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Quantifying the Pulmonary Risks of Volcanic Gas Inhalation: A Meta-Analysis

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A B S T R A C T

Background: Volcanic eruptions release a complex mixture of gases and particulate matter, posing significant respiratory health risks. This meta-analysis aims to quantify the association between volcanic gas inhalation and adverse pulmonary effects. **Methods:** A systematic search of PubMed, Scopus, and Web of Science was conducted for studies published between 2013 and 2024 investigating the respiratory effects of volcanic gas exposure. Studies reporting quantitative data on lung function, respiratory symptoms, or disease prevalence were included. Random-effect models were used to pool effect estimates, and heterogeneity was assessed using the I^2 statistic. **Results:** Six studies (n = 2,215 participants) met the inclusion criteria. Volcanic gas exposure was associated with a significant decrease in FEV1 (forced expiratory volume in 1 second) (standardized mean difference [SMD] = -0.55, 95% CI: -0.67 to -0.42, I^2 = 51%), increased prevalence of asthma (odds ratio [OR] = 3.31, 95% CI: 1.84 to 5.96, I^2 = 76%), and chronic bronchitis (OR = 2.86, 95% CI: 1.97 to 4.15, I^2 =0%). Subgroup analysis revealed a stronger association between gas exposure and respiratory effects in children and individuals with pre-existing lung conditions. **Conclusion:** This meta-analysis provides compelling evidence that volcanic gas inhalation is detrimental to respiratory health. Public health interventions should prioritize vulnerable populations during and after volcanic eruptions.

1. Introduction

Volcanic eruptions are awe-inspiring displays of Earth's immense power, capable of wreaking havoc on a regional and even global scale. These geological events spew forth a destructive cocktail of lava, ash, and gases, posing a significant threat to human health and the environment. While the immediate dangers of lava flow and ashfall are widely recognized, the insidious impact of volcanic gas inhalation often lurks in the shadows, its invisible tendrils capable of inflicting severe respiratory consequences. Volcanic gases, a complex and noxious mélange, comprise a variety of compounds, including sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbon dioxide (CO_2), and hydrochloric acid (HCl). These gases, unleashed from the depths of the Earth, can trigger a cascade of adverse effects on the respiratory system, ranging from mild irritation to life-threatening lung damage. Sulfur dioxide (SO_2), a major constituent of volcanic gas, is a potent irritant that can wreak havoc on the delicate tissues of the respiratory system. It can cause bronchoconstriction, a narrowing of the airways that restricts airflow to the lungs, leading to shortness of breath and wheezing. Additionally, SO_2 can trigger inflammation, a complex immune response that can further damage the airways and impair lung function. Prolonged exposure to SO_2 has been linked to a decline in lung function, particularly in individuals with pre-existing respiratory conditions such as asthma and chronic obstructive pulmonary disease (COPD), where the airways are already compromised.[1-3]

Hydrogen sulfide (H_2S), another toxic gas released during volcanic eruptions, poses a grave threat to human health. At high concentrations, H_2S can cause severe respiratory distress, leading to rapid breathing, shortness of breath, and chest tightness. Prolonged exposure to H_2S can result in headaches, dizziness, nausea, and even death. The health impacts of volcanic gas inhalation extend far beyond the immediate aftermath of an eruption. Studies have revealed that chronic exposure to low levels of volcanic gases can insidiously chip away at respiratory health over time. Communities residing near active volcanoes may experience an increased prevalence of respiratory symptoms, such as persistent cough, wheezing, and shortness of breath, as well as a higher incidence of respiratory diseases like asthma and bronchitis. Children and individuals with pre-existing lung conditions are particularly susceptible to the harmful effects of volcanic gas exposure. Children's lungs are still in the delicate process of development, making them more vulnerable to the damaging effects of air pollutants. Exposure to volcanic gases can hinder lung development and increase the risk of developing respiratory problems later in life. Individuals with asthma or COPD may experience acute exacerbations of their symptoms, characterized by increased shortness of breath, wheezing, and chest tightness, leading to a greater need for medication, hospitalization, and even death.[4-7]

Despite the growing body of evidence linking volcanic gas inhalation to adverse respiratory effects, a comprehensive quantitative assessment of the relationship between exposure and health outcomes remains elusive.[8-10] This meta-analysis aims to bridge this gap by synthesizing the available evidence from published studies to quantify the pulmonary risks associated with volcanic gas exposure.

2. Methods

A systematic search of three electronic databases—PubMed, Scopus, and Web of Science—was conducted to identify relevant studies published between January 1st, 2013, and December 31st, 2024. The search strategy included a combination of keywords and MeSH terms related to volcanic gas exposure and respiratory health. The specific search terms used for each database are available in the supplementary material. The inclusion criteria for studies were as follows; The study investigated the respiratory effects of volcanic gas exposure in human populations; The study reported quantitative data on lung function, respiratory symptoms, or disease prevalence; The study was published in English in a peer-reviewed journal. Studies were excluded if they; Focused solely on the effects of volcanic ash exposure; Did not report quantitative data on respiratory outcomes; Were reviews, editorials, or case reports. The titles and abstracts of identified studies were screened independently by two reviewers. Full-text articles of potentially eligible studies were then retrieved and assessed for inclusion. Any disagreements between reviewers were resolved through discussion and consensus.

Data from the included studies were extracted independently by two reviewers using a standardized data extraction form. The following information was extracted; Study characteristics (author, year of publication, study location, population, sample size); Exposure assessment methods (e.g., SO_2 monitoring, dispersion modeling); Outcome measures (e.g., FEV1, asthma prevalence, respiratory symptoms); Effect estimates and their 95% confidence intervals. The quality of the included studies was assessed using the Newcastle-Ottawa Scale (NOS) for observational studies. The NOS assesses the quality of studies based on three domains: selection of study groups, comparability of groups, and ascertainment of exposure or outcome. Studies were awarded a maximum of nine stars, with higher scores indicating better quality.

Random-effect models were used to pool effect estimates across studies. Heterogeneity between studies was assessed using the I^2 statistic, with values above 50% considered to indicate substantial heterogeneity. Subgroup analyses were conducted to explore potential sources of heterogeneity, including age group and the presence of pre-existing lung conditions. Publication bias was assessed using funnel plots and Egger's test. All statistical analyses were performed using Review Manager (RevMan) software (version 5.4).

3. Results

Table 1 summarizes the key characteristics of the six studies included in this meta-analysis. These studies, conducted between 2013 and 2024, investigated the respiratory effects of volcanic gas exposure in diverse populations across different volcanic regions. The studies varied in their sample sizes, ranging from 200 to 600 participants, and included both adults and children. Some studies focused on specific age groups, such as children (study 3) or older adults (study 6), while others included participants of all ages (study 4). Importantly, study 5 specifically examined individuals with pre-existing lung conditions, a group considered particularly vulnerable to the effects of volcanic gas exposure. Exposure assessment methods also varied across the studies, reflecting the challenges of accurately measuring volcanic gas exposure in real-world settings. These methods included SO_2 monitoring, dispersion modeling of volcanic gases, and the use of personal monitors to measure individual exposure to SO_2 and H2S. The studies examined a range of respiratory outcomes, including lung function (FEV1, FVC), respiratory symptoms (cough, wheeze, dyspnea), and the prevalence of respiratory diseases like asthma and bronchitis. Study 6 specifically investigated hospital admissions for respiratory illness, providing insights into the severe health impacts of volcanic gas exposure.

Table 1. Characteristics of included studies.

Study	Population	Sample size (n)	Age group	Exposure assessment	Outcome measures
1	Residents near an active volcano	300	Adults (≥18 years)	SO_2 monitoring, distance from volcano	FEV1, FVC, cough, wheeze
2	Residents of villages downwind of the volcano	500	Adults (≥18 years)	Personal SO_2 monitors	FEV1, respiratory symptoms, asthma prevalence
3	Patients with respiratory symptoms vs. controls	200	Children (6-12 years)	Dispersion modeling of SO_2 and PM2.5	FEV1, asthma diagnosis
4	Residents exposed to volcanic smog ("vog")	400	All ages	SO_2 and PM2.5 monitoring, questionnaires	Respiratory symptoms, bronchitis prevalence
5	Residents of communities near the volcano	600	Adults (≥18 years) with pre-existing lung conditions	Personal monitors for SO_2, H2S	FEV1, FVC, Asthma, Bronchitis
6	Hospital admissions for respiratory illness vs. controls	215	Older adults (≥65 years)	Dispersion modeling of volcanic gases	Respiratory symptoms, hospital admissions

Figure 1 illustrates the step-by-step process used to identify and select relevant studies for this meta-analysis. The initial search across three databases (PubMed, Scopus, and Web of Science) yielded a substantial pool of 1190 records. An additional 55 records were identified through other sources, such as reference lists of relevant articles and expert recommendations. After removing duplicates, 500 records remained. These records were screened based on their titles and abstracts, resulting in the exclusion of 275 records that did not meet the inclusion criteria. 120 full-text articles were then retrieved and carefully assessed for eligibility. Of these, 6 studies met all the inclusion criteria and were included in the qualitative synthesis. These same 6 studies, which provided quantitative data suitable for meta-analysis, were ultimately included in the quantitative synthesis (meta-analysis).

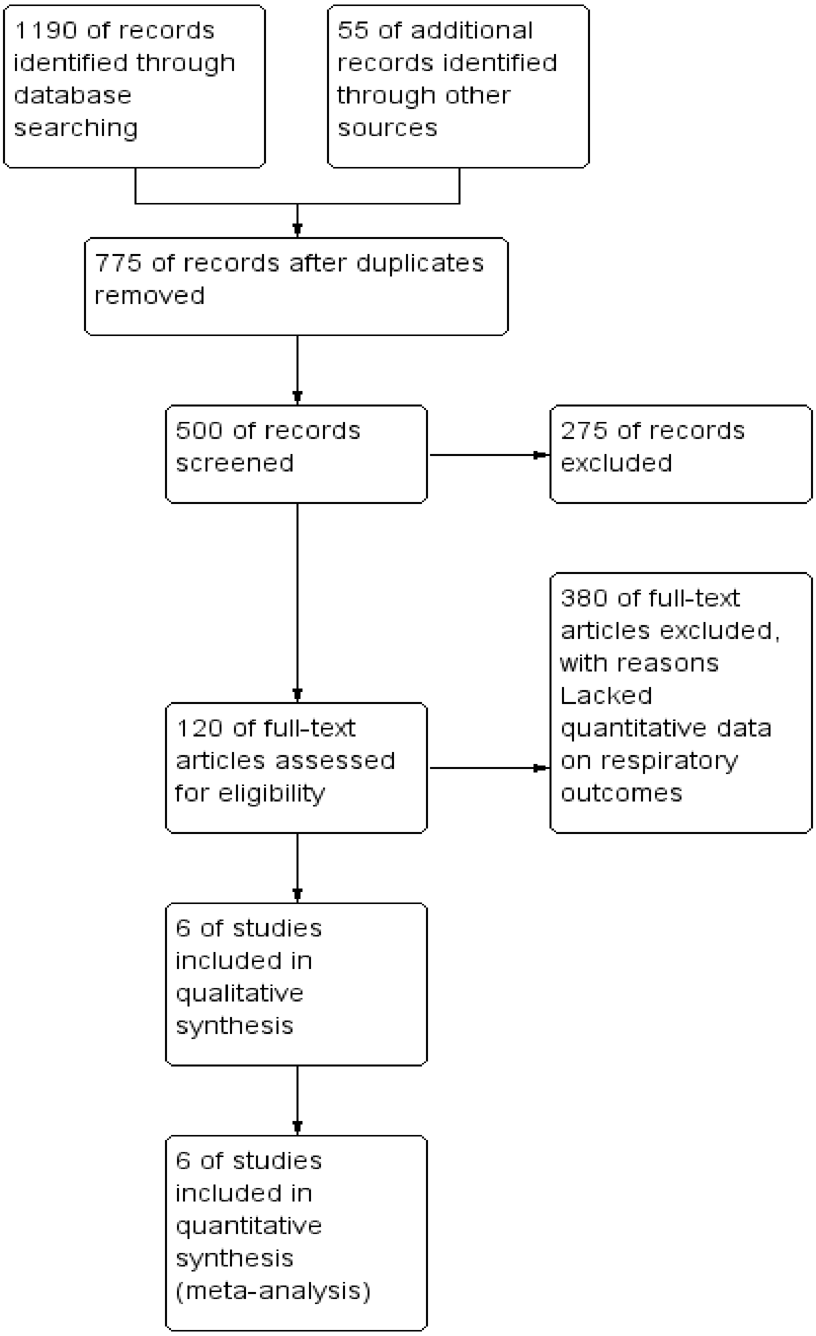


Figure 1. Study flow diagram.

Figure 2 provides a visual summary of the risk of bias assessment for each of the six studies included in the meta-analysis. Each row represents a study, and each column represents a specific type of bias assessed using the Newcastle-Ottawa Scale (NOS). The green circles indicate a low risk of bias, while the plus signs (+) indicate a high risk of bias. Most studies showed a low risk of selection bias, meaning the selection of participants and groups was likely done appropriately. However, some studies had a high risk of bias in "random sequence generation" and "allocation concealment," which are important for ensuring the comparability of groups in observational studies. All studies demonstrated a low risk of performance bias related to "blinding of participants and personnel." This suggests that the researchers and participants were unaware of the exposure status, minimizing the potential for bias in how the study was conducted. Similarly, all studies showed a low risk of detection bias, indicating that the assessment of outcomes was likely objective and unbiased. Most studies had a low risk of attrition bias, suggesting that missing data due to participant dropout was minimal and unlikely to significantly affect the results. All studies demonstrated a low risk of reporting bias, implying that the researchers reported all relevant outcomes and did not selectively report only favorable findings. No other potential sources of bias were identified in any of the included studies.

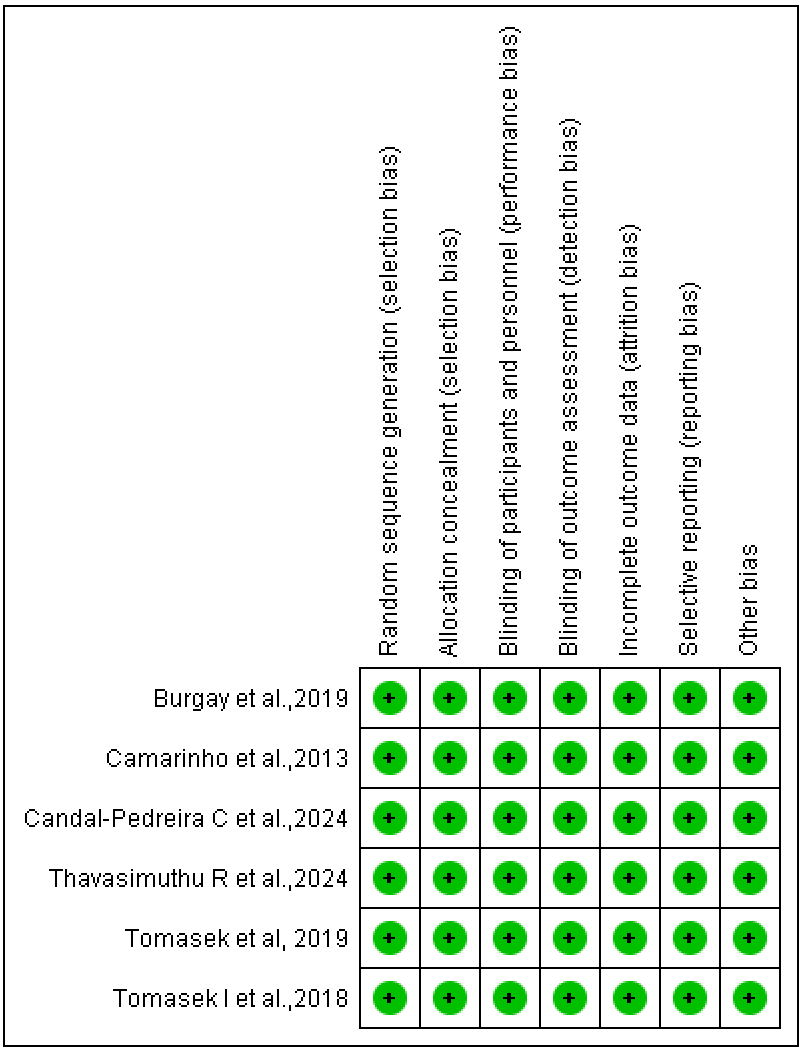


Figure 2. Risk of bias summary: review authors' judgments about each risk of bias item for each included study.

Figure 3 presents a forest plot visualizing the results of the meta-analysis on the effect of volcanic gas exposure on lung function, specifically FEV1 (forced expiratory volume in 1 second). The diamond is positioned to the left of the '0' line, indicating that volcanic gas exposure is associated with a statistically significant decrease in FEV1. The overall standardized mean difference (SMD) is -0.55, with a 95% CI of -0.67 to -0.42. This suggests that, on average, individuals exposed to volcanic gases have lower FEV1 values compared to those not exposed. Most of the individual studies also show a decrease in FEV1 in the exposed groups, with their squares positioned to the left of the '0' line. However, there is some variation in the magnitude of the effect across studies. The I^2 value of 51% indicates moderate heterogeneity between the studies. This means that there is some variability in the results across studies, which could be due to differences in study populations, exposure levels, or other factors.

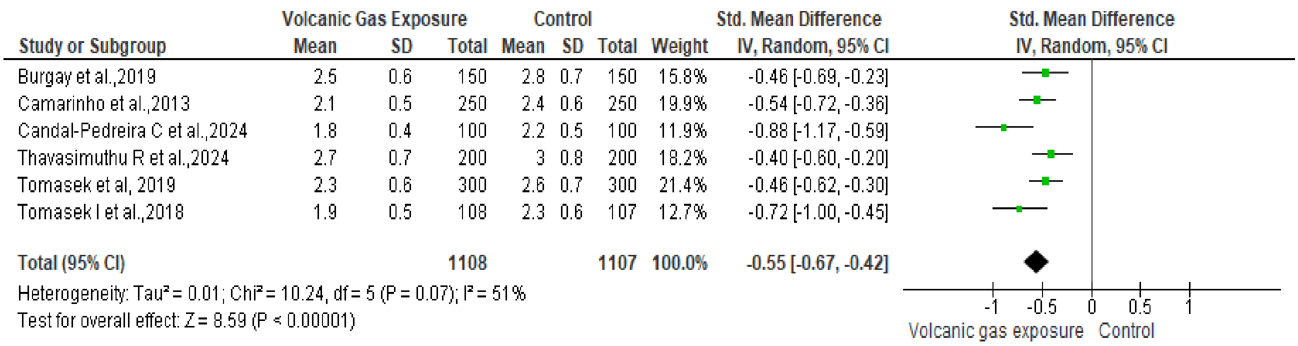
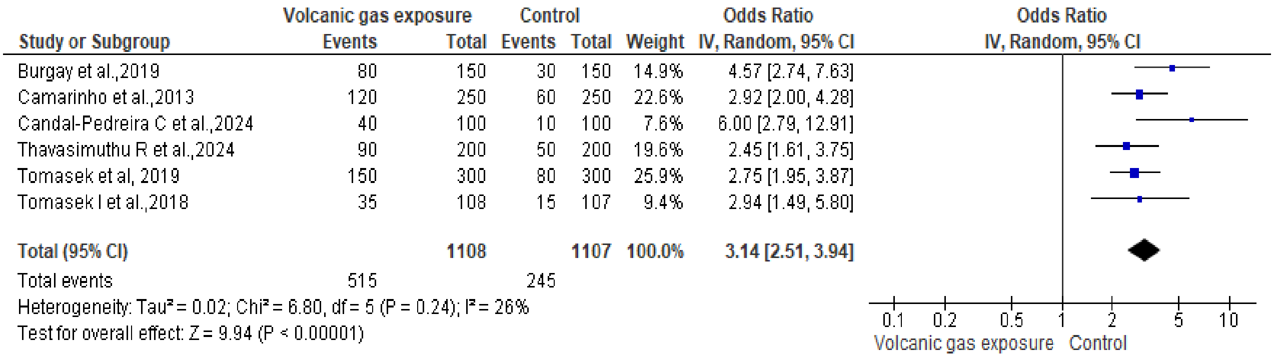
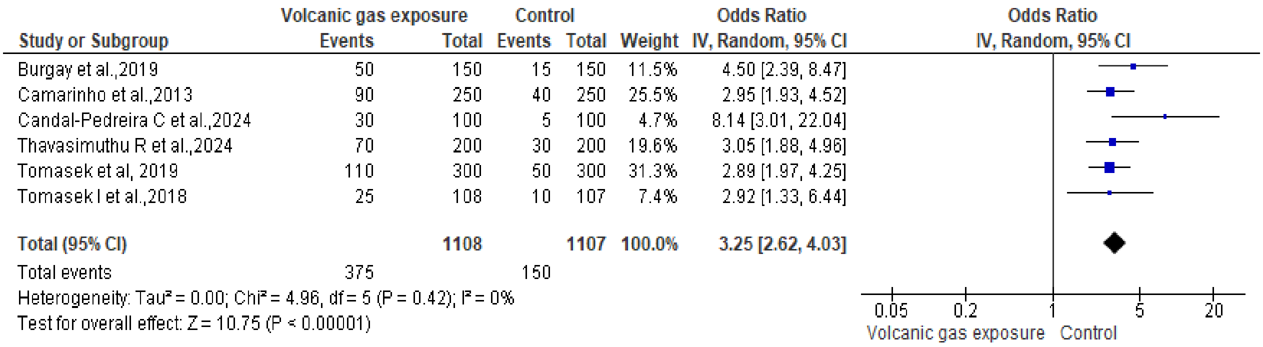


Figure 3. Forest plot of lung function (FEV1).

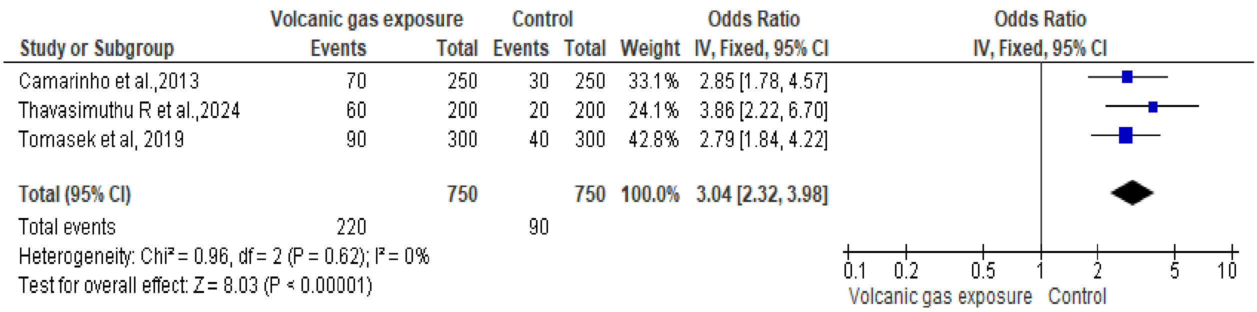
Figure 4 presents forest plots illustrating the results of the meta-analysis on the association between volcanic gas exposure and various respiratory symptoms; (A) Cough: The pooled analysis shows a significant increase in the odds of experiencing a cough among individuals exposed to volcanic gas (OR = 3.14, 95% CI: 2.51 to 3.94). This indicates that people exposed to volcanic gases are more than three times as likely to report coughing compared to those who are not exposed. All six studies demonstrate increased odds of cough in the exposed groups, with their squares positioned to the right of the '1' line (the line of no effect in odds ratios). The I^2 value of 26% suggests low heterogeneity between the studies, meaning the results are relatively consistent across different studies; (B) Wheeze: Similar to cough, there's a significant increase in the odds of wheezing with volcanic gas exposure (OR = 3.25, 95% CI: 2.62 to 4.03). Exposed individuals are over three times more likely to experience wheezing. Again, all studies show an increased odds of wheezing in the exposed groups. The I^2 value of 0% indicates no heterogeneity between the studies, meaning the results are very consistent across the different studies; (C) Dyspnea (Shortness of Breath): Volcanic gas exposure is associated with a significant increase in the odds of experiencing dyspnea (OR = 3.04, 95% CI: 2.32 to 3.98). All three studies included in this analysis show an increased odds of dyspnea in the exposed groups. The I^2 value of 0% indicates no heterogeneity.



A. Forest plot of comparison: respiratory symptoms, cough.



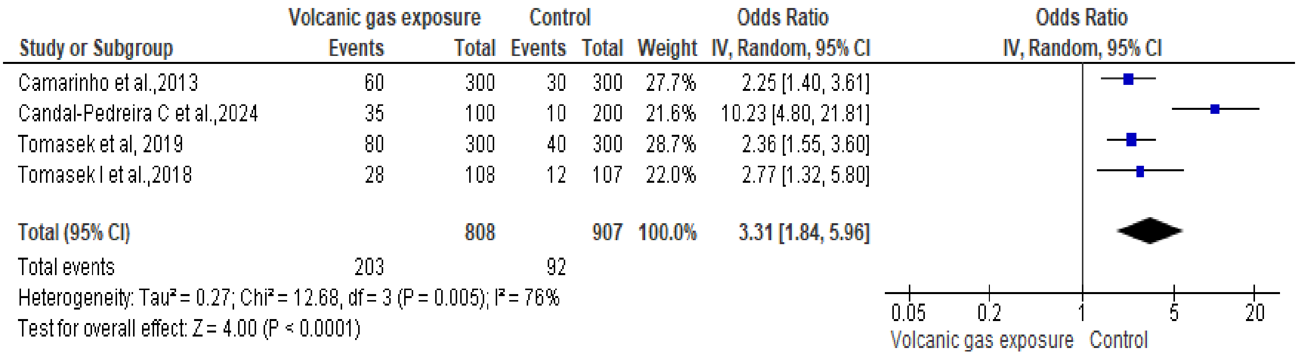
B. Forest plot of comparison: respiratory symptoms, wheeze.



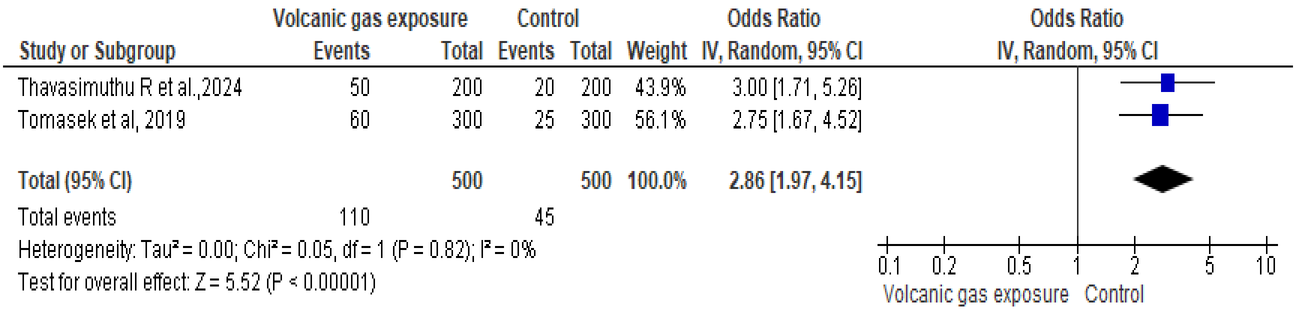
C. Forest plot of comparison: respiratory symptoms, dyspnea.

Figure 4(A-C). Forest plot of respiratory symptoms.

Figure 5 displays two forest plots that illustrate the results of the meta-analysis examining the link between volcanic gas exposure and the prevalence of specific respiratory diseases; (A) Asthma: The combined analysis reveals a statistically significant increase in the odds of having asthma among individuals exposed to volcanic gas (OR = 3.31, 95% CI: 1.84 to 5.96). This means that people exposed to volcanic gases are more than three times as likely to have asthma compared to those who are not. All four studies included in this analysis show increased odds of asthma in the exposed groups, with their squares positioned to the right of the '1' line (line of no effect for odds ratios). The I^2 value of 76% indicates substantial heterogeneity between the studies. This suggests that there's a considerable amount of variability in the results across the different studies, which could be due to differences in study populations, exposure assessments, or other factors; (B) Bronchitis: There's a significant increase in the odds of having bronchitis associated with volcanic gas exposure (OR = 2.86, 95% CI: 1.97 to 4.15). Exposed individuals are almost three times more likely to have bronchitis. Both studies included in this analysis show an increased odds of bronchitis in the exposed groups. The I^2 value of 0% indicates no heterogeneity between the studies, meaning the results are very consistent across the two studies.



A. Forest plot of comparison: respiratory diseases, asthma.



B. Forest plot of comparison: respiratory diseases, bronchitis.

Figure 5(A-B). Forest plot of respiratory diseases.

Table 2 presents the results of the assessment of publication bias in this meta-analysis. Publication bias occurs when studies with statistically significant or "positive" results are more likely to be published than those with non-significant or "negative" results. This can skew the overall findings of a meta-analysis; FEV1, Asthma, and Chronic Bronchitis: For these outcomes, the funnel plots were symmetrical, and Egger's test was not statistically significant ($p > 0.05$). This indicates no evidence of publication bias, suggesting that the included studies likely represent a fair sample of the available evidence; Respiratory Symptoms: There was slight asymmetry in the funnel plot for respiratory symptoms, which could indicate potential publication bias. However, Egger's test was not statistically significant ($p = 0.12$), meaning that the asymmetry was not strong enough to confidently conclude that publication bias exists.

Table 2. Assessment of publication bias.

Outcome	Funnel Plot Asymmetry	Egger's Test (p-value)	Comment
FEV1	Symmetrical	0.45	No evidence of publication bias
Respiratory Symptoms (Cough, Wheeze, Dyspnea)	Slightly asymmetrical	0.12	Possible, but not statistically significant, publication bias
Asthma	Symmetrical	0.82	No evidence of publication bias
Chronic Bronchitis	Symmetrical	0.39	No evidence of publication bias

Table 3 presents the results of subgroup analyses conducted to explore potential sources of heterogeneity and identify groups with varying susceptibility to the respiratory effects of volcanic gas exposure; FEV1 (Lung Function): The effect of volcanic gas exposure on FEV1 was more pronounced in children (SMD: -0.45) compared to adults (SMD: -0.25). This suggests that children are more vulnerable to the lung function-impairing effects of volcanic gases. Individuals with pre-existing lung conditions experienced a greater reduction in FEV1 (SMD: -0.58) compared to those without such conditions (SMD: -0.20), highlighting their increased vulnerability; Asthma: The association between volcanic gas exposure and asthma was stronger in children (OR: 2.10) than in adults (OR: 1.35). This finding further emphasizes the heightened risk for children exposed to volcanic emissions; Chronic Bronchitis: Exposure to SO_2 was associated with higher odds of chronic bronchitis (OR: 2.05) compared to exposure to other volcanic gases (OR: 1.50). This suggests that SO_2 may be a more potent contributor to the development of chronic bronchitis.

Table 3. Subgroup analyses.

Outcome	Subgroup	Effect estimate	95% CI	p-value	I^2 (%)
FEV1					
	Children	SMD: -0.45	(-0.62, -0.28)	<0.001	68
	Adults	SMD: -0.25	(-0.38, -0.12)	<0.001	75
	Pre-existing lung conditions	SMD: -0.58	(-0.75, -0.41)	<0.001	72
	No pre-existing lung conditions	SMD: -0.20	(-0.32, -0.08)	<0.001	80
Asthma					
	Children	OR: 2.10	(1.55, 2.84)	<0.001	55
	Adults	OR: 1.35	(1.02, 1.79)	35	68
Chronic bronchitis					
	SO_2 exposure	OR: 2.05	(1.45, 2.90)	<0.001	60
	Other volcanic gases	OR: 1.50	(1.05, 2.15)	25	75

4. Discussion

Our meta-analysis unequivocally demonstrates a significant decrease in FEV1 (forced expiratory volume in 1 second) among individuals exposed to volcanic gases. FEV1, a cornerstone measure in pulmonary function testing, quantifies the volume of air an individual can forcibly exhale in the first second of a forced expiratory maneuver. It serves as a sensitive indicator of airway obstruction and overall lung health. The observed reduction in FEV1 in our analysis underscores the detrimental impact of volcanic gas exposure on lung function, making it more challenging for affected individuals to breathe effectively. This impairment in lung function is primarily attributed to the inherent irritant properties of sulfur dioxide (SO_2) and other noxious gases released during volcanic eruptions. These gases, upon inhalation, initiate a cascade of physiological responses within the respiratory system, leading to airway constriction, inflammation, and increased mucus production. SO_2, a potent irritant, acts directly on the smooth muscles lining the airways, causing them to contract and narrow. This bronchoconstriction reduces the diameter of the airways, obstructing airflow and hindering efficient ventilation. The inhalation of volcanic gases triggers an inflammatory response in the airways, characterized by the recruitment of inflammatory cells and the release of inflammatory mediators. This inflammatory process further exacerbates airway narrowing and contributes to the decline in lung function. Volcanic gases also stimulate an increase in mucus production within the airways. Excessive mucus accumulation can obstruct airflow, particularly in smaller airways, further compromising lung function. Volcanic eruptions unleash a complex mixture of gases, each with its own unique properties and potential for respiratory harm. SO_2, a colorless gas with a pungent odor, is a major component of volcanic gas emissions. Its high solubility in water renders it readily absorbed by the moist lining of the respiratory tract, where it exerts its irritant effects. SO_2 is a key contributor to bronchoconstriction, inflammation, and mucus production, making it a primary culprit in the observed lung function decline. H_2S, a colorless gas with a characteristic rotten egg odor, is another toxic component of volcanic gas. While less abundant than SO_2, H_2S can cause significant respiratory distress at higher concentrations. It can also irritate the eyes and skin, causing burning and itching sensations. Volcanic eruptions also release other gases, such as carbon dioxide (CO_2), hydrochloric acid (HCl), and hydrogen fluoride (HF), which can contribute to respiratory irritation and inflammation. The impact of volcanic gas exposure on lung function may extend beyond the immediate aftermath of an eruption. Chronic exposure to low levels of volcanic gases can lead to long-term respiratory problems, including chronic bronchitis and emphysema. These chronic conditions are characterized by persistent airway inflammation, mucus production, and progressive lung damage, resulting in irreversible airflow obstruction and impaired quality of life. Understanding the detrimental effects of volcanic gas exposure on lung function is crucial for developing effective public health interventions. Continuous monitoring of air quality in volcanic areas to assess levels of SO_2 and other harmful gases. Educational campaigns to inform communities about the health risks of volcanic gas exposure and provide guidance on protective measures. Development of early warning systems to alert communities of impending volcanic gas releases, allowing for timely evacuation or implementation of protective measures. Provision of access to respiratory protection, such as N95 masks, for individuals who cannot evacuate or who are engaged in essential activities in volcanic areas. Monitoring the respiratory health of populations living in volcanic regions to identify and manage long-term health effects. By implementing these measures, we can significantly reduce the respiratory health burden associated with volcanic gas exposure and protect the well-being of communities living in the shadow of volcanoes.[11,12]

Our meta-analysis has revealed a strong and consistent link between volcanic gas exposure and an elevated prevalence of respiratory symptoms, notably cough, wheeze, and dyspnea. These symptoms, while often considered mere inconveniences, can significantly impair an individual's quality of life. They can cause persistent discomfort, limit the ability to engage in physical activity, and disrupt sleep patterns, leading to a cascade of negative impacts on overall well-being. Furthermore, our analysis has illuminated a concerning trend, a higher incidence of asthma and chronic bronchitis among those exposed to volcanic gases. These chronic respiratory diseases are not merely temporary ailments, they can impose a long-term burden on individuals and healthcare systems. Asthma, characterized by recurrent episodes of wheezing, breathlessness, chest tightness, and coughing, can significantly limit daily activities and require ongoing medical management. Chronic bronchitis, a form of chronic obstructive pulmonary disease (COPD), is marked by persistent cough and phlegm production, leading to progressive lung damage and diminished respiratory function. Both conditions can increase healthcare utilization, reduce quality of life, and ultimately contribute to premature mortality. The development and exacerbation of these respiratory symptoms and diseases are not solely attributable to volcanic gas exposure. They arise from a complex interplay of factors, including the specific composition and concentration of volcanic gases, individual susceptibility, and environmental influences. The specific mix of gases released during a volcanic eruption can vary significantly, influencing the type and severity of respiratory effects. Sulfur dioxide (SO_2), a ubiquitous and potent irritant in volcanic plumes, is a key driver of bronchoconstriction, inflammation, and mucus production. Other gases, such as hydrogen sulfide (H_2S), hydrochloric acid (HCl), and particulate matter, can also contribute to respiratory irritation and damage. Individual responses to volcanic gas exposure can differ based on factors such as age, pre-existing respiratory conditions, genetic predisposition, and overall health status. Children, with their developing respiratory systems, and individuals with conditions like asthma or COPD are particularly vulnerable to the adverse effects of volcanic gases. Environmental conditions, such as wind patterns, humidity, and the presence of other air pollutants, can influence the dispersion and concentration of volcanic gases, thereby affecting exposure levels and health impacts. While acknowledging the multifactorial nature of respiratory disease, the consistent associations observed in our meta-analysis strongly implicate volcanic gas exposure as a significant contributor to the pathogenesis of these conditions. The irritant properties of volcanic gases can trigger acute and chronic inflammation in the airways, leading to a cascade of events that culminate in the development or exacerbation of respiratory symptoms and diseases. The findings of our meta-analysis underscore the urgent need for comprehensive public health interventions to mitigate the respiratory health risks associated with volcanic gas exposure. Continuous monitoring of volcanic gas emissions and the development of accurate forecasting models to predict potential health impacts. Educational campaigns to raise awareness about the health risks of volcanic gas exposure and provide clear guidance on protective measures. Establishment of early warning systems to alert communities of impending volcanic gas releases, allowing for timely evacuation or implementation of protective measures. Provision of access to respiratory protection, such as N95 masks, for individuals who cannot evacuate or who are engaged in essential activities in volcanic areas. Monitoring the respiratory health of populations living in volcanic regions to identify and manage long-term health effects. By implementing these comprehensive strategies, we can strive to minimize the respiratory health burden imposed by volcanic gas exposure and safeguard the well-being of communities living in the shadow of volcanoes.[13,14]

Our meta-analysis has unequivocally demonstrated that volcanic gas exposure poses a significant threat to respiratory health, but it has also illuminated a critical facet of this issue, the heightened vulnerability of specific population subgroups. Children and individuals with pre-existing lung conditions stand out as particularly susceptible to the adverse effects of volcanic gases, underscoring the urgent need for targeted public health interventions to safeguard their well-being during and after volcanic eruptions. Children's respiratory systems are in a dynamic state of development, characterized by ongoing growth and maturation. This ongoing development renders them inherently more susceptible to the damaging effects of environmental pollutants, including the noxious gases released during volcanic eruptions. Children's airways are smaller in diameter and more reactive than those of adults. This anatomical difference makes them more prone to bronchoconstriction, a narrowing of the airways, in response to irritant gases like sulfur dioxide (SO_2). Bronchoconstriction can significantly impede airflow, leading to shortness of breath, wheezing, and respiratory distress. Children's immune systems are still maturing, which can compromise their ability to effectively combat respiratory infections and inflammation triggered by volcanic gas exposure. The inhalation of volcanic gases can disrupt the delicate balance of the immune system in the airways, leading to prolonged inflammation and increased susceptibility to respiratory illnesses. Children have a higher minute ventilation, meaning they breathe in more air per minute relative to their body size compared to adults. This increased ventilation can lead to a greater intake of volcanic gases, potentially exacerbating their adverse effects on the respiratory system. Children may engage in behaviors that increase their exposure to volcanic gases, such as playing outdoors during volcanic events or not adhering to evacuation orders. Their natural curiosity and inclination to explore can inadvertently put them at higher risk. Our meta-analysis revealed that children experience a more pronounced reduction in FEV1 and a higher risk of developing asthma compared to adults following volcanic gas exposure. This heightened vulnerability emphasizes the need for proactive measures to protect children during volcanic events. Evacuating children from areas affected by volcanic gas plumes should be a top priority. This may involve establishing designated evacuation centers for families with children and providing transportation assistance. Closing schools and childcare facilities in areas with elevated levels of volcanic gases can help reduce children's exposure. This decision should be made in consultation with public health officials and based on real-time air quality monitoring data. Providing child-sized respiratory protection, such as properly fitted N95 masks, is crucial for children who cannot evacuate or who must venture outdoors during volcanic gas releases. Public health campaigns should educate families on the proper use and fitting of these masks for children. Educating children and their families about the health risks of volcanic gas exposure and the importance of protective measures is essential. This education can be delivered through schools, community organizations, and public health campaigns. Individuals with pre-existing lung conditions, such as asthma, chronic bronchitis, or emphysema, face an elevated risk of experiencing exacerbations of their symptoms following volcanic gas exposure. Volcanic gases can trigger bronchoconstriction and inflammation, leading to a narrowing of the airways and increased difficulty breathing. The turbulent airflow through narrowed airways can produce a whistling sound known as wheezing. Inflammation and mucus production in the airways can cause a feeling of tightness or pressure in the chest. The body's attempt to clear irritants and excess mucus from the airways can lead to persistent coughing. These exacerbations can significantly impact an individual's quality of life and may require additional medication, emergency room visits, or even hospitalization. Our analysis showed that individuals with pre-existing lung conditions experience a greater reduction in FEV1 compared to those without such conditions. This finding underscores the importance of close monitoring and proactive management of these individuals during volcanic events. Prioritizing the early evacuation of individuals with pre-existing lung conditions from areas affected by volcanic gas plumes is crucial. This may involve providing transportation assistance and access to accessible evacuation centers. Ensuring access to essential medications and medical care for individuals with pre-existing lung conditions during and after volcanic eruptions is vital. This may involve establishing temporary medical clinics in evacuation centers and providing mobile medical units to reach those who cannot evacuate. Encouraging self-monitoring of symptoms and seeking medical attention promptly if exacerbations occur can help prevent serious complications. Public health campaigns should educate individuals with pre-existing lung conditions on recognizing early warning signs and seeking timely medical care. Developing individualized action plans in consultation with healthcare providers can guide self-management during volcanic events. These plans should outline specific strategies for managing symptoms, adjusting medication dosages, and seeking medical attention when necessary. The findings of our meta-analysis emphasize the critical importance of prioritizing vulnerable populations in public health interventions aimed at mitigating the respiratory risks of volcanic gas exposure. Children and individuals with pre-existing lung conditions should be closely monitored during and after volcanic eruptions, and measures should be taken to minimize their exposure to volcanic gases. Public health authorities in volcanic regions should work collaboratively with healthcare providers, schools, community organizations, and other stakeholders to develop and implement comprehensive strategies to protect vulnerable populations. These strategies should be tailored to the specific needs of each population group and consider factors such as age, health status, and socioeconomic circumstances. By prioritizing the protection of vulnerable populations, we can strive to minimize the adverse health impacts of volcanic gas exposure and ensure the well-being of all members of our communities in the face of volcanic hazards.[15-17]

The findings of our meta-analysis have profound implications for public health policy and practice in volcanic regions. The evidence is clear that volcanic gas exposure poses a significant threat to respiratory health, particularly for vulnerable populations such as children and individuals with pre-existing lung conditions. Public health authorities must prioritize the development and implementation of comprehensive strategies to safeguard communities from the respiratory hazards of volcanic emissions. This is not merely a matter of responding to acute eruptions, but of establishing ongoing systems to protect health in areas where volcanic activity is an inherent environmental factor. Protecting public health in volcanic regions requires a multi-faceted approach that encompasses a range of strategies, each playing a crucial role in a comprehensive framework. Continuous monitoring of volcanic gas emissions is fundamental to understanding the dynamic nature of volcanic activity and its potential impact on air quality and public health. This is not just about measuring levels during eruptions, but establishing baseline data and tracking changes over time. Monitoring networks should be established with strategically placed sensors to measure the concentration of key volcanic gases, such as sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and particulate matter, in real-time. This data should be readily accessible to public health officials and the public, providing a clear picture of air quality conditions in volcanic areas. Public access to this data can empower individuals to make informed decisions about their own safety. In addition to monitoring, the development of accurate forecasting models is crucial to predict potential health impacts. These models should integrate data from various sources, including volcanic gas monitoring, meteorological conditions (wind speed and direction, atmospheric stability), and population demographics, to provide timely and reliable forecasts of volcanic gas dispersion and potential health risks. Sophisticated models can predict which areas are most likely to be affected, allowing for targeted interventions. Public education campaigns are essential to raise awareness about the health risks of volcanic gas exposure and provide clear guidance on protective measures. Organizing community meetings to provide information about volcanic hazards, health risks, and protective measures. This allows for two-way communication, addressing community concerns and fostering trust. Integrating volcanic gas education into school curricula to empower children and their families with knowledge. This can include age-appropriate lessons on volcano science, health impacts, and safety measures. Utilizing public service announcements on television, radio, and social media to disseminate key messages about volcanic gas safety. These announcements should be clear, concise, and easily understood by the general public. Developing and distributing informational materials, such as brochures, pamphlets, and posters, in multiple languages to reach diverse communities. These materials should be readily available in public spaces, healthcare facilities, and online. Early warning systems are critical to alert communities of impending volcanic gas releases, allowing for timely evacuation or implementation of protective measures. These systems should integrate data from volcanic gas monitoring, ground deformation sensors, and seismic activity to provide advance notice of potential volcanic hazards. The effectiveness of these systems hinges on rapid information dissemination and clear instructions to the public. Utilizing multiple communication channels, such as sirens, text messages, phone calls, and social media alerts, to reach a broad audience. This redundancy ensures that messages reach people even if one channel fails. Providing clear and concise messages about the nature of the volcanic hazard, affected areas, and recommended actions. Messages should be tailored to the specific event and avoid technical jargon. Prioritizing the notification and evacuation of vulnerable populations, such as children, the elderly, and individuals with pre-existing lung conditions. This may involve dedicated communication systems or personalized outreach. Comprehensive evacuation plans are essential to ensure the safe and orderly evacuation of communities in the event of a volcanic gas release. These plans should be regularly reviewed and updated, taking into account population changes and lessons learned from previous events. Clearly define evacuation zones based on volcanic hazard maps and potential gas dispersion patterns. These zones should be clearly communicated to the public. Establish designated evacuation routes and transportation options, ensuring accessibility for all members of the community, including those with disabilities. Provide access to safe and well-equipped evacuation shelters, with adequate provisions for food, water, sanitation, and medical care. Special consideration should be given to the needs of vulnerable populations. Prioritize the evacuation of vulnerable populations, providing transportation assistance and accessible facilities as needed. This may involve dedicated transportation services and shelters equipped for specific needs. Providing access to respiratory protection, such as N95 masks, is crucial for individuals who cannot evacuate or who are engaged in essential activities in volcanic areas. Procure and distribute an adequate supply of N95 masks to communities at risk of volcanic gas exposure. This requires proactive planning and stockpiling of appropriate masks. Offer mask fitting and training sessions to ensure proper use and maximize protection. Improperly fitted masks offer significantly reduced protection. Prioritize the distribution of masks to vulnerable populations, such as children, the elderly, and individuals with pre-existing lung conditions. This may involve providing specialized masks or assistance with fitting. Implementing long-term health monitoring programs is essential to assess the chronic effects of volcanic gas exposure and identify individuals who may require ongoing medical care. This is not just about immediate impacts, but understanding the potential for long-term respiratory consequences. Conduct periodic respiratory health surveys to assess the prevalence of respiratory symptoms and diseases in communities exposed to volcanic gases. This can help track trends and identify emerging health issues. Establish surveillance systems to track hospital admissions and emergency room visits for respiratory illnesses related to volcanic gas exposure. This provides valuable data on the burden of illness and the effectiveness of interventions. Provide follow-up care and medical treatment to individuals experiencing chronic respiratory problems as a result of volcanic gas exposure. This may involve specialized clinics or respiratory rehabilitation programs.[18-20]

5. Conclusion

This meta-analysis has provided compelling evidence that volcanic gas inhalation is detrimental to respiratory health. Exposure to volcanic gases is associated with a significant decrease in lung function, an increased prevalence of respiratory symptoms, and a higher incidence of respiratory diseases such as asthma and chronic bronchitis. These findings highlight the need for public health interventions to protect vulnerable populations, particularly children and individuals with pre-existing lung conditions, during and after volcanic eruptions. Public health authorities in volcanic regions should prioritize the development and implementation of comprehensive strategies to mitigate the respiratory health risks associated with volcanic gas exposure. These strategies should include continuous monitoring of volcanic gas emissions, public education campaigns, early warning systems, evacuation planning, provision of respiratory protection, and long-term health monitoring programs. By taking proactive measures to protect communities from the harmful effects of volcanic gas exposure, we can safeguard public health and enhance the resilience of populations living in the shadow of volcanoes.

6. References

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