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PERSPECTIVES

Volcanic air pollution and human health: recent advances and future directions

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Abstract
Volcanic air pollution from both explosive and effusive activity can affect large populations as far as thousands of kilometers away from the source, for days to decades or even centuries. Here, we summarize key advances and prospects in the assessment of health hazards, effects, risk, and management. Recent advances include standardized ash assessment methods to characterize the multiple physicochemical characteristics that might influence toxicity; the rise of community-based air quality monitoring networks using low-cost gas and particulate sensors; the development of forecasting methods for ground-level concentrations and associated public advisories; the development of risk and impact assessment methods to explore health consequences of future eruptions; and the development of evidence-based, locally specific measures for health protection. However, it remains problematic that the health effects of many major and sometimes long-duration eruptions near large populations have gone completely unmonitored. Similarly, effects of prolonged degassing on exposed populations have received very little attention relative to explosive eruptions. Furthermore, very few studies have longitudinally followed populations chronically exposed to volcanic emissions; thus, knowledge gaps remain about whether chronic exposures can trigger development of potentially fatal diseases. Instigating such studies will be facilitated by continued co-development of standardized protocols, supporting local study teams and procuring equipment, funding, and ethical permissions. Relationship building between visiting researchers and host country academic, observatory, and agency partners is vital and can, in turn, support the effective communication of health impacts of volcanic air pollution to populations, health practitioners, and emergency managers.

Keywords Volcanic emissions · Air pollution · Review · Health effects · Health hazard assessment · Risk management

Introduction

Globally, over a billion people are estimated to live within 100 km of an active volcano (Freire et al. 2019). Volcanic eruptions may cause injuries and fatalities via a range of hazardous phenomena (e.g., pyroclastic density currents, ballistics, lahars, lava flows, and localized accumulations or flows of asphyxiant gases such as CO_2 and H_2S), affecting communities within tens of kilometers of the vent (Brown et al. 2017). Eruptions may also displace large numbers of people temporarily or permanently (Cuthbertson et al. 2020) with cascading health and social impacts including disease outbreaks due to overcrowding, food insecurity, mental health issues, and violence (Connell and Lutkehaus 2017). Airborne volcanic emissions, often referred to as "volcanic air pollution" (Tam et al. 2016; Crawford et al. 2021), can also present chronic, far-reaching hazards which may have harmful and long-lasting effects on populations across large geographic areas (Oppenheimer et al. 2003). Here, we address the state of knowledge regarding volcanic air pollution and health. This includes a discussion of hazard assessment methods, a summary of reported human health effects, a review of risk assessment, population preparedness and

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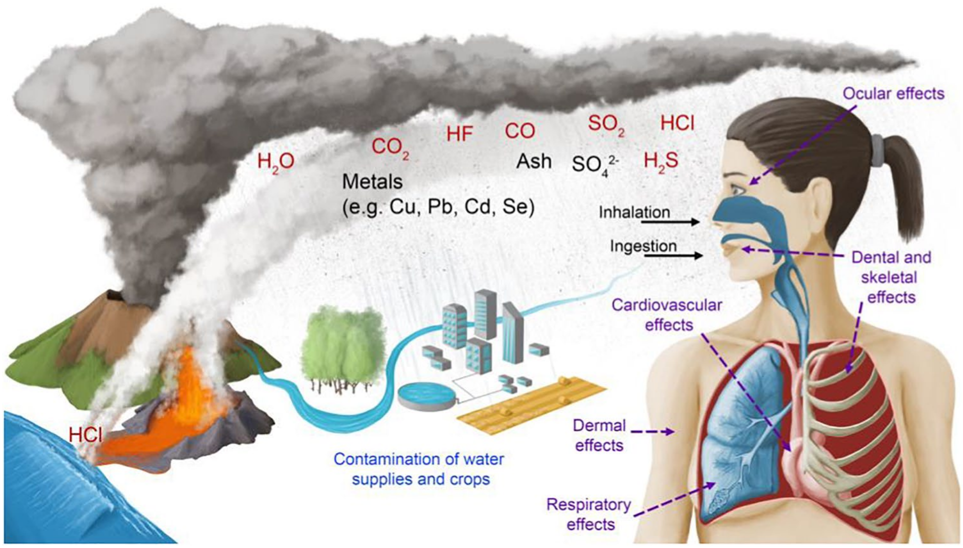

Fig. 1 Volcanic emission components, exposure pathways, and categories of human health effects. Gaseous species are shown in red and particulate species in black. The upper plume represents airborne emissions from an explosive eruption, while the lower plume is generated by effusive activity. A steamy "laze" plume, created by interaction of molten lava with seawater, contains hydrochloric acid, various metals, and volcanic glass particles. Important plume processes include gas to particle conversion and adsorption of gas onto silicate ash surfaces. Contamination of water supplies by volcanogenic fluoride (from gaseous HF) is proposed to be the major ingestion pathway leading to human dental and skeletal effects.

protection practices, and a discussion of emerging themes and future directions.

Volcanic emission hazards

Airborne volcanic emissions comprise variable mixtures of silicate ash, gases (H_2O, CO_2, SO_2, H_2S, CO, HF, and HCl), volatile metal vapors, and sulfate aerosol, formed through SO_2 gas-to-particle conversion (Fig. 1; Oppenheimer et al. 2003). Ash can be generated during a variety of eruptive processes and can contain substantial amounts of respirable-sized particles (<4 µm diameter) that can penetrate into the lungs (Horwell 2007). The physical and chemical properties of ash can vary significantly across eruptions and with distance (Jenkins et al. 2015). As volcanic gases cool and react in the atmosphere, they may condense into particles and/or adsorb to ash surfaces (Oppenheimer et al. 2003). Volcanic aerosol particles formed through gas condensation are extremely fine-grained, typically ~0.2–0.5 µm in diameter (Mather et al. 2003). Volcanic particulate matter (PM) thus encompasses a heterogeneous mixture of ash PM and acidic sulfate- and metal-bearing aerosol PM. A further airborne hazard is generated when lava flows into seawater, generating a "laze" (lava + haze) plume that contains HCl, volcanic glass fragments, and various metals (Mason et al. 2021; Fig. 1).

Sulfur gases (in particular SO_2), sulfate aerosol, and ash are the most important airborne hazards for population-scale, longer-term impacts and have been shown to affect air quality locally as well as hundreds to thousands of kilometers from source during large fissure or explosive eruptions (e.g., Schmidt et al. 2011, 2015; de Lima et al. 2012; Durant et al. 2012; Eychenne et al. 2015; Ilyinskaya et al. 2017). Many of the volatile trace elements emitted by volcanoes are classified as metal pollutants by environmental and health protection agencies (e.g., lead, zinc, arsenic, cadmium),[1] and emission rates can reach levels comparable to anthropogenic fluxes from industrialized countries (Ilyinskaya et al. 2021). Near persistently degassing volcanoes, elevated levels of metals have been reported in air, soils, surface waters, and plants (Delmelle 2003), which are common exposure sources for humans (Prüss-Ustün et al. 2011), especially in areas where communities consume catchment or surface water and locally grown crops. Persistent degassing is also the source of fluoride contamination of water resources close to certain volcanoes, notably Ambrym and Tanna, Vanuatu (Cronin and Sharp 2002; Allibone et al. 2012; Webb et al. 2021). Acidified rainfall from persistent degassing can leach lead from plumbing fittings or roofing materials into roof catchment rainwater tanks (Macomber 2020). Ash deposition into water supplies can raise concentrations of fluoride and other potentially toxic elements (e.g., copper, manganese) as well as elements that impart an unpleasant taste or color to the water (Stewart et al. 2006, 2020).

[1] https://uk-air.defra.gov.uk/networks/network-info?view=metals

Hazard and exposure assessment

In an eruption crisis, it is rare for there to be an immediate assessment of the health impact of exposure to volcanic air pollution. With limited resources, health agencies must prioritize ensuring sanitary conditions for evacuated communities and monitoring these communities for infectious disease outbreaks, as well as dealing with casualties. In lieu of data to directly measure the health impact, the physicochemical characteristics of the emissions, along with exposure concentrations and durations, may be assessed to get a first indication of whether they may be hazardous to human health.

For volcanic ash, characteristics that inform whether ash may cause harm if inhaled or ingested include particle size, particle shape, surface area, and the presence of leachable elements. Additional, specific hazards can vary according to magma composition and eruption dynamics. For lava dome-related or intermediate to felsic explosive ash samples, crystalline silica (quartz and its polymorphs) is important to quantify as it is the mineral of greatest health concern in ash due to its capacity to cause disease in industrial settings (Baxter et al. 1999; Greenberg et al. 2007). For mafic samples, reactive surface iron and associated generation of free radicals, which are implicated in respiratory diseases (Kelly 2003), can be determined (Horwell et al. 2007). Leachate analyses can determine concentrations of readily soluble elements on fresh ash particles relevant to inhalation or ingestion pathways. These methods may require adaptation for ash from hydrothermal system eruptions which typically contain fluoride in slowly soluble forms (Cronin et al. 2014; Stewart et al. 2020). Ash can also scavenge biologically potent organic pollutants from the atmosphere (Tomašek et al. 2021a). Toxicological assays can be used to assess whether the ash can trigger a biological response, which gives an indication of potential pathogenicity for humans (Damby et al. 2016).

The International Volcanic Health Hazard Network (IVHHN)[2] has developed methods and protocols for rapid, standardized screening of ash samples (Le Blond et al. 2009; Horwell 2007; Horwell et al. 2007; Stewart et al. 2020; Tomašek et al. 2021b), which have been applied during various eruption crises. Table 1 presents post-2000 studies that have determined health-relevant characteristics of ash samples and whether they have used IVHHN methods or not. The major challenges associated with ash characterization relate to timely collection of ash samples, prior capacity building and training in suitable laboratories, funding analyses, and shipping of samples, given that transportation is often disrupted during an eruption. In practice, analyses are rarely completed within the days to weeks over which acute exposures may be occurring, so cannot be relied upon to inform decision-making. Thus, in advance of future eruptions, the hazard could be informed by study of archived ash samples from historic eruptions (Hillman et al. 2012; Horwell et al. 2010b, 2017; Damby et al. 2017).

Exposure to volcanic emissions rarely occurs in clean atmospheres, raising concerns about co-exposures of volcanic emissions and existing air pollution, particularly in urban areas. Preliminary work on these combined hazards indicates that the specific mixture may be important, with a heightened pro-inflammatory response (in laboratory in vitro tests) reported for simultaneous exposure to respirable ash and diesel exhaust particles (Tomašek et al. 2016) but not for ash and complete gasoline exhaust (Tomašek et al. 2018).

Real-time monitoring of airborne gas and PM concentrations can be used as a proxy for assessing population exposure during eruptions, for persistent degassing, and for post-eruption ash resuspension episodes (Wilson et al. 2011). Indoor and outdoor measurements may be made via fixed monitors or portable sensors. Ambient air quality limits exist for airborne contaminants common to volcanic emissions such as PM_{10}, $PM_{2.5}$, and SO_2, and monitoring data can be used to help alert both healthy and sensitive populations. However, air quality monitoring equipment is not installed at many volcanic locations, and installing instrumentation following eruption onset can present significant challenges (Felton et al. 2019). This can hinder agencies in making evidence-based decisions on community protection. An additional challenge to characterizing volcanic air pollution is that SO_2 and PM concentrations can vary significantly over short distances and durations (Holland et al. 2020). This issue has received significant attention recently with the introduction of low-cost fixed networks and hand-held, portable sensors that augment higher accuracy but costly regulatory air quality monitoring. These low-cost PM and SO_2 sensors perform reasonably well for monitoring volcanic air pollution in communities, as demonstrated during the Kīlauea 2018 eruption (Whitty et al. 2020; Crawford et al. 2021) and in Iceland (Gíslason et al. 2015). Air quality forecast models can complement ambient air monitoring and now play an important role in informing the public about current and predicted levels of volcanic pollution in some locations (Barsotti 2020; Holland et al. 2020).

Assessment of health effects

Post-2000 clinical and epidemiological studies conducted on communities affected by volcanic emissions are presented in Table 2. Collectively, these studies support pre-2000 findings, from studies conducted predominantly at Mount St. Helens, Soufrière Hills, and Sakurajima, that exposures to airborne volcanic emissions can exacerbate

[2] www.ivhhn.org

Table 1 Peer-reviewed studies reporting health-relevant characteristics of volcanic ash (2001–2021)

Volcano and eruption year	Reference	Ash characterization				Bioreactivity[1]			Leaching[2]		
		Particle size	Surface area	Particle morphology	Crystalline silica	Acellular	In vitro	In vivo	Water leach	Gastric leach	SLF leach
Kīlauea 2018	Tomašek et al. (2021a)[3]								x		x
	Damby et al. (2018a)[3]	x							x		
Ambae 2018	Tomašek et al. (2021a)[3]								x		x
Whakaari 2016	Tomašek et al. (2021a)[3]								x		x
	Stewart et al. (2021)[3]								x		
Copahue 2016	Paez et al. (2021)								x		
	Bia et al. (2020)								x		
Kelud 2014	Tomašek et al. (2021b)	x	x			x					
	Stewart et al. (2020)[3]								x	x	
Sinabung 2014	Stewart et al. (2014)[3]								x	x	
Tongariro 2012	Cronin et al. (2014)[3]								x	x	
Grímsvötn 2011	Horwell et al. (2013)[3]	x	x	x	x	x	x		x		
	Olsson et al. (2013)	x	x	x					x		
Cordón Caulle 2011	Tesone et al. (2018)	x		x			x				
	Stewart et al. (2016)[3]	x							x	x	
	Daga et al. (2014)			x							
	Wilson et al. (2013)	x			x				x		
Eyjafjallajökull 2010	Wygel et al. (2019)		x	x					x		
	Horwell et al. (2013)[3]	x	x	x	x	x	x		x		
	Monick et al. (2013)	x					x		x		
Merapi 2010	Damby et al. (2016)	x		x	x						
	Damby et al. (2013)[3]	x	x	x	x	x	x		x		
	Damby (2012)[3]	x	x	x	x	x	x		x		x
	Budianta (2011)	x			x						
Chaitén 2008	Tomašek et al. (2018)	x		x			x				
	Daga et al. (2014)			x							
	Horwell et al. (2010a)[3]	x	x	x	x				x		
	Reich et al. (2009)			x	x						
Oldoinyo Lengai 2007–2008	Bosshard-Stadlin et al. (2017)[3]								x		
Rabaul 2007–2008	Le Blond et al. (2010)[3]	x	x	x	x	x	x		x		
Langila 2007	Le Blond et al. (2010)[3]	x	x	x	x	x					
Stromboli 2007	Cangemi et al. (2017)								x	x	
El Reventador 2002	Horwell et al. (2007)[3]	x	x			x					
Mt Cameroon 1999	Atanga et al. (2009)	x		x							

Table 1 (continued)

Volcano and eruption year	Reference	Ash characterization				Bioreactivity[1]			Leaching[2]		
		Particle size	Surface area	Particle morphology	Crystalline silica	Acellular	In vitro	In vivo	Water leach	Gastric leach	SLF leach
Yasur and Ambrym 1999	Cronin and Sharp (2002)								x		
Etna 2001–2013	Tomašek et al. (2021b)	x				x					
	Barone et al. (2021)		x						x		x
	Cangemi et al. (2017)								x	x	
	Horwell et al. (2017)[3]	x	x	x		x					
	Horwell et al. (2007)[3]	x	x			x					
	Horwell (2007)[3]	x									
Tungurahua 1999–2014	Tomašek et al. (2021b)	x				x					
	Horwell et al. (2007)[3]	x	x			x					
	Horwell (2007)[3]	x									
Soufrière Hills 1997–2010	Tomašek et al. (2019)	x		x			x				
	Damby et al. (2018b)	x	x	x			x				
	Tomašek et al. (2018)	x		x			x				
	Tomašek et al. (2016)	x	x	x			x				
	Damby et al. (2016)	x		x	x		x				
	Horwell et al. (2014)[3]				x						
	Jones and BéruBé (2011)					x					
	Horwell et al. (2007)[3]	x	x			x					
	Horwell (2007)[3]	x									
	BéruBé et al. (2004)							x			
	Horwell et al. (2003a)[3]	x		x	x						
	Horwell et al. (2003b)[3]		x			x					
	Cullen et al. (2002)							x			
Popocatépetl 1994–2008	Armienta et al. (2011)								x		
	Armienta et al. (2002)	X							x		
	Nieto-Torres and Martin-Del Pozzo (2021)	x		x	x						
Fuego 1974–2018	Tomašek et al. (2021b)	x				x					
	Horwell et al. (2007)[3]	x	x			x					
Sakurajima 1471–2013	Tomašek et al. (2021b)	x				x					
	Hillman et al. (2012)[3]	x	x	x		x					
	Horwell (2007)[3]	x									

Table 1 (continued)

Volcano and eruption year	Reference	Ash characterization				Bioreactivity[1]			Leaching[2]		
		Particle size	Surface area	Particle morphology	Crystalline silica	Acellular	In vitro	In vivo	Water leach	Gastric leach	SLF leach
Ancient samples											
Icelandic volcanoes: (Askja, Hekla, Katla, Grímsvötn, Öræfajökull, Reykjanes, Snæfellsjökull, Bárðarbunga) 4.2 ka BP to 1980	Damby et al. (2017)[3]	x	x	x	x	x					
Italian and Greek volcanoes: Vulcano (1888–1890), Santorini (Minoan, ~172 kA), Nea Kameni (1613 BCE), Milos (~480 kA)	Cangemi et al. (2017)								x	x	
Vesuvius 2710 ± 60 BP to 1944	Cangemi et al. (2017)								x	x	
	Horwell et al. (2010b)[3]	x	x	x	x	x					
	Horwell (2007)[3]	x									

[1]Bioreactivity assays are divided into acellular tests (laboratory tests of particle reactivity without cells), in vitro tests (with cellular models), and in vivo tests (with animal models)

[2]Ash-leachate studies are categorized by the leachant used: water, gastric (intended to mimic the chemistry of the gut), and SLF (synthetic lung fluid, which mimics the chemistry of the airways)

[3]Study conducted using standardized IVHHN methods

Table 2 Peer-reviewed health studies[1] of human exposure to volcanic emissions (2001–2021)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Primary studies						
Ambrym and Yasur, Vanuatu (2005 degassing)	Allibone et al. (2012)	HF gas, F in drinking water	Children (6–18 yrs) from islands Ambrym, Malekula, Tongoa and Tanna ($N = 835$)	Pediatric dental health survey: high prevalence of dental fluorosis especially in children exposed proximal to degassing or in volcanic plume pathway; no difference in prevalence related to gender	Epidemiological descriptive study: cross-sectional health screening of exposed population	Low to moderate
Asama, Japan (2004 eruption)	Shimizu et al. (2007)	Ashfall	Resident adult patients with asthma ($N = 236$)	Asthma disease management: reports of acute asthma symptoms, lung function effects, 43% had symptom exacerbations, patients with mild-moderate disease most at risk, behavioral interventions effective (e.g. staying indoors)	Descriptive comparative study: cross-sectional health screening	Moderate to low
Etna, Italy (2002 eruption)	Lombardo et al. (2013)	Ashfall PM_{10} and $PM_{2.5}$	General population of Catania (N >4,000 visits)	Emergency visits for acute cardiorespiratory diseases: significant association for exposure and upper and lower respiratory, cardiovascular diseases and eye symptoms	Epidemiological retrospective cohort study: exposed vs unexposed time frames	Moderate
Etna, Italy (2002 eruption)	Fano et al. (2010)	Ashfall (proximal) PM_{10}	General population of Catania	Cardiorespiratory mortality and hospital admissions: No associations of exposure with mortality; hospital admissions increased for ischemic heart diseases and cerebrovascular diseases in the elderly	Epidemiological retrospective 3-month cohort study: exposed vs unexposed time frame	Moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Eyjafjallajökull, Iceland (2010 eruption)	Hlodversdóttir et al. (2018)	Ashfall (proximal) PM_{10}	Children <18 yr. in proximal areas to the volcano (*N* = 1,153; data reported from parents)	Long-term physical and mental health sequelae: increased respiratory symptoms and anxiety/worries in exposed children; boys had sleep disturbances and headaches	Epidemiological prospective 3-yr. cohort study: exposed vs. unexposed	Moderate
Eyjafjallajökull, Iceland (2010 eruption)	Hlodversdóttir et al. (2016)	Ashfall (proximal) PM_{10}	Adult residents in proximal areas to the volcano (*N* = 1,255)	Long-term physical and mental health sequelae: exposure was associated with increased wheeze with cold, phlegm, skin rash or eczema, back pain, insomnia and use of asthma meds. PTSD symptoms decreased	Epidemiological prospective 3-yr. cohort study: exposed vs. unexposed	Moderate
Eyjafjallajökull, Iceland (2010 eruption)	Elliot et al. (2010)	Ashfall (distal) PM_{10}	General population of the UK and Scotland	Population syndrome surveillance for incidence of asthma, conjunctivitis, allergic rhinitis, wheeze, lower and upper respiratory tract infection, breathing problems, and cough: no unusual increases in the monitored conditions	Epidemiological surveillance study: 3-yr. compared to eruption time frame	Moderate
Eyjafjallajökull, Iceland (2010 eruption)	Carlsen et al. (2012a)	Ashfall (proximal) PM_{10}	Residents proximal to volcano to Vı´k village (*N* = 207)	Health symptoms, mental health and lung function: reported eye irritation, upper respiratory symptoms and asthma exacerbations. Mental health symptoms in 39% of residents >34 yr. age. No lung function effect	Epidemiological descriptive study: cross-sectional health screening of exposed population	Low to moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Eyjafjallajökull, Iceland (2010 eruption)	Carlsen et al. (2012b)	Ashfall (proximal) PM_{10}	Residents of unexposed Skagafjörður and southern exposed area of the island (N = 1,658)	Post-eruption symptoms (6–9 months): significant associations of exposure with cough, phlegm, eye irritation, and psychological symptoms; dose-response relationship noted	Epidemiological descriptive comparative study: cross-sectional health survey of exposed vs unexposed residents	Low to moderate
Furnas Volcano, Azores, Portugal (non-eruptive degassing)	Linhares et al. (2015)	CO_2	Subjects from villages of exposed Furnas and unexposed Ribeira Quente (N = 505)	Respiratory symptoms and lung function screening: significantly higher restrictive and obstructive disease (COPD) was associated with exposure	Quasi-experimental study: exposed vs unexposed	Moderate to high
Furnas Volcano, Azores, Portugal (1991–2001; active degassing)	Amaral and Rodrigues (2007)	CO_2, H_2S, and SO_2	General population of Furnas and Santa Maria (N = 57)	Chronic bronchitis: significantly higher risk of disease associated with exposure, especially in females	Epidemiological retrospective 10-yr. community-based cohort study: exposed vs unexposed residents	Low to moderate
Grimsvötn, Iceland (2011 eruption)	Oudin et al. (2013)	Ashfall (distal)	General populations of 21 regions in Sweden	All-cause mortality: no significant differences between the regions (mortality ratio; low statistical power due to short time frame of data, inconclusive findings)	Epidemiological descriptive comparative study: exposed vs unexposed regions and time frames	Low
Guagua Pichincha, Ecuador (2000 eruption)	Naumova et al. (2007)	Ashfall (proximal) PM_{10}	Children from Quito area (N = 5,169)	Pediatric emergency visits: 2.2× and 1.7× increases for lower and upper respiratory infections 3 weeks after eruption. Disease burden: 345 extra visits in 28 days	Time series: before, during and after eruption over 1-yr	Moderate
Holuhraun, Iceland (2014–2015 eruption)	Carlsen et al. (2021a, b)	SO_2 and sulfate aerosols ($PM_{2.5}$) vog	General population of Reykjavík (250 km from eruption site)	Respiratory morbidity: exposure was associated with increase in healthcare and asthma medication use. Lack of public advisories is associated with increased clinic and emergency visits	Time series study: days with varied exposure over 4 months	Moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Holuhraun, Iceland (2014–2015 eruption)	Carlsen et al. (2019)	SO_2	Eruption workers: earth scientists, technicians, law enforcement personnel ($N = 32$)	Respiratory health & lung function: lung function was normal both before and after exposure; eye and nasal irritation were reported	Quasi-experimental: pre-post exposure	Moderate to high
Kīlauea, USA (2012; continuous summit eruption)	Longo (2013)	SO_2 and sulfate aerosols $PM_{2.5}$ (vog)	Adult residents of 2 Hawai`i Island areas for 7+ yr. (N = 220)	Cardiorespiratory signs and self-reported symptoms: significant associations of chronic exposure and increased cough, phlegm, sore/dry throat, shortness of breath, sinus congestion, wheezing, eye and skin irritation, hypertension. Significantly elevated BP and lower oxygenation	Mixed methods: epidemiological descriptive comparative: cross-sectional health survey of exposed vs unexposed residents Descriptive qualitative; interviews	Low to moderate
Kīlauea, USA (2011; summit eruption)	Camara and Lagunzad (2011)	SO_2 and sulfate aerosols (distal) vog	Clinic patients, residents of O'ahu ≥7 yr. ($N = 45$)	Case descriptions of eye irritation attributed to vog exposure: conjunctival injection, clear mucous discharge, papillary reaction, itching and burning, respiratory symptoms	Case series study	Low
Kīlauea, USA (2008; start of summit eruption)	Longo et al. (2010)	SO_2 and sulfate aerosols (vog)	Clinic patients in an exposed community, Hawai`i Island ($N =$ 1,189)	Medically diagnosed acute illness morbidity: significant associations with high exposure and increased clinic visits for cough, headache, acute pharyngitis, and pediatric airway problems	Epidemiological retrospective 7-month cohort study	Moderate
Kīlauea, USA (2006–2008; east rift and summit eruption)	Chow et al. (2010)	SO_2 and sulfate aerosols (vog)	Healthy adult subjects from 4 exposure zones on Hawai`i Island ($N = 72$)	Heart rate variability: no appreciable effects of vog exposure on the autonomic nervous system of the heart	Descriptive comparative study: cross-sectional health screening	Moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Kīlauea, USA (2004; continuous east rift eruption)	Longo (2009)	SO_2 and sulfate aerosols (vog)	Adult residents in Ka'ū district ($N = 16$)	Descriptions of living with vog: 35% believed volcano affected health, asthmatics had difficulty managing their disease	Descriptive qualitative study: in-depth interviews	Low
Kīlauea, USA (2004–2006; continuous east rift eruption)	Longo and Yang (2008)	SO_2 (vog)	General population from 2 Hawai`i Island communities ($N = 683$ visits)	Acute bronchitis ER/clinic visits: Significant elevated risk was associated with exposure. Highest risk in children and females	Epidemiological retrospective 3-yr. community cohort study: exposed vs unexposed	Moderate
Kīlauea, USA (2004; continuous east rift eruption)	Longo et al. (2008)	SO_2 and sulfate aerosols (vog)	Adult residents of 3 Hawai`i Island areas for 7+ yr. ($N = 335$)	Cardiorespiratory signs and symptoms: significant associations of chronic exposure and increased cough, phlegm, sore/dry throat, sinus congestion, wheezing, eye irritation, bronchitis, pulse rate, and blood pressure	Epidemiological descriptive comparative study: cross-sectional health survey of exposed vs unexposed residents	Low to moderate
Kīlauea, USA (2002–2005; continuous eruption)	Tam et al. (2016)	SO_2 and sulfate aerosols (vog)	Hawai`i Island school children in 4th and 5th grades ($N = 1,957$)	Respiratory symptoms and lung function: chronic exposure was associated with increased cough and possible reduced FEV_1/FVC^3, but not with asthma or bronchitis	Epidemiological prospective open cohort study: cross-sectional health survey, 4 exposure zones	Moderate
Kīlauea, USA (2000; lava ocean entry)	Heggie et al. (2009)	HCl aerosol (laze)	Tourists ($N = 2$)	Mortality: acute pulmonary edema from inhalation, burns	Case study	Low
Kīlauea, USA (1997–2001; near-continuous eruption)	Michaud et al. (2004)	SO_2 and sulfate aerosols; PM_1 (vog)	General population from Hilo area on Hawai`i Island	Emergency visits for asthma/COPD[3], cardiac/respiratory issues and gastroenteritis: small significant association of exposure with asthma/COPD visits	Time series study: days with varied exposure over 4.5 yr.[3]	Low

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Kīlauea, USA (1992–2002; near-continuous eruption	Heggie (2005)	Volcanic gases	Tourists to national park	Acute injury morbidity and mortality: 7 deaths from inhalation of high levels of volcanic fumes. Most fatalities had previous asthma or heart problems	Case reports study	Low
Merapi, Indonesia (2010)	Trisnawati et al. (2015)	Ashfall (proximal, 10 km)	Male non-smoking worker, 25 yr. age with 10-month exposure	Lung effects: presented with breathing difficulty and pain. Diagnosis was anthrosilicosis	Case study	Low
Miyakejima, Japan (2010 eruption; continuous degassing)	Iwasawa et al. (2015)	SO_2	School-aged children of Miyakejima village (N = 59)	Respiratory symptoms and lung function: no lung function changes; dose-response relationship for respiratory symptoms	Quasi-experimental repeated measures 6-yr. study, annual health screen	Moderate to High
Miyakejima, Japan (2005; continuous degassing)	Ishigami et al. (2008)	SO_2	Healthy workers exposed for short time periods (1–15 days) ($N = 611$)	Incidence of respiratory symptoms: significant associations between exposure and cough, scratchy and sore throat, and breathlessness	Epidemiological prospective 6-month cohort study (varying exposure level)	Moderate
Miyakejima, Japan (2004–2006)	Iwasawa et al. (2009)	SO_2	Adult residents of Miyakejima village ($N = 823$)	Respiratory symptoms and lung function: no deterioration in lung function. Significant increase in cough, phlegm and chronic bronchitis-like symptoms after 2-yr	Quasi-experimental repeated measures 2-yr. study: health screening	Moderate to high
Miyakejima, Japan (2000 eruption; continued degassing)	Shiozawa et al. (2018)	SO_2	Newly returning adult resident patients of Miyakejima central clinic ($N = 269$)	General self-reported symptoms: 32% of patients reported symptoms from exposure, which may include throat irritation, headache, eye pain and tearing, dry cough, insomnia, or anxiety	Epidemiological descriptive cross-sectional health survey study, 3 exposure regions encircling volcano	Low to moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Miyakejima, Japan (2000 eruption; continued degassing)	Kochi et al. (2017)	SO_2	Adult residents of Miyakejima village ($N = 168$)	Respiratory symptoms and lung function: No deterioration in lung function. Reported cough, eye & throat irritation continued after 6-yr.; dose-response relationship noted	Quasi-experimental repeated measures 6-yr. study: annual health screen	Moderate to high
Miyakejima, Japan (2000 eruption)	Shojima et al. (2006)	Ashfall	Female, 57 yr. old exposed for 1-month without mask wearing	Lung effects: presented with abnormality on X-ray, asymptomatic, diagnosed with lung inflammation that resolved	Case study	Low
Nyiragongo and Nyamulagira, Democratic Republic of Congo (2000–2010; episodic eruptions)	Michellier et al. (2020)	SO_2	General populations of region near volcanoes	Medically diagnosed acute respiratory illness morbidity: no consistent evidence for an association between yearly incidence and eruptions. Visits for medically diagnosed illnesses were significantly increased after some eruptions, especially in proximal areas (< 26 km)	Time series: months with varied exposure over a decade	Moderate
Piton de la Fournaise, Reunion Island (2005–2007; intermittent eruptions)	Viane et al. (2009)	SO_2 (vog)	General population of Réunion Island	Asthma hospitalizations: no overall island population associations with exposure; significant associations of increased hospitalizations in selected island areas	Time series study: days with varied exposure over 3 yr	Low to moderate
Popocatépetl, Mexico (1994–2008 explosive eruptions)	Nieto-Torres and Martin-Del Pozzo (2021)	Ashfall	General population of 98 municipalities adjacent to the volcano and two reference municipalities	Non-infectious respiratory disease (NIRD) healthcare visits: Consistently, the annual NIRD rates increased significantly in areas exposed to ashfall when compared to NIRD rates in non-exposed areas. As ash thickness increased so did annual rates of NIRD	Epidemiological descriptive comparative study over 17 years (15 exposed and 2 non-exposed) of 625 ashfall events	Moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Popocatépetl, Mexico (1994–1995 explosive eruptions)	Rojas-Ramos et al. (2001)	Ashfall (exposed ≥ 80hr outdoors)	Non-smoking farmers proximal to the volcano (N = 35; 10% of population)	Respiratory symptoms and lung function: cough, runny nose, eye irritation and sore throat decreased post exposure. Acute effects noted in lung function but returned to normal over time except FEV_1/FVC[3]; short exposure was associated with reversible inflammation of the airways	Quasi-experimental: baseline during exposure and 7 months post exposure	Moderate to high
Puyehue-Cordón Caulle, Chile (2011 eruption)	Balsa et al. (2016)	Ashfall (distal) PM_{10} (exposure above WHO Guideline)	Mother-Baby Dyads in Montevideo, Uruguay (N = 79,328)	Prenatal exposure and live births: A 10-µg/m^3 increase in PM_{10} during 3rd trimester was associated with preterm birth. No associations between exposure and birth weight	Time series: days with varied exposure over 3 yr	Moderate to high
Rotorua, New Zealand (non-eruptive degassing)	Bates et al. (2015)	H_2S	Adult residents of Rotorua for 3+ yr. (N = 1,637)	Lung function screening: no evidence of long-term H_2S exposure associated with increased risk of COPD or asthma	Quasi-experimental study: high, medium and low exposure	Low to moderate
Rotorua, New Zealand (non-eruptive degassing)	Bates et al. (2013)	H_2S	Adult residents of Rotorua for 3+ yr. (N = 1,637)	Asthma symptoms: self-reported, doctor-diagnosed asthma and asthma symptoms were not associated with exposure	Cross-sectional health survey study	Low to moderate
Rotorua, New Zealand (non-eruptive degassing)	Durand and Wilson (2006)	H_2S	General population of Rotorua area (N = 12,215 admissions)	Hospital admissions for non-infectious respiratory illness: risk of hospitalization (especially COPD) was associated with exposure	Epidemiological 10-yr. open community-based cohort: varying levels of exposure	Moderate
Ruapehu, New Zealand (1996 eruption)	Newnham et al. (2010)	Ashfall (distal) PM_{10}	General population of Hamilton and Auckland, 166–282 km from the volcano; Wellington was reference city	Respiratory mortality: highest rates of respiratory mortality in a decade occurred in the month following the ashfall but concurrent with an influenza epidemic	Time series study: years of non-exposure compared with 1-month of ashfall	Moderate

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Sakurajima, Japan (1994 to 2003)	Kimura et al. (2005)	Ashfall (proximal) PM_{10}	School children, 6 to 15 yr. in areas near the volcano ($N = 19{,}585$)	Ocular signs and symptoms: high exposure (within 4-km of volcano) was associated with increased redness, discharge, foreign body sensation, and itching	Epidemiological prospective open 10-yr. cohort study: cross-sectional health survey, high vs low exposure	Moderate
Sakurajima, Japan (1968–2002 eruptions)	Higuchi et al. (2012)	Ashfall	General populations of Sakurajima and Taramizu	Respiratory mortality: elevated mortality risk of pre-existing lung cancer found in higher exposed Sakurajima City	Epidemiological retrospective community cohort: exposed vs. unexposed	Moderate
Soufrière Hills, Montserrat (2010 eruption)	Cadelis et al. (2013)	Ashfall (70 km)	Adult residents of archipelago of Guadeloupe, West Indies ($N = 70$ visits)	Emergency visits for acute asthma exacerbation: exposure was associated with increased visits during and after ashfall	Time series study: Days with varied exposure over 22-days	Moderate
Soufrière Hills, Montserrat	Forbes et al. (2003)	Ashfall PM_{10}	Resident school children in exposed areas of island ($N = 383$)	Respiratory symptoms and lung function: significant association of mod/high exposure with wheeze and decreased peak flow rates	Quasi-experimental	Moderate to high
Yasur, Vanuatu (1999 degassing)	Cronin and Sharp (2002)	HF gas, F in drinking water	General population of Tanna island near Yasur volcano	Subjective general health descriptions: no unusual increases in acute/chronic respiratory problems, eye infections or irritations, compared to other non-exposed areas; recommendations provided to decrease exposure of residents	Descriptive clinical reports and expert opinion from public health nurses	Low
Reviews						
Global volcanoes	Doocy et al. (2013)	Volcanic air pollution (all types) and eruptive activity	Studies from 1900 to 2012	Morbidity, mortality, injury, and displacement study information. Changes in land use practices and population growth add to risk	Systematic literature review study	High

Table 2 (continued)

Volcano, country, year/s of activity	Reference	Exposure	Subjects/population	Outcome(s)	Study design	Evidence level[2]
Global volcanoes	Horwell and Baxter (2006)	Volcanic ash	Number of studies = 60	Respiratory health effects: incidence of acute respiratory symptoms varies greatly after ashfalls. Research gaps noted; more systematic approach and multi-disciplinary studies are needed	Systematic literature review study	High
Global volcanoes	Hansell and Oppenheimer (2004)	Volcanic gases	Number of studies = 29	Health effects and mortality: limited body of knowledge, exposure associated with respiratory morbidity and mortality. Research gaps noted; need for more high quality and collaborative multi-disciplinary studies	Systematic literature review study	High
Icelandic volcanoes	Gudmundsson (2011)	Volcanic ash	Inclusive of available studies	Acute and chronic respiratory effects of volcanic ash exposure	Historical literature review and expert opinion	Low

[1]Study inclusion criteria for this table were peer-reviewed journal studies published between 2001 and mid-2021, which directly involved human subjects as focus of the research. Exclusion criteria were non-peer reviewed journal articles, technical governmental or NGO reports, conference abstracts, studies that only involved human tissues, animal subjects, and studies that estimated risk on populations from environmental data only

[2]Evidence levels were subjectively assessed by the limitations of the study's design (case study, descriptive, epidemiological, time series or experimental); and strength of methods employed (probability-based sampling for generalizability and reducing bias, subjective vs. objective measurements of health data, and statistical methods for controlling confounding effects and testing hypotheses)

[3]Abbreviations: *COPD* chronic obstructive pulmonary disease, FEV_1:forced expiratory volume in 1 s, *FVC* Forced vital capacity, *yr*. year or years

symptoms of pre-existing lung conditions (reviewed in Horwell and Baxter 2006). However, very few of these studies have followed populations longitudinally using the timeframes needed (on the order of decades) for long-latency diseases such as pneumoconioses or cancers to manifest. Further, situations that produce chronic exposure to ash are rare, with the best-documented examples being the 15-year cumulative exposure to ash from Soufrière Hills volcano, Montserrat (Baxter et al. 2014) and the eruption of Sakurajima volcano, Japan, with frequent ash exposures since the 1970s (reviewed by Hillman et al. 2012). Overall, major knowledge gaps remain about whether chronic exposures can trigger development of potentially fatal cardiorespiratory diseases and also whether chronic health effects can result from acute exposures.

Beyond respiratory health, studies of human exposure to volcanic emissions have also reported on ocular, dermal, and cardiovascular effects, gastroenteritis, birth outcomes, dental fluorosis, acute injury, and increased use of healthcare services and medications (summarized in Table 2). Documented instances of human fluorosis associated with active volcanism are rare globally (D'Alessandro 2006; Table 2) but may be under-reported. Mental health has also received attention, but few studies have addressed specific mental health impacts resulting from exposure to volcanic air pollution.

The evidence base is weak on which characteristics of volcanic or other air pollution sources are responsible for the observed negative health outcomes. Routine monitoring does not cover all species of concern (e.g., metal pollutants and aerosol acidity). In the past decade, many air pollution studies in cities with traffic-related emissions have shown the importance of fine particulate matter, particularly $PM_{2.5}$, in the development of certain acute and chronic health conditions (respiratory, including lung cancer, and cardiovascular, in particular) and daily mortality. A future challenge will be to determine whether this applies to volcanic PM, as the World Health Organization has concluded that these outcomes relate to geogenic as well as anthropogenic particulate exposures (World Health Organization 2013).

Currently we have little clinical evidence of whether chronic exposures to volcanic crystalline silica can trigger silicosis or lung cancer (World Health Organization 1997). Some toxicology studies have indicated biological mechanisms for silica-related diseases (Lee and Richards 2004; Damby et al. 2018b). However, there is also evidence that volcanic crystalline silica may not be particularly toxic (Damby et al. 2016). Geochemical and crystallographic studies indicate that, as with other forms of silica dusts (International Agency for Research on Cancer 1997; Donaldson and Borm 1998), there are inherent characteristics of the silica, and external factors, which may dampen its toxicity, such as chemical (e.g. aluminum) impurities in the crystal structure or the presence of the crystalline silica within an occluding complex mineral matrix (Horwell et al. 2012; Damby et al. 2014; Nattrass et al. 2017).

Conducting high-quality studies on health effects is challenging during an eruption crisis, and the need is often secondary to emergency response. Consequently, important opportunities to study population exposures and health impacts have been missed. Furthermore, many countries with frequent volcanism do not routinely gather public health statistics, or they may have low-quality population registers and no exposure monitoring in place. These conditions make health assessment and follow-up even more challenging. It is also extremely difficult to follow a cohort of people over decades, especially if exposures of study participants are curtailed due to evacuation or permanent migration following the eruption. Obtaining funding for longitudinal studies and having the long-term support of local healthcare professionals and facilities are also great challenges.

Risk assessment and management

Increased knowledge about the hazards posed by volcanic emissions now enables risk assessments (also known as Health Impact Assessments; HIA) to be conducted prior to, or during, eruptions. To date, three such assessments have been published: Hincks et al. (2006), on crystalline silica-rich ash exposures on Montserrat; and Schmidt et al. (2011) and Heaviside et al. (2021) on SO_2/sulfate exposures from a future Laki-style eruption.

Mueller et al. (2020a) recently reviewed the potential for conducting HIAs in volcanic locations to predict future morbidity and mortality due to ash exposures from eruptions, given knowledge of eruption scenarios, baseline health data, and expected exposures. They concluded that, given the scarcity of published clinical/epidemiological studies and exposure data from eruptions, the application of outdoor urban air pollution risk estimates (concentration-response functions) to eruption scenarios was the best way to estimate the impact from volcanic ash exposures. Local climate, socioeconomic status, and quality of healthcare facilities also influence vulnerability and should be included in risk calculations.

Progress is being made in integrating atmospheric, volcanological, and medical information for real-time risk management. For example, detailed modeling of volcanic plume chemistry and transport from the 2014 to 2015 Holuhraun eruption informed exposure assessment (Carlsen et al. 2021a). At Kīlauea, characterizing vog (SO_2 and aerosol concentrations) has led to improved exposure assessments for studies seeking to understand vog health impacts (Tam et al. 2016).

Civil protection exercises for volcanic eruptions are now starting to include volcanic emissions (Holland et al. 2020; Witham et al. 2020). Such preparedness steps will help to identify where risks from volcanism need to be balanced against other local background issues and environmental hazards.

Due to the knowledge gaps, especially those related to the health effects of chronic exposures (e.g., to crystalline silica), a precautionary approach is generally taken to the management of health risks. Many agencies around the world will advise communities to reduce their exposures to volcanic air pollution. Little data exists on the efficacy of intervention strategies (air purifiers, dehumidifiers, or air conditioners) on indoor air quality in a volcanic environment. However, recent studies have provided an evidence base for the efficacy of wearing personal respiratory protection to reduce exposure to volcanic ash (Mueller et al. 2018; Steinle et al. 2018). The finding that industry-certified N95-style masks are most effective but hard to source and afford has led to some humanitarian organizations donating or crowdfunding such masks (Horwell et al. 2020). However, many government agencies distribute less-effective stockpiled masks, raising important ethical questions about the morality and legality of providing suboptimal protection (McDonald et al. 2020; McDonald and Horwell 2021). Provision of information on intervention effectiveness that is specific to local climates and cultures can help address such concerns. For example, IVHHN has produced informational products on protection from volcanic emissions, including on how to fit facemasks[3]. In Hawai'i, the advice has been tailored to local community lifestyles and published on a dedicated "vog dashboard"[4] that is a single, freely accessible source of information, supported by multiple agencies. In multiple locations, ash, gas, and aerosol dispersion forecasts are linked to health information and advice for ongoing eruptions (Businger et al. 2015; Shiozawa et al. 2018; Barsotti et al. 2020). In Iceland, volcanic air pollution forecasts have been broadcast via radio and television and are available online (including social media) (Barsotti et al. 2020).

Emerging themes, knowledge gaps, and future directions

In general, few studies of health hazards and impacts are conducted relative to the number of eruptions that occur globally. Since 2001, the Global Volcanism Program[5] has reported 124 eruptions of VEI ≥3, while Table 2 reports 48 primary medical studies (at 23 volcanoes) assessing physical health effects of volcanic emissions. However, most of these studies were conducted in advanced-economy countries, notably the USA, Japan, and Iceland. Indonesia, with a 2021 population of ~277 million[6] and recent sustained and/or major eruptions of Merapi, Sinabung, Agung, and Semeru volcanoes, is notably under-represented, with a single clinical case study (Trisnawati et al. 2015). This inequality in attention, which relates to resources, opportunity, contacts, politics, and historical legacy, has meant that the health impacts of many major and sometimes long-duration eruptions near large populations have gone completely unstudied. Additionally, with a few exceptions (e.g., Kīlauea, Holuhraun, and Miyakejima) where multiple studies of the health effects of exposure to SO_2 and sulfate aerosol are reported (Table 2), effects of prolonged degassing have received little attention, relative to explosive eruptions, despite the chronic exposures and likely health effects.

A major research direction must be the development of methods for accurate exposure assessment. Further improvement of meteorological and dispersion models can help calculate ground-based pollutant concentrations at higher spatial and temporal resolution. Refining input parameters, plume models, and dynamic boundary layer representation, or incorporating advanced mathematical models such as Large Eddy Simulation, may also lead to much improved modeled concentrations (Barsotti et al. 2020; Burton et al. 2020, Holland et al. 2020; Filippi et al. 2021). Limitations in the accuracy and speciation of ground-level concentrations from models or space-based instruments will require the continuation of ground-based in situ measurements. Installation of networks of low-cost gas and particulate sensors is becoming increasingly feasible with a proliferation of technology in the past decade[7]. Such networks provide exciting opportunities for collaborative science with local communities. However, there are challenges for deployment during crises in terms of procurement and delivery in humanitarian situations where agencies have other priorities, and transport and other critical infrastructure networks may be disrupted. Currently, the utility of low-cost sensors is much greater when they are benchmarked against reference-grade instruments, which may not be available, even regionally. Future improvements in sensor accuracy, calibration, and reliable global satellite internet may contribute to better exposure assessment (Kizel et al. 2018; Crawford et al. 2021).

[3] https://www.ivhhn.org/information#printable

[4] https://www.vog.ivhhn.org

[5] https://volcano.si.edu/

[6] https://www.worldometers.info/world-population/indonesia-population/

[7] http://www.aqmd.gov/aq-spec

We also foresee that air pollution research, in general, will move beyond a reliance on PM mass concentrations to assess impact and towards an understanding of the distinct PM chemical constituents, including metals and organic compounds, as well as towards physicochemical (e.g., surface area) or biological (e.g., oxidative potential) exposure metrics.

Interactions between volcanic eruptions and the ambient atmosphere and climate are an important future research direction with respect to health impacts. Ambient conditions influence the atmospheric dispersion and lifetime of volcanic emissions (for example, the sulfur gas-to-particle conversion rate; Gíslason et al. 2015), and ash remobilization in arid, windy climates may prolong population exposure (Jarvis et al. 2020). The consequences of global climate change for volcanic emission hazards are poorly understood but likely appreciable; for example, predicted weakening of Pacific trade winds will affect dispersion of emissions in Hawai'i and Vanuatu (Collins et al. 2010).

The greatest overall barrier to advancing our understanding of volcanic air pollution effects on human health is the scarcity of epidemiological and clinical studies. To facilitate future studies, and support risk management, especially where local syndromic surveillance is absent, standardized epidemiological protocols (Mueller et al. 2020b) and crisis response resources[8] have recently been developed. Instigating such studies will be facilitated by continued co-development of standardized protocols, supporting local study teams and procuring equipment, funding, and ethical permissions. Relationship building between visiting researchers and host country academic, observatory, and agency partners is vital for preserving host countries' intellectual property and ensuring beneficial research outcomes for impacted communities. In turn, this can support the effective communication of health impacts of volcanic air pollution to populations, health practitioners, and emergency managers.

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Author contribution CS formulated the initial proposal. CS and DED coordinated the content. CS, DED, CJH, and TE wrote parts of, and extensively revised, the manuscript. EI, IT, AS, HKC, EM, BML, PJB, and CW wrote part of the manuscript and/or assisted with the preparation of tables and figures (Table 1 IT; Table 2 BML). SC contributed to conceptual development and review. All authors read and approved the final manuscript.

[8] https://www.ivhhn.org/crisis-management

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Declarations

Conflict of interest The authors declare no competing interests.

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