Human health effects of volcanic eruptions – a systematic review

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Abstract

Objectives: There is evidence of the exacerbation of certain pathologies due to exposure to ashes and volcanic gases. We evaluated the relationship between volcanic eruptions and short- and long-term effects on human health.

Methodology: A systematic peer review was carried out. The included diseases were respiratory, ophthalmological, cardiovascular, gastrointestinal, as well as other effects on human health. All volcanoes on the planet were included. We included standard terms for volcanic eruptions and diseases related to them.

Results: Of 57 included studies, 26 evaluated the relationship between volcanic eruptions and short-term effects on human health and 31 considered long-term effects on human health. The most frequently analyzed short-term diseases were respiratory pathologies (92%, n=24), ophthalmological (23%, n=6) and cardiovascular (23%, n=6), and respiratory pathologies (32%, n=10) and cancer (26%, n=8) in the long term. Most volcanoes were in the USA, Iceland, Japan, and Italy. 81% (n = 21) of the short-term and 74% (n=23) of the long-term studies consider that there is an affectation due to volcanic eruptions, compared to 11% (n=3) and 13% (n=4), respectively, that did not find this relationship.

Conclusion: Heterogeneous results among studies reinforce the need to continue developing new studies for the evaluation of short- and long-term effects of volcanic eruptions on human health. Despite this, currently, most of the scientific community and international organizations agree that volcanic eruptions impact human health. Therefore, it is important to develop contingency plans to protect vulnerable populations from suffering the effects of these natural phenomena.

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Introduction

Volcanic eruptions occur worldwide, including in regions with high population density or near large cities. At least 500 million people are at high risk of exposure to volcanic gases and ash, with a variety of negative effects on human health ranging from acute respiratory, cardiovascular, or ophthalmological illnesses, or chronic diseases [1]. These harmful and pernicious consequences can even affect populations living as far as hundreds of km away from the volcano caldera [2].

A volcano is an opening in the earth's crust through which magma emerges to the surface, either due to the movement of tectonic plates when they collide or separate, or spontaneously in volcanic hot spots [3]. According to their morphology, there are different types of volcanoes; cinder cones, formed by the accumulation of volcanic material on the margins of a volcanic vent, stratovolcanoes, made up of multiple layers of hardened lava organized into strata, shield volcanoes which, unlike the previous two, are characterized by its slight slope, and the lava domes, unpredictable and of various shapes, and calderas [4]. In addition, volcanoes could be affected by climate change. Apparently, volcanoes could be reactivated due to the increase in temperatures caused by climate change. The impact of climate change, therefore, endangers human health [5]. The problems caused by volcanic eruptions must be addressed, but not only since climate change, as mentioned before, is one of the precipitants.

According to data from the United States Geological Survey (USG), there are currently 1,350 active volcanoes in the world. Most of these volcanoes are concentrated in the so-called Belt or Ring of Fire of the Pacific Ocean. The countries with the most volcanoes in their territory are the United States, Indonesia, Japan, Russia, and Chile. Among the most famous volcanoes in the world are Mount Saint Helena, in the United States, Eyjafjallajökull, in Iceland, Etna, in Italy, and Sakurajima, in Japan, which are stratovolcanoes, and the Kilauea volcano in the Hawaiian Islands which are formed by a chain of shield volcanoes [6][7]. According to data provided by the Smithsonian Institution's Global Volcanism Program, 80 volcanoes erupted during the year 2022 [6].

The volcano of the Cumbre Vieja Natural Park on the Spanish island of La Palma in the Canary Islands archipelago erupted in 2021, forcing inhabitants to evacuate and killing one person [8], which highlights the need to investigate the possible consequences for human health that could be derived from it. It is important to understand that, in the event of a large volcanic eruption, medical treatment plays a minimal role. However, preventive measures, the use of technology, planning and emergency response can reduce injuries and loss of life [9]. Therefore, to carry out this series of preventive measures and minimize the impact on human health derived from volcanic eruptions, the health consequences of these must first be known.

In this study, we have reviewed the available scientific evidence on short- and long-term effects of volcanic eruptions on human health. We aimed to clarify and assess the relationship between human health consequences to provide the basis for containment measures and contingency plans.

Material and Methods

A systematic review was performed on the influence of volcanic eruptions and related factors, such as vog or water pollution, and its short- and long-term impact on human health following PRISMA-P 2015 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for systematic reviews and meta-analyses [10]. The study protocol was registered on October 21, 2021, and accepted on November 21, 2021, in the PROSPERO database (Registration ID CRD42021286607) (https://www.crd.york.ac.uk/PROSPERO/).

Search strategy

Two main reviewers searched for indexed articles published in the PubMed, Scopus, Embase and CENTRAL databases between 21/11/2021 and 10/01/2022.

The following search terms were screened in title, abstract and keywords using the AND Boolean logic operator:

(("volcanic eruption") OR ("volcanic ash") OR ("volcano") OR ("volcanic ash") OR ("volcanic gas") OR ("volcanic water quality") OR ("volcanic water pollution") OR ("volcanic water contamination") OR ("volcanic air pollution") OR ("volcanic air pollution")) AND (("pneumonia") OR ("ards") OR ("respiratory disease") OR ("asthma") OR ("silicosis") OR ("lung cancer") OR ("psychological effects") OR ("thyroid cancer") OR ("bronchospasm") OR ("giardiasis") OR ("occular disease") OR ("dental fluorosis") OR ("multiple sclerosis") OR ("kaposi sarcoma") OR ("mesothelioma") OR ("asbestosis") OR ("food insecurity") OR ("podoconiosis") OR ("medical effects") OR ("Health hazards") OR ("health impact"))

Eligibility criteria

The search was performed in English, French, Portuguese, German, Italian and Spanish languages. Only original research studies with quantitative analysis were considered, thereby excluding reviews, short communications, posters, and conference abstracts.

The studies identified through electronic searches were listed in Rayyan. After the exclusion of duplicate citations, two independent reviewers screened titles and abstracts, followed by full-text reviews if discrepancies exist. The article was discarded if the study did not assess volcanic eruptions or human health effects. Discrepancies were solved through consensus. The reference lists of all included articles were also cross-checked for relevant studies.

The inclusion and exclusion criteria for selected studies are listed in Table 1.

Table 1. Eligibility criteria.

Inclusion criteria	Exclusion criteria
Original research studies	Other type of study
Studies must refer to volcanic eruptions and/or related factors	Not assessing volcanic eruptions and/or related factors
Studies must assess human health	Not assessing the impact of volcainc eruptions on human health
Languages: English, French, Portuguese, Italian, German and Spanish	Assessing only material damage of volcanic eruptions

A PRISMA flowchart summarizing the search and inclusion/exclusion process was produced.

Data collection and analysis

The selected papers were systematically and thematically analyzed. Each reviewer read all of the selected articles and entered the information of interest and the variables into a concept database, including: identifier, reference, first author, year of publication, journal, country of the study, time frame of observed data or year of study, aim, data source, volcano, health effects, study design, analytical approach, summary of the results, impact on human health (Yes/No) and projected or observed changes in disease epidemiology. We divided health effects into short- and long-term if the volcanic eruption occurred less or more than a year ago.

Quality assessment

To evaluate the internal and external validity of the selected publications, a 12-item quality assessment tool was used and adapted[11]. The quality of each manuscript was assessed by reviewing the study objective/s, study design, data presentation and discussion, granting 1 if the criterion was met, and zero if it was not. The maximum achievable total score was 12 points.

A standardized Excel (Version 2010, Microsoft Corporation, Richmond, WA, USA) spreadsheet was used to extract information from the included studies. References retrieved were saved in Zotero software 5.0.67 (www.zotero.org). We also used the free systematic review tool Rayyan (https://www.rayyan.ai/).

Results

The search strategy yielded 565 articles, of which 129 duplicated articles were excluded. We retained 176 articles for full-text screening after excluding 260 articles after screening the titles and abstracts. Finally, 57 studies were included in the review [12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43][44][45][46][47][48][49][50][51][52][53][54][55][56][57][58][59][60][61][62][63][64][65][66][67][68]. Figure 1 presents the PRISMA chart of the study selection process.

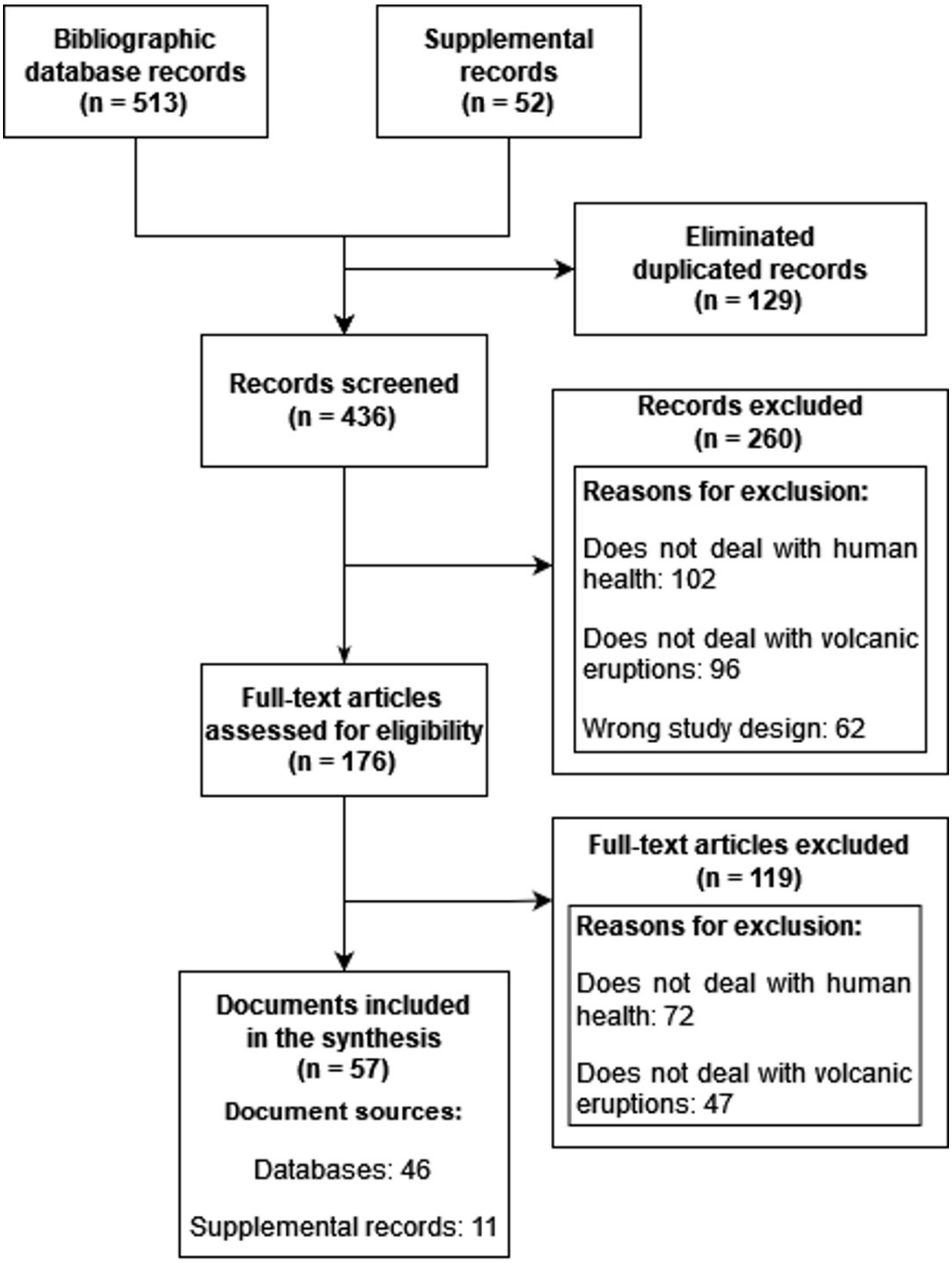

Figure 1. Study selection process.

Descriptive characteristics of the studies

Most studies have been published since 2003 (n=39). The countries where human health effects of volcanic eruptions were studied most frequently were the United States of America (USA) (n=15) and Italy (n=11). Similarly, the majority of analyzed erupted volcanoes were in the USA (n=15) and Italy (n=11). In addition, 31 studies focused on long-term human health effects. The descriptive characteristics of the included studies are shown in Table 2.

Table 2. Characteristics of the papers included in this study (n=57).

ID	First author	Publication year	Effects	Country	Region	Volcano	Volcano type	Volcanic hazards	Analyzed disease groups	Increased health conditions after eruption	Diseases	Analytic approach
1	Forbes L (17)	2003	ST	France	Montserrat	Mt Soufrière Hills	Lava dome	Ash	Respiratory	Yes	Broncoespasmo/Asthma	Time series analysis

2	Baxter PJ (18)	1983	ST	USA	Yakima, Washington	Mt Saint Helens	Stratovolcano	Ash	Respiratory	Yes	Asthma, bronchitis & chronic lung disease	Case-control
3	Longo BM (19)	2010	ST	USA	Ka'u District, Hawaii	Mt Kilauea	Shield volcano	Vog & SO2	Respiratory, ophthalmological & otorhinolaryngological	Yes	Asthma, bronchitis, chronic lung disease	Retrospective cohort
4	Naumova EN (20)	2007	ST	Ecuador	Quito	Mt Guagua Pichinch	Stratovolcano	Ash	Respiratory	Yes	Asthma	Time series analysis
5	Weniger BG (21)	1983	ST	USA	Red Lodge, Montana	Mt Saint Helens	Stratovolcano	Water pollution	Gastronintestinal	Yes	Giardia lamblia	Time series analysis
6	Nania J (22)	1982	ST	USA	Spokane, Washington	Mt Saint Helens	Stratovolcano	Ash	Respiratory	Yes	Asthma, bronchitis, pneumonia & COPD/emphysema	Time series analysis
7	Heaviside C (23)	2021	ST	UK	NS	Mt Bárðarbunga	Stratovolcano	SO2 & SO4	Cardiorespiratory	Yes	Hospital admission & death	Predictive model
8	Michellier C (24)	2020	ST	Democratic Republic of Congo	Goma	Mt Nyamulagira & Mt Nyiragongo	Shield volcano & Stratovolcano	SO2	Respiratory	Yes	Acute respiratory syndrome	Time series analysis
9	Carlsen HK (25)	2015	ST	Iceland	Reykjavík	Mt Eyjafjallajökull & Mt Grímsvötn	Stratovolcano & shield volcano	PM10	Cardiorespiratory	Yes	Hospital admission	Time series analysis
10	Lombardo D (26)	2013	ST	Italy	Sicily	Mt Etna	Stratovolcano	Ash	Cardiorespiratory & ophthalmological	Yes	NS	Retrospective cohort
11	Viane C (27)	2009	ST	France	Reunion Island	Mt Piton de la Fournaise	Shield volcano	SO2	Respiratory	No		Time series analysis
12	Hickling J (28)	1999	ST	New Zealand	NS	Mt Ruapehu	Stratovolcano	Ash	Cardiorespiratory	Yes	COPD, ischemic heart disease & stroke	Case-control
13	Kraemer MJ (29)	1985	ST	USA	Spokane County, Washington	Mt Saint Helens	Stratovolcano	Air pollution	Respiratory	Yes	Asthma	Transversal
14	Merchant JA (30)	1982	ST	USA	Washington, Idaho, Montana & North Dakota	Mt Saint Helens	Stratovolcano	Ash & gas	Respiratory	Yes	Various	Case-control
15	Le Guern F (31)	1982	ST	Indonesia	Java	Diëng Plateau	Caldera	Gas	Respiratory	Yes	Suffocation	Transversal
16	Baxter PJ (32)	1981	ST	USA	Washington & Oregon	Mt Saint Helens	Stratovolcano	Air pollution	Respiratory	Yes	Asthma, bronchitis & hyperventilation	Transversal
17	Carlsen HK (33)	2021	ST	Iceland	Reykjavík	Mt Bárðarbunga	Stratovolcano	Air pollution	Respiratory	Yes	Asthma, infections & COPD	Predictive model
18	Bergin CJ (34)	2021	ST	New Zealand	NS	Mt Whakaari/White Island	Stratovolcano	PM10	Respiratory	Yes	Radiological changes	Transversal
19	Carlsen HK (35)	2012	ST	Iceland	NS	Mt Eyjafjallajökull	Stratovolcano	Ash	Respiratory, ophthalmological, musculoskeletal, dermatological & mental	Yes	Various	Retrospective cohort
20	Carlsen HK (36)	2012	ST	Iceland	Vík	Mt Eyjafjallajökull	Stratovolcano	Ash	Respiratory, ophthalmological, neurological, gastrointestinal & mental	Yes	Various	Transversal
21	Shimizu Y (37)	2007	ST	Japan	Gunma	Mt Asama	Stratovolcano	Ash	Respiratory	Yes	Asthma	Transversal
22	Fano V (38)	2010	ST	Italy	Sicily	Mt Etna	Stratovolcano	Ash	Cardiorespiratory, ophthalmological & orthopedic	No		Time series analysis
23	Baxter PJ (39)	1989	ST	Cameroon	NS	Lake Nyos	Crater lake	Gas	Respiratory, ophthalmological, dermatological, musculoskeletal, gastrointestinal & neurological	Yes	Various	Transversal
24	Wilkie MEM (40)	2010	ST	Iceland	NS	Mt Eyjafjallajökull	Stratovolcano	Ash	Respiratory	Yes	Asthma & COPD	Transversal
25	Oudin A (41)	2013	ST	Sweden, Norway, Finland	NS	Mt Grímsvötn	Shield volcano	Ash	Mortality	Ambiguous	Death	Transversal
26	Johnson KG (42)	1982	ST	USA	Missoula, Montana	Mt Saint Helens	Stratovolcano	Ash	Respiratory	No		Transversal
27	Amaral AFS (43)	2007	LT	Portugal	Azores	NS	NS	Gas, Rn, CO2	Respiratory	Yes	Bronchitis	Transversal
28	Amaral A (44)	2006	LT	Portugal	Azores	NS	NS	Gas, Rn, CO2	Cancer	Yes	Various	Transversal
29	Michaud JP (45)	2004	LT	USA	Hilo, Hawaii	Mt Kilauea	Shield volcano	PM10 & vog	Cardiorespiratory, infectious & gastrointestinal	Yes	Asthma, bronchitis, pneumonia & COPD	Transversal

									gastrointestinal			
30	Ng'walali PM (46)	1999	LT	Japan	Kumamoto	Mt Aso	Caldera	Gas	Respiratory	Yes	Death	Transversal
31	Buist AS (47)	1986	LT	USA	Washington & Oregon	Mt Saint Helens	Stratovolcano	Ash	Respiratory	No		Cross-sectional
32	Russo M (48)	2015	LT	Italy	Sicily	Mt Etna	Stratovolcano	Ash, heavy metals & gas	Cancer	Yes	Thyroid, lymphatic leukemia, Hodgkin's lymphoma, stomach, breast & prostate	Transversal
33	Nicoletti A (49)	2013	LT	Italy	Sicily	Mt Etna	Stratovolcano	Heavy metals	Neurological	Yes	Multiple sclerosis	Transversal
34	Higuchi K (50)	2012	LT	Japan	Sakurajima & Tarumizu	Mt Sakurajima	Stratovolcano	Ash	Respiratory & cancer	Yes	Death	Transversal
35	Chow DC (51)	2010	LT	USA	Hawaii	Mt Kilauea	Shield volcano	Vog & SO2	Cardiorespiratory	No		Cross-sectional
36	Ohta Y (52)	2003	LT	Japan	Nagasaki	Mt Unzen	Stratovolcano	Mental	Mental	Yes	Psychological distress	Cross-sectional
37	Ohta Y (53)	1998	LT	Japan	Nagasaki	Mt Unzen	Stratovolcano	Mental	Mental	Yes	Psychological distress	Cross-sectional
38	Lima BR (54)	1987	LT	Colombia	Armero	Mt Nevado del Ruiz	Stratovolcano	Mental	Mental	Yes	Psychological distress	Transversal
39	Shore JH (55)	1986	LT	USA	Washington	Mt Saint Helens	Stratovolcano	Mental	Mental	Yes	Psychological distress	Transversal
40	Hlodversdottir H (56)	2016	LT	Iceland	NS	Mt Eyjafjallajökull	Stratovolcano	Ash	Cardiorespiratory, ophthalmological, dermatological, musculoskeletal & mental	Ambiguous	Various	Retrospective cohort
41	Boffetta P (57)	2020	LT	Italy	Sicily	Mt Etna	Stratovolcano	Gas	Cancer	Yes	Thyroid	Transversal
42	Allibone R (58)	2012	LT	Vanuatu	NS	Mt Ambrym	Shield volcano	Gas	Dental	Yes	Dental fluorosis	Transversal
43	Yano E (59)	1990	LT	Japan	Kyushu	Mt Sakurajima	Stratovolcano	Ash	Respiratory	No		Transversal
44	Choudhury AH (60)	1997	LT	USA	Anchorage, Alaska	Mt Spurr	Stratovolcano	Ash	Respiratory	Yes	Asthma & bronchitis	Predictive model
45	Tam E (61)	2016	LT	USA	Hawaii	Mt Kilauea	Shield volcano	Gas	Respiratory	Ambiguous	Asthma, bronchitis & COPD	Predictive model
46	Yano E (62)	1986	LT	Japan	Kyushu	Mt Sakurajima	Stratovolcano	Ash	Respiratory	Yes	Asthma & bronchitis	Transversal
47	Zabert I (63)	2020	LT	Argentina	San Carlos de Bariloche & Cipolletti	Mt Calbuco	Stratovolcano	Ash	Respiratory	No		Transversal
48	Nicoletti A (64)	2020	LT	Italy	Catania, Sicily	Mt Etna	Stratovolcano	Ash	Neurological	Yes	Multiple sclerosis	Transversal
49	Linhares DPS (65)	2018	LT	Portugal	Azores	Mt Furnas	Stratovolcano	Gas, Rn	Respiratory & cancer	Yes	Lung	Transversal
50	Malandrino P (66)	2016	LT	Italy	Sicily	Mt Etna	Stratovolcano	Gas	Cancer	Yes	Thyroid	Transversal
51	Linhares D (67)	2015	LT	Portugal	Azores	Mt Furnas	Stratovolcano	Gas	Respiratory	Yes	COPD	Transversal
52	van Manen SM (68)	2014	LT	Nicaragua	NS	Mt Masaya	Shield volcano	Gas	Respiratory, ophthalmological, dental, nephrological & rheumatological	Yes	Various	Transversal
53	Giacoppo S (69)	2014	LT	Italy	Sicily	Mt Etna	Stratovolcano	Gas, heavy metals	Neurological	Yes	Multiple sclerosis & Alzheimer disease	Transversal
54	Censi P (70)	2011	LT	Italy	Sicily	Mt Etna	Stratovolcano	Ash, PM10	Respiratory	Yes	Pulmonary fibrosis exacerbation	Transversal
55	Pellegriti G (71)	2009	LT	Italy	Catania, Sicily	Mt Etna	Stratovolcano	Water pollution	Cancer	Yes	Thyroid	Transversal
56	Pelser C (72)	2009	LT	Italy	Sicily	NS	NS	Soil contamination	Cancer	Ambiguous	Kaposi sarcoma	Case-control
57	Longo BM (73)	2008	LT	USA	Hawaii	Mt Kilauea	Shield volcano	SO2 & PM10	Cardiorespiratory	Ambiguous	Various	Transversal

CO2: carbon dioxide, COPD: chronic obstructive pulmonary disease, LT: long-term, Mt: mount, NS: not specified, SO2: sulfur dioxide, ST: short-term, UK: United Kingdom, USA: United States of America

Twenty-five different volcanoes were analyzed. The most frequently analyzed volcanoes were Mount Etna (n=10), Mount Saint Helens (n=9) and Mount Kilauea (n=5). Fifteen of the analyzed volcanoes were stratovolcanoes and six were shield volcanoes (Table 2).

The main limitations were the lack of individual data[18][21][38][42][44][46][47][49] and the inability to measure all volcanic factors independently and thus establish associations [12][14][15][18][19][21][22][47][52][55].

Short-term human health effects of volcanic eruptions

Short-term human health effects were addressed in 26 studies. Most studies were performed in the USA (n=8) and Iceland (n=5). The most frequently analyzed volcanoes were Mount Saint Helens (n=7) in the USA, Mounts Eyjafjallajökull (n=4), Holuhraun (n=2) and Grímsvötn (n=2) in Iceland and Mount Etna in Italy (n=2). Other volcanoes were Lake Nyos Volcanic Plateau (n=1) in Cameroon; Mounts Nyamulagira and Nyiragongo (n=1) in the Democratic Republic of Congo (DRC), Mount Guagua Pichincha (n=1) in Ecuador, Mount Piton de la Fournaise (n=1) in France, the Indonesian Diëng Plateau (n=1), Japanese Mount Asama (n=1), Mounts Ruapehu (n=1) and Whakaari (n=1) in New Zealand, the British Soufriere Hills (n=1) and Mount Kilauea (n=1) in the USA. In addition, the short-term human health effects of Icelandic Mounts Grimsvötn and Holuhraun were analyzed in nearby countries Sweden, Norway, and Finland for the first one (n=1) and in the United Kingdom (UK) for the latter (n=1) (figure 2, table 2).

Figure 2. Countries where studies were performed and analyzed volcanoes, as well as observed short-term increases of certain diseases (n=26).

The main volcanic pollutants were volcanic ash (n=15), volcanic gases such as sulfur dioxide and carbon dioxide (n=7), volcanic vog (n=4) and other, like the emission of pyroclasts (n=1), glass (n=1) and lava (n=1) (table 2).

Studies focused on effects on respiratory health (n=24), especially asthma (n=13) and chronic obstructive pulmonary disease (COPD) (n=9); cardiovascular diseases (n=6) like ischemic myocardiopathy (n=3) and ophthalmologic health (n=6). Other analyzed health effects were digestive (n=3), musculoskeletal (n=3), neurological (n=2), mental health issues (n=2), dermatological (n=2), otorhinolaryngological (n=1) and overall mortality (n=3). Ten studies focused on more than one outcome (Table 2).

Most studies observed an increase in the analyzed diseases and human health effects because of volcanic eruptions (n=21). Increases were observed in respiratory (n=20), ophthalmological (n=5), cardiovascular (n=3), digestive (n=3), neurological (n=2), dermatological (n=2), musculoskeletal (n=2), mental health (n=2), otorhinolaryngological diseases (n=1) and overall mortality (n=2). The eruption of Mount Saint Helens in 1980 was related to increases in respiratory diseases, especially asthma and acute bronchitis (n=5), *Giardia lamblia* infections and overall mortality in the first twelve months after eruption. The eruption of Mount Eyjafjallajökull in 2010 and the exposure to volcanic ashes were related to increases in respiratory (n=4), ophthalmological (n=2), musculoskeletal, cardiovascular, dermatological, neurological, and mental health issues in the first months after the eruption. Similarly, eruptions of other Icelandic volcanoes were related to increases in asthma exacerbations. A positive association between exposure to volcanic ash from the 2002 eruption of Mount Etna and acute respiratory and ophthalmologic health effects in the following days and weeks was observed in nearby residents. Signs of asphyxia were observed after the 1979 eruption of the Diëng Plateau in Java. Eruptions of Mount Soufriere in 1995, Mount Kilauea in 2008, Mount Guagua Pichincha, Mount Nyamulagira in 2004 and Mount Nyiragongo in 2006, Mount Asama in 2004, Mount Whakaari in 2019 and Lake Nyos in 1986 led to increased respiratory morbidity. In addition, episodes of diarrhea, nausea, ocular irritation, and muscle weakness, among others, were reported after the Lake Nyos outbreak (figure 2, table 2).

Only a few studies observed no changes in disease epidemiology (n=3) or showed contradictory results, i.e., both increases and decreases in disease incidence and prevalence (n=2). Contradictory results were observed if more than three months or less than three days had passed since the volcanic eruption. No global increases in asthma exacerbations were observed in the days and weeks following an eruption of Mount Piton de la Fournaise and sulfur dioxide emission (n=1). In addition, the eruption of Mount Etna and the exposure to its ashes showed no increase in overall mortality or cardiorespiratory disease incidence in the 47 days following the eruption, nor did the ashes of Mount Saint Helens in the first three days after its eruption. Uncertainty remains about the effect of Mount Ruapehu ashes in the first three months of posteruption on cardiorespiratory health and about the effect on overall mortality of Mount Grímsvöttn's ashes in nearby countries (Table 2).

Long-term human health effects of volcanic eruptions

Long-term human health effects were addressed in 31 studies. Most studies were performed in Italy (n=9), the USA (n=7) and Japan (n=4). The most frequently analyzed volcanoes were Mount Etna in Italy (n=8), Mount Kilauea in the USA (n=4) and Mount Sakurajima in Japan (n=3). Three studies did not specify any volcano but focused on islands with volcanic activity, specifically the Azores in Portugal (n=2) and Sicily in Italy (n=1) (Figure 3, Table 2).

Figure 3. Countries where studies were performed and analyzed volcanoes, as well as observed long-term increases of certain diseases (n=31).

The main volcanic pollutants were volcanic gases such as sulfur dioxide or radon (n=15), volcanic ash (n=9), volcanic vog (n=2) or elements in water and soil (n=5) (table 2).

Five studies addressed the mental consequences of surviving a volcanic eruption. Other studies focused on cancer incidence (n=8), respiratory health (n=6), cardiovascular diseases (n=4) and neurological pathologies (n=3). Other analyzed health effects were digestive (n=1), musculoskeletal (n=2), dermatological (n=1) ophthalmologic health issues (n=2) and nephrological diseases (n=1), as well as adverse odontology outcomes (n=2). Five studies focused on more than one outcome (Table 2).

Most studies observed an increase in the analyzed diseases and human health effects because of volcanic eruptions (n=23). Increases were observed in respiratory disease (n=10), cancer (n=8), ophthalmological (n=1), cardiovascular (n=1), digestive (n=1), neurological (n=3), dermatological (n=2) and musculoskeletal disease incidence (n=1), as well as mental health (n=4) and odontology issues (n=1). The exposure to Mount Etna ashes and trace elements was related to an increased incidence of thyroid cancer (n=3) and other cancers and multiple sclerosis (n=3). An increase in respiratory disease incidence and mortality was observed in the inhabitants of municipalities that were close to Mount Sakurajima. Increased psychological distress was reported in evacuees from Mount Unzen (n=2), Mount Nevado del Ruiz and Mount Saint Helens. Chronic exposure to Mount Ambym gases was related to dental fluorosis (Figure 3, Table 2).

Only a few studies observed no changes in disease epidemiology (n=4) or showed contradictory results, i.e., both increases and decreases in disease incidence and prevalence (n=4). No global increases in respiratory (n=3) or cardiac disease (n=1) were observed after chronic exposure to ashes and vog from Mount Saint Helens, Mount Kilauea, Mount Sakurajima, or Mount Calbuco. Chronic exposure to Mount Kilauea gases and vog were related to increased coughing and phlegm, but not to other pathologies, as was the exposure to the 2010 Eyjafjallajökull eruption. In addition, one study showed contradictory results about the relationship between exposure to Mount Etna soil and the development of Kaposi sarcoma (Table 2).

Discussion

We observed that the most common human health effects, both short- and long-term, were respiratory diseases [12][13][14][15][17][18][19][20][21][23][24][26][27][28][29][30][31][32][34][35][38][40][41][45][55][57][60][62][63][65][69]. These pathologies occurred mainly because of exposure to ash [12][13][15][17][21][23][25][30][31][32][35][45][55][57][65] and volcanic gases [25][26][34][38][41][60][62][63]. The effects of volcanic ash depend not only on exposure itself, but also on the composition of ash. Ash often contains heavy metals and other minerals that may irritate the respiratory tract or may lead to lung deposition that causes long-term effects. In addition, smaller ash particles penetrate deeper into the lung [1]. Short-term effects of volcanic ash and gases produce changes in histology and compromise pulmonary function, which ultimately leads to long-term effects like emphysema [70].

In addition, a short-term rise in infectious diseases was observed[16][30][34]. Following a natural disease, infectious disease outbreaks are common due to the displacement of evacuees and environmental changes [71].

Cancer, especially thyroid cancer, was observed in studies in Italy[43][52][61][66], Portugal [39][60] and Japan [45]. Environmental pollutants, such as iodine, nitrate, asbestos, benzene, formaldehyde, and pesticides are known risk factors for thyroid cancer [72]. Minerals and trace elements that are often released during volcanic eruptions include vanadium, selenium, zinc, iodine, cadmium, and sulphur thiocyanates and may be involved in thyroid carcinogenesis [73].

Most analysed volcanoes were stratovolcanoes [13][15][16][17][18][19][20][21][23][24][25][27][28][29][30][31][32][33][35][37][42][43][44][45][47][48][49][50][51][52][54][55][57][58][59][60][61][62][64][65][66]. These volcanoes are known for their explosive eruptions as a result of gas building in their viscous lava [4], which might explain their damaging effects and threat to human health. However, we cannot exclude that health hazards due to the eruption of other volcanoes in other regions of the world might be underreported.

Our study has some shortcomings. Our search was bound to certain inclusion criteria, thus excluding articles that did not meet our criteria but that might provide additional evidence. In addition, the included studies presented different methodological quality. However, to limit this bias we used a specific tool for quality evaluation.

Conclusion

Volcanic eruptions pose a significant threat to human health. The most common human health effects are of a respiratory nature because of exposure to volcanic ash and gas. In the long term, volcanoes might produce cancer, especially thyroid cancer. Although most studies observed effects on human health, some contradictory results were observed. Therefore, we recommend focussing research on this issue to clarify how volcanic eruptions can affect human health in the short- and long-term.

Statements and Declarations

- CRediT roles: Conceptualization: CG, GAB; Data curation: CG, GAB; Formal analysis: CG, GAB; Investigation: CG, GAB; Methodology: CG, GAB; Project administration: CG, GAB; Validation: CG, GAB; Visualization: CG, GAB; Roles/Writing - original draft: CG, GAB; Writing - review & editing: CG, GAB.
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