and environmental conditions such as rainfall and hydrothermal flow patterns. In addition, the low pH (as low as 0.02 in 1993) indicates the extreme acidity of the lake water, which allows heavy metals to remain dissolved in the water. Extreme changes were seen in the concentrations of certain metals. For example, sodium (Na) concentrations increased drastically in 1998–1410 mg/l compared to 1990 which was only 585 mg/l. Similarly, aluminum (Al) experienced a significant decrease in 2014–3006 mg/l compared to 2009 which reached 5596 mg/l, before increasing again in 2016. In other elements, potassium (K) showed fluctuations with a significant decrease in 2014 of 825 mg/l, then increased to 1312 mg/l in 2016. Meanwhile, lead (Pb) concentrations peaked in 2000 with a value of 4.9 mg/l, indicating a potential risk of toxicity. These concentration fluctuations can be associated with varying hydrothermal activity and changes in local environmental conditions.

Several toxic metals such as lead (Pb), arsenic (As), and cadmium (Cd) were also detected in varying concentrations. Lead concentration, for example, was recorded at 4.9 mg/l in 2000, indicating a potential toxicity risk to the environment and organisms around the lake. Meanwhile, arsenic (As) content reached 1.6 mg/l in 2009, which is also above the safe limit for surface water. These elements tend to come from volcanic activity and fumarole gas releases that dissolve in the highly acidic lake water.

3.3. SO_2 source identification

Our continuous observations show that Ijen Crater hosts a sulfur gas emission source primarily located in the southeastern part of the mountain. These emission sources, represented by ground fracture points emitting yellowish-white smoke, are a constant feature of the volcano's behavior. The main source of SO_2 in the ICV is the ongoing volcanic activity within the crater, which releases SO_2 gas from the crater's surface through cracks. In addition to surface volcanic activity, sulfur gas can also be released through natural vents from deep within the earth, driven by underground pressures and geological properties that allow gases such as SO_2 to reach the surface through fissures and fractures in the rock.

These fractures are composed of components of the abdomen of the earth. In 2017, Van Hinsberg et al. [30] made a schematic model of the Ijen crater system that identifies the source of the Ijen crater elements where the gas components released by the Ijen crater were H_2O (717 g/kg), CO_2 (210 g/kg), SO_2 (30 g/kg), H_2S (41 g/kg), and N_2 (1.3 g/kg) [30].

The majority of the gas component was H_2O (70 %), which is by the underground system scheme of the ICV, where magma in the core of the ICV first reacted with the groundwater reservoir and then exited through the cracks in the point source fracture. Degassing magma is a source of compounds and chemical elements, such as iron, magnesium, nickel, and copper. The metal compounds commonly found in magma include sulfides, oxides, and silicates [37,38]. The amount of this composition varies depending on the geological conditions in a particular area.

The blue fire phenomenon occurs from these fractures. Blue fire occurs due to the reaction of sulfur gas from within the Earth at a temperature of $\pm$ 600°C, which then reacts with oxygen [39]. This blue fire can only be seen at night. Mine workers utilize this sulfur gas emission source fracture by flowing sulfur vapor and collecting it. The sulfur processing process begins with a pipe attached to the sulfur source, channeling the gas to a reservoir. During this process, the sulfur gas from the crater core is cooled. This process converts sulfur gas into a liquid phase, which then solidifies into a solid. The result of this process is chunks of sulfur rock. These chunks are then picked up by sulfur miners and transported to sulfur collection points.

Not all sulfur emission source fractures can be managed by miners to flow into the solid phase, but many fractures still emit smoke. In addition, workers' pipes also have gaps that cause fumes to escape. Therefore, the amount of SO_2 gas smoke released from this process is still very large as a result of the activity of the crater at the ICV. This underscores the potential risks involved and the urgent need for safety measures in this process.

3.4. SO_2 spatial distribution

The SO_2 distribution at the ICV, as illustrated in Fig. 4, is a fascinating subject of study. The SO_2 concentrations at the 32 sampling points displayed a significant variability, ranging from 480 to 6960 ppb. This variability, which may indicate differences in SO_2 emissions from the Ijen crater source, is a key finding of our research.

High SO_2 concentrations were detected at points 27, 31, and 32. These points are the closest areas to the source of SO_2 emission fractures. In particular, at point 27, at a concentration of 6960 ppb, the distance between the sampling point and the source of fracture emission is ± 10 m, the closest sampling point to the source. On the other hand, points with lower SO_2 concentrations occur at points 1, 2, 3, and 19. Points 1, 2, and 3 are sampling points located behind the wall of the ICV cliff; thus, although the distance between the source and the sampling point is quite close, the SO_2 concentration is low. However, point 19 is the farthest point from the source.

Other points that exhibited high SO_2 concentrations were points 7, 8, and 9, the highest area of the ICV. These points are also where the majority of tourists and workers gather. This is the starting point of the summit of ICV, which features a stunning view of the crater. The potential impact of these high SO_2 concentrations on the health and well-being of the local community is a matter of concern and requires further attention.

The distribution of SO_2 is not haphazard but is significantly influenced by climate and wind direction [40]. The climate data for the August sampling, detailed in Table 3 show relatively stable atmospheric conditions, with daily temperatures between 21°C and 25°C. These temperatures, which are typical for August, are not extreme. Humidity levels are moderate to high, with relative humidity (RH) ranging from 68 % to 84 %, which can affect thermal comfort in the area.

The wind rose diagram in Fig. 5 shows the wind direction and speed pattern in August 2023. The wind most often comes from the south (S) with a frequency of almost 80 %. Wind speed varies, with the dominant speed range between 2 and 3 m/s, as shown by the dominant orange color in the diagram. This diagram also shows that the average wind speed is 2.3871 m/s. There are no windless conditions (calm), with a calm percentage of 0 %. Consistent wind directions from the south (S) play an important role in spreading SO_2 gas to certain areas. The wind speed recorded during the study period also affects the extent to which SO_2 gas can spread in the atmosphere.

Rainfall on most days in August showed dry conditions, with most days recording zero rainfall values. However, some days, such as the 7th, 15th, 18th, and 28th, experienced a slight increase in rainfall, which likely contributed to the temporary decrease in gas concentrations in the air due to the wet deposition process.

3.5. Health effect of SO_2 exposure

The Fig. 6 shows comparison of SO_2 concentration data with TLVs set by various local and international organizations. The data shows that all SO_2 concentration values exceed the TLVs set by the Environmental Protection Agency (EPA) of 75 ppb, with the lowest concentration reaching six times the standard value. When compared to the American Conference of Governmental Industrial Hygienists (ACGIH) standard of 250 ppb, almost all SO_2 concentration values in the data also exceed the TLVs, indicating that exposure at this level still poses a significant health risk, both in the context of the general environment and in the workplace.

Furthermore, when compared to the stricter standard of the

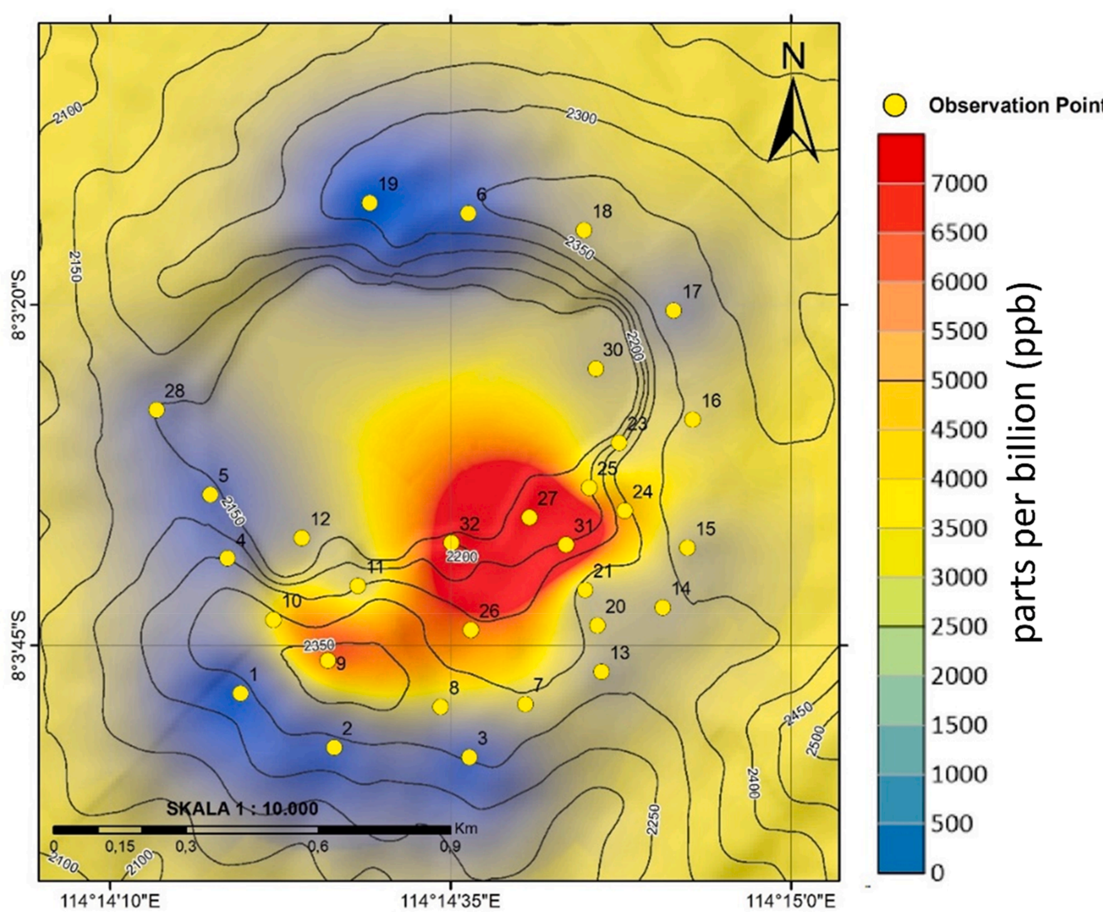

Fig. 4. SO_2 distribution at ICV.

Table 3
Climate data.

Date	temperature rate	RH average	Most wind direction	Rainfall average (mm)
01/08/2023	23.5	83	SE	0
02/08/2023	22.9	80	S	0
03/08/2023	23.9	78	S	0
04/08/2023	23.4	78	W	0
05/08/2023	25	82	S	0
06/08/2023	24.9	84	SW	0
07/08/2023	24.4	82	S	0.6
08/08/2023	21.2	76	S	0
09/08/2023	23	76	SW	0
10/08/2023	21.4	70	W	0
11/08/2023	21	68	W	0
12/08/2023	21.2	69	SE	0
13/08/2023	22	77	S	0
14/08/2023	22	76	S	0
15/08/2023	23.6	80	S	0.2
16/08/2023	24	78	SW	0
17/08/2023	23.3	82	SW	0
18/08/2023	23	81	W	5
19/08/2023	22	79	SE	0
20/08/2023	21.9	83	S	0
21/08/2023	23.6	82	SW	1.8
22/08/2023	23.6	76	S	0
23/08/2023	24	76	S	0
24/08/2023	23.6	79	SW	0
25/08/2023	24	81	S	0.2
26/08/2023	24.7	76	S	0
27/08/2023	23	78	SE	0
28/08/2023	22.9	82	SE	4.4
29/08/2023	23	77	W	0
30/08/2023	23.3	75	S	0
31/08/2023	24.1	76	SW	0

Source: Local station Ijen, Meteorology, Climatology, and Geophysics Agency station, 2023.

Indonesian government, which sets a safe SO_2 TLVs of 150 ppb, all recorded concentration values far exceed this standard, with the highest concentration reaching 46 times greater. In the context of the standard set by the Occupational Safety and Health Administration (OSHA) of 2000 ppb, most concentration values are still below this limit, but five values in the data exceed the OSHA TLVs, indicating the potential risk of acute exposure to workers and tourists. These results underscore the

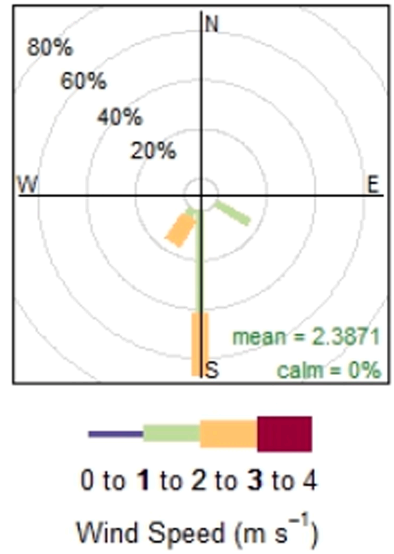

Fig. 5. The climate wind rose.

crucial need for stricter control measures and intensive monitoring. Your role in implementing these measures is vital to protect the public and workers from the negative impacts of exposure to SO_2 at very high concentration levels.

High concentrations of SO_2 present a grave threat to the health of individuals involved in activities around the ICV area, particularly mine workers and tourists. Prolonged exposure to SO_2 can lead to respiratory tract irritation, respiratory issues such as asthma and bronchitis, and even permanent lung damage [41,42]. These potential health risks underscore the importance of understanding and mitigating the dangers posed by volcanic activity.

The EPA categorizes SO_2 exposure into six levels based on concentration. At the "Good" level (0–0.1 ppm), no health concerns exist, while "Moderate" (0.1–0.2 ppm) suggests that unusually sensitive individuals should limit prolonged outdoor activity. At "Unhealthy for Sensitive Groups" (0.2–1.0 ppm), active children, adults, and those with lung conditions like asthma are advised to reduce exertion. As levels rise to "Unhealthy" (1.0–3.0 ppm), people with respiratory conditions should avoid heavy activity outdoors, and others, especially children, should limit exertion. The "Very Unhealthy" range (3.0–5.0 ppm) requires those with lung issues to avoid all outdoor activity, while everyone else should limit physical activity. Emergency conditions at "Hazardous" levels (above 5.0 ppm) pose risks to the entire population, requiring people to stay indoors and possibly evacuate if directed.

Moreover, extraordinary conditions emerged in March 2018; the Center for Volcanology and Geological Hazard Mitigation [43] documented observations of the ICV. The observations noted the presence of toxic gases reaching residential areas from a sudden gas burst in the crater lake, which led to 27 villagers collapsing and being referred to the health center. Frequent phreatic eruptions have also been recorded from the crater lake, including an eruption in 1993 and increased activity in 2011–2012. In 2017 and 2018, three CO_2 and SO_2 outbursts were recorded, causing gas to flow down the Banyu Pait River valley to a distance of more than 7 km. The most recent surge in activity occurred on January 17, 2020, marked by an increase in shallow volcanic earthquakes. These data highlight the urgent need for a comprehensive understanding of seismic and volcanic activity complexity at the Ijen Crater, which is crucial for enhancing disaster risk mitigation strategies [44].

3.6. Health risk assessment

Health risk assessment is a methodology to measure potential health

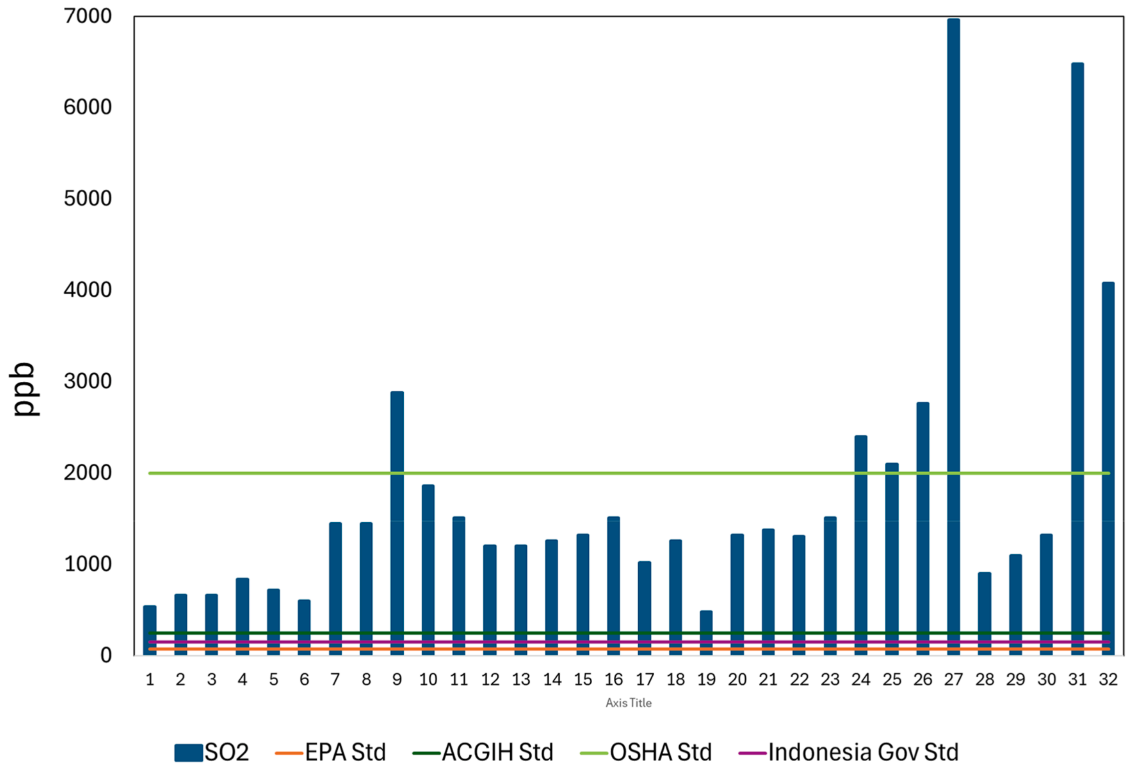

Fig. 6. Threshold limit value (TLVs) of SO_2.

risks arising from long-term exposure [45]. Table 4 shows the components used in calculating the health risk assessment. The SO_2 concentration data came from measurements at 32 sampling points, with an inhalation rate of 0.83 m^3 /hour. The exposure time used was projected for three scenarios, namely exposure for 1 hour, 2 hours, and 3 hours. This approach is used to evaluate the duration of exposure that workers can still tolerate. The frequency of exposure is assumed to be 240 days per year, with a projected exposure duration of 30 years for non-carcinogenic pollutants. In addition, this projection uses an average body weight of 65 kg. The reference concentration (RfC) value is 0.026 mg/kg/day, as issued by the EPA.

The results of I inh and HQ calcualtion show in Table 5. The calculation is based on the estimated duration of exposure per hour, from 1st hour to 8th hour. This calculation aims to determine the duration of exposure that is still safe and acceptable without causing health symptoms, both for workers and tourists.

Based on the Hazard Quotient (HQ) of SO_2 exposure at 32 sampling points, there is a significant variation in the health risks workers and tourists face in the area. Several important areas for workers and tourists, such as points 7, 8, 13, and 20, are rest areas for workers and peak areas for climbing tourists. The HQ values at these points indicate a significant potential for exposure, especially at points 7 and 8, with a value of 3.652 after 3 hours of exposure. This HQ value exceeds the safe threshold (HQ > 1), indicating a real health risk from long-term exposure. Workers often in this area may face health risks due to higher exposure to SO_2. In addition, areas that are popular as places to watch the sunrise, such as points 15, 16, 17, and 18, also show HQ values above 3.5 after 3 hours of exposure. Tourists who frequently visit this area, especially in the morning, may be exposed to significant levels of SO_2, especially if they are in the area for a long time. The HQ value at point 16 reached 3.807, indicating a serious risk of exposure. Tourists who spend hours in this place to enjoy the scenery can experience short-term health effects such as shortness of breath, throat irritation, and other irritating effects on the respiratory system.

Points 27 and 32, situated in the sulfur mining work area, present a grave concern with their very high HQ values. At point 27, the HQ value spiked to 17.671 after 3 hours of exposure, and at point 32, it reached 10.356. It shows that miners working in this area are at a significantly higher risk than in other areas. Such extreme exposure to SO_2 not only has the potential to cause acute respiratory problems but also poses a serious threat to chronic health issues such as bronchitis, decreased lung function, and potential cardiovascular problems, highlighting the urgent need for preventive measures [47].

While this study has its limitations, such as the calculation of the risk of exposure without wearing PPE and the influence of wind direction on SO_2 concentration, it is crucial to note that any HQ value > 1 indicates the necessity for exposure risk control in the area. This control is vital to minimize SO_2 exposure to both tourists and workers. The recommended controls include engineering control, administrative control, and the use of PPE [48].

Table 4
Component of health risk assessment.

Description	Value	Ref.
C (Concentration) (mg/m^3)	Each point	This study
R (Inhalation rate) (m^3/hr)	0.83	[12]
Te (Time exposure) (hr)	Every hour from the 1st hour to the 8th hour	This study
Fe (frequency of exposure) (day/years)	240	This study
Dt (Duration time 30 years projection for non-carcinogenic) (years)	30	
Wb (Weight) (kg)	65	This study
Rfc (References SO_2 concentration) (mg/kg/day)	0.026	[46]

3.7. Limitation

The distribution of sampling points at 32 locations in this study may

Table 5
Calculation of intake inhalation and hazard quotion.

ID	Intake inhalation (mg/kg/day)								HQ							
	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	7 hr	8 hr	1 hr	2 hr	3 hr	4 hr	5 hr	6 hr	7 hr	8 hr
1	0.012	0.024	0.036	0.047	0.059	0.071	0.083	0.095	0.455	0.911	1.366	1.821	2.277	2.732	3.187	3.643
2	0.015	0.029	0.044	0.058	0.073	0.087	0.102	0.116	0.559	1.117	1.676	2.235	2.793	3.352	3.911	4.469
3	0.015	0.029	0.044	0.058	0.073	0.087	0.102	0.116	0.559	1.117	1.676	2.235	2.793	3.352	3.911	4.469
4	0.018	0.037	0.055	0.074	0.092	0.111	0.129	0.148	0.710	1.421	2.131	2.842	3.552	4.263	4.973	5.684
5	0.016	0.032	0.048	0.063	0.079	0.095	0.111	0.127	0.610	1.221	1.831	2.441	3.052	3.662	4.272	4.883
6	0.013	0.026	0.040	0.053	0.066	0.079	0.092	0.105	0.507	1.014	1.521	2.028	2.535	3.042	3.549	4.056
7	0.032	0.063	0.095	0.127	0.158	0.190	0.222	0.253	1.217	2.435	3.652	4.870	6.087	7.305	8.522	9.740
8	0.032	0.063	0.095	0.127	0.158	0.190	0.222	0.253	1.217	2.435	3.652	4.870	6.087	7.305	8.522	9.740
9	0.063	0.127	0.190	0.254	0.317	0.380	0.444	0.507	2.438	4.876	7.314	9.753	12.191	14.629	17.067	19.505
10	0.041	0.082	0.123	0.164	0.204	0.245	0.286	0.327	1.573	3.145	4.718	6.291	7.863	9.436	11.009	12.581
11	0.033	0.066	0.099	0.132	0.165	0.198	0.231	0.264	1.269	2.538	3.807	5.076	6.346	7.615	8.884	10.153
12	0.026	0.053	0.079	0.105	0.132	0.158	0.185	0.211	1.014	2.028	3.042	4.056	5.070	6.084	7.098	8.112
13	0.026	0.053	0.079	0.105	0.132	0.158	0.185	0.211	1.014	2.028	3.042	4.056	5.070	6.084	7.098	8.112
14	0.028	0.055	0.083	0.111	0.139	0.166	0.194	0.222	1.066	2.131	3.197	4.263	5.328	6.394	7.460	8.525
15	0.029	0.058	0.087	0.116	0.145	0.174	0.203	0.232	1.117	2.235	3.352	4.469	5.587	6.704	7.821	8.939
16	0.033	0.066	0.099	0.132	0.165	0.198	0.231	0.264	1.269	2.538	3.807	5.076	6.346	7.615	8.884	10.153
17	0.022	0.045	0.067	0.090	0.112	0.135	0.157	0.179	0.862	1.724	2.587	3.449	4.311	5.173	6.036	6.898
18	0.028	0.055	0.083	0.111	0.139	0.166	0.194	0.222	1.066	2.131	3.197	4.263	5.328	6.394	7.460	8.525
19	0.011	0.021	0.032	0.042	0.053	0.063	0.074	0.085	0.407	0.814	1.221	1.628	2.034	2.441	2.848	3.255
20	0.029	0.058	0.087	0.116	0.145	0.174	0.203	0.232	1.117	2.235	3.352	4.469	5.587	6.704	7.821	8.939
21	0.030	0.061	0.091	0.122	0.152	0.182	0.213	0.243	1.169	2.338	3.507	4.676	5.845	7.014	8.183	9.352
22	0.029	0.058	0.086	0.115	0.144	0.173	0.202	0.230	1.108	2.215	3.323	4.431	5.538	6.646	7.754	8.861
23	0.033	0.066	0.099	0.132	0.165	0.198	0.231	0.264	1.269	2.538	3.807	5.076	6.346	7.615	8.884	10.153
24	0.053	0.106	0.158	0.211	0.264	0.317	0.370	0.422	2.031	4.062	6.094	8.125	10.156	12.187	14.219	16.250
25	0.046	0.092	0.139	0.185	0.231	0.277	0.323	0.369	1.776	3.552	5.328	7.104	8.881	10.657	12.433	14.209
26	0.061	0.121	0.182	0.243	0.304	0.364	0.425	0.486	2.335	4.670	7.004	9.339	11.674	14.009	16.344	18.678
27	0.153	0.306	0.459	0.613	0.766	0.919	1.072	1.225	5.890	11.781	17.671	23.561	29.451	35.342	41.232	47.122
28	0.020	0.040	0.059	0.079	0.099	0.119	0.139	0.159	0.762	1.524	2.286	3.048	3.811	4.573	5.335	6.097
29	0.024	0.048	0.073	0.097	0.121	0.145	0.169	0.193	0.930	1.860	2.790	3.720	4.650	5.580	6.510	7.440
30	0.029	0.058	0.087	0.116	0.145	0.174	0.203	0.232	1.117	2.235	3.352	4.469	5.587	6.704	7.821	8.939
31	0.143	0.285	0.428	0.570	0.713	0.855	0.998	1.141	5.483	10.967	16.450	21.933	27.417	32.900	38.384	43.867
32	0.090	0.180	0.269	0.359	0.449	0.539	0.628	0.718	3.452	6.904	10.356	13.809	17.261	20.713	24.165	27.617

not fully represent the entire ICV area, especially in areas with extreme terrain that are difficult to reach. Measurement of SO_2 concentrations also only reflects conditions at a certain time, so it does not describe temporal fluctuations that can occur due to changes in volcanic activity or weather conditions. The focus of the study is more on acute exposure, making the health impacts of long-term exposure not yet adequately estimated. In addition, the effect of SO_2 on local ecosystems, especially flora and fauna, has not been studied in depth, so aspects of environmental sustainability still contain uncertainty. These limitations provide opportunities for further research with a broader scope and a more in-depth approach.

4. Conclusion

The Ijen crater volcano (ICV) is an active volcano that originated from the eruption of the ancient ICV, forming Indonesia's largest caldera and producing seven new mountains within it, including the ICV. The crater lake at ICV is highly acidic, with a pH below one and a depth of up to 200 m, rendering it uninhabitable for organisms. Emissions from the crater, primarily through fractures, include H_2O (71.1 %), CO_2 (21 %), SO_2 (3 %), H_2S (4.1 %), and N_2 (1.3 %). These emissions, particularly SO_2, result from magma interacting with volcanic gases. The distribution of SO_2 at ICV varies significantly, with concentrations ranging from 480 to 6960 ppb, influenced by proximity to emission fractures and atmospheric conditions such as temperature, humidity, and wind direction. Areas near emission sources and those frequented by tourists have the highest SO_2 concentrations, posing health risks. The comparison of SO_2 concentration data with Threshold Limit Values (TLVs) reveals that all measurements exceed safe limits, further underscoring the potential health hazards for both workers and tourists. Health risk assessments also indicate significant exposure at several points, particularly at points 7, 8, 16, 27, and 32, where Hazard Quotient (HQ) values far exceed safety thresholds. This highlights the urgent need for preventive measures to mitigate acute and chronic respiratory and cardiovascular risks in these high-exposure areas.

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Author contributions

Septian Hadi Susetyo: Conceptualize, sampling, analyzing, writing draft, visualizing. Azham Umar Abidin: writing draft, analyzing. Kyosuke Sano: Conceptualizing, administering, evaluation. Minoru Yoneda: Supervisor, Lab support, evaluation. Yasuto Matsui: Supervisor, conceptualizing, evaluating, and revision.

CRediT authorship contribution statement

Septian Hadi Susetyo: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Azham Umar Abidin**: Writing – review & editing, Writing – original draft. **Kyosuke Sano**: Writing – original draft, Validation, Project administration. **Minoru Yoneda**: Supervision, Resources. **Yasuto Matsui**: Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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