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CHILE Y SU EXTENSA GEOGRAFÍA VOLCÁNICA: EFECTOS Y DESAFÍOS EN LA SALUD HUMANA, ANIMAL Y MEDIOAMBIENTAL

CHILE AND ITS VAST VOLCANIC LANDSCAPE: IMPACTS AND CHALLENGES FOR HUMAN HEALTH, ANIMAL HEALTH AND WELFARE, AND THE ENVIRONMENT

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RESUMEN

Chile, con su extensa y activa geografía volcánica, enfrenta importantes desafíos para la salud humana, animal y ambiental. Este artículo presenta una revisión interdisciplinaria de los impactos en la salud de las erupciones volcánicas, con un enfoque en los efectos de la exposición a cenizas volcánicas. La revisión integra evidencia de geología, salud pública, medicina veterinaria y ciencias ambientales, destacando los resultados de salud agudos y crónicos, incluidos los trastornos respiratorios, oculares y dérmicos, así como los impactos en la salud mental y la alteración ecológica. La ceniza volcánica también representa una amenaza para la agricultura y la calidad del agua, mientras que los suelos derivados de la ceniza pueden alterar la movilidad de los contaminantes, como lo demuestra la sorción diferencial de herbicidas en los tipos de suelo volcánico. Basándose en erupciones históricas y estrategias actuales de gestión de riesgos lideradas por la agencia geológica de Chile (SERNAGEOMIN), el estudio critica la respuesta fragmentada a las crisis volcánicas y aboga por un enfoque de Una Sola Salud. Este marco integrador promueve la coordinación entre los sectores de salud humana, animal y ambiental. Los autores argumentan que la preparación debe incluir la capacitación de profesionales de la salud, sistemas de monitoreo en tiempo real y educación comunitaria. Los hallazgos subrayan la necesidad de políticas de salud pública actualizadas e innovación curricular para abordar los desafíos únicos y multifacéticos que plantea la actividad volcánica en Chile y otras regiones geológicamente activas.

Palabras clave: Agricultura, Contaminación, Gestión de crisis, Una Sola Salud, Volcanes.

ABSTRACT

Chile, with its extensive and active volcanic geography, faces significant challenges for human, animal, and environmental health. This article presents an interdisciplinary review of the health impacts of volcanic eruptions, with a focus on the effects of exposure to volcanic ash. The review integrates evidence from geology, public health, veterinary medicine, and environmental sciences, highlighting both acute and chronic health outcomes, including respiratory, ocular, and dermal disorders, as well as mental health impacts and ecological disruption. Volcanic ash also poses threats to agriculture and water quality, while ash-derived soils can alter pollutant mobility, as demonstrated by differential herbicide sorption in volcanic soil types. Drawing on historical eruptions and current risk management strategies led by Chile's geological agency (SERNAGEOMIN), the study critiques the fragmented response to volcanic crises and advocates for a One Health approach. This integrative framework promotes coordination across human, animal, and environmental health sectors. The authors argue that preparedness must include training of health professionals, real-time monitoring systems, and community education. The findings underscore the need for updated public health policies and curriculum innovation to address the unique and multifaceted challenges posed by volcanic activity in Chile and other geologically active regions.

Keywords: Agriculture, Contamination, Crisis management, One Health, Volcanoes.

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1. INTRODUCTION

Volcanic eruptions are recurring natural phenomena that have a significant impact on the health of people, animals, and the environment. Chile is a country with high volcanic activity and is constantly exposed to these phenomena, as it has more than 500 volcanoes along the Andes mountain range (Grob et al., 2012; Lohmar et al., 2007; Motoki et al., 2006; National Service of Geology and Mining - SERNAGEOMIN, 2018). Collectively, the Andean region—which includes countries such as Argentina, Chile, Colombia, Ecuador, and Peru—is home to some 66 of the world's approximately 550 active volcanoes, representing between 10% and 15% of the total (Tilling, 2009). Chile, in particular, has 36 active volcanoes (Tilling, 2009), making it a high-risk volcanic zone (Grob et al., 2012). The country has a long history of volcanic eruptions, ranging from the almost mythical eruption of the Osorno volcano in 1835, described by Charles Darwin (Darwin, 1921), to one of the most recent, which led to the displacement and relocation of the town of Chaitén (National Geology and Mining Service - SERNAGEOMIN, 2018).

On his journey, Darwin witnessed first-hand the activity of the Osorno volcano:

> On the night of the 19th the volcano of Osorno was in action. At midnight the sentry observed something like a large star, which gradually increased in size till about three o'clock, when it presented a very magnificent spectacle. By the aid of a glass, dark objects, in constant succession, were seen, in the midst of a great glare of red light, to be thrown up and to fall down. The light was sufficient to cast on the water a long bright reflection. Large masses of molten matter seem very commonly to be cast out of the craters in this part of the Cordillera (Darwin, 1921, p. 55).

In this context, volcanic ash generated during eruptions constitutes one of the greatest threats due to its massive reach. These particles of pulverised rock and volcanic glass (less than 2 mm in diameter) can be dispersed thousands of kilometres by the wind, affecting not only populations near the volcano but also distant areas and even neighbouring countries (Carn, 2024). Consequently, volcanic ash can compromise human respiratory, ocular, and skin health, affect the well-being of animals and wildlife, and pose a risk to agriculture and local ecosystems.

Growing scientific evidence warns about the adverse effects of volcanic ash. There is an urgent need to understand the impacts of this material on human and animal health, as well as the most effective ways to mitigate these impacts, which extend to public health and affect the economic and social dynamics of the affected region. Effectively addressing this problem requires a multidisciplinary approach integrating health sciences, geology, ecology, social sciences, and public policy (Wilson et al., 2012; Plaza et al., 2019). Recent eruptions in Chile, *e.g.*, Chaitén volcano in 2008 and the Cordón Caulle volcano in 2011, have highlighted the need for in-depth studies of the ash effects on human and animal health, as well as the effectiveness of mitigation strategies implemented in these situations (Zabert et al., 2019; Lara & Calderón, 2015).

The research question guiding this study is: How does volcanic ash affect human and animal health in Chile, and what are the most effective strategies to reduce these impacts? The central research question concerns understanding the magnitude of the ash effects. Volcanic ash impacts the respiratory, ocular, and dermal health of humans and animals, and how these effects vary depending on the characteristics of exposure and environmental conditions. Based on this, we hypothesise that exposure to volcanic ash has a considerable negative impact on human and animal health, particularly on the respiratory, ocular, and dermal systems, and that the risk increases in rural communities with greater direct exposure. It is also proposed that prevention and mitigation strategies, *e.g.*, the use of masks and initiatives for water and food protection, are essential to reduce the adverse effects of ash.

This study aims to evaluate the effects of volcanic ash on human and animal health in Chile, employing a multidisciplinary approach to identify the most effective risk mitigation strategies. The long-term goal is to contribute to the development of public policies and volcanic risk management strategies that integrate human health, animal health, and the protection of agricultural and livestock ecosystems, thereby improving preparedness for and response to future volcanic eruptions in Chile and other volcanically active regions worldwide.

2. METHODOLOGY

This literature review adopted a multidisciplinary approach to assess the effects of volcanic ash on human health, animal health, and the environment, integrating scientific sources from diverse areas of knowledge, *e.g.*, geology, public health, veterinary medicine, ecology, and the social sciences. We addressed the following aspects through a comprehensive compilation of journal articles, books, technical reports, and previous studies:

(i) Human Health: Epidemiological studies analysing the acute and chronic effects of volcanic ash exposure on respiratory, ocular, and dermal health. Particular attention was given to studies documenting respiratory symptoms (*e.g.*, cough, shortness of breath, throat irritation), ocular symptoms (*e.g.*, irritation, conjunctivitis), and dermal symptoms (*e.g.*, skin irritation). Data on the relationship between airborne ash concentration and the onset of these symptoms were analysed, as well as risk factors such as pre-existing conditions (*e.g.,* chronic respiratory diseases) (Grob et al., 2012; Horwell & Baxter, 2006).

(ii) Animal Health: Analyses of the scientific literature on the effects of volcanic ash on domestic and farm animals. Studies reporting on respiratory, ocular, digestive, and dental effects in animals exposed to ash were reviewed, as well as indirect impacts on forage and water availability and consequences for animal welfare (USGS, 2015; Plaza et al., 2019).

(iii) Environmental and Agricultural Effects: Studies on the impact of volcanic ash on ecosystems, crops, and agricultural production. Reports on soil acidification, its effects on photosynthesis, and the potential long-term benefits to soil fertility resulting from the addition of volcanic minerals were examined (Lara & Calderón, 2015). We have given special attention to cases in which ash affected wildlife, such as the Andean condor in Patagonia (Plaza et al., 2019).

(iv) Risk management and public policies: The review included an assessment of public policies related to volcanic risk management based on previous case studies in Chile and other countries affected by volcanic eruptions. Approaches adopted for ashfall prevention, mitigation, and response were analysed, including evacuation measures, distribution of informational materials, and health protection recommendations (Cuevas & Arellano, 2022). Psychosocial aspects associated with volcanic risk perception and community behaviour in response to these events were also addressed.

To conduct this review, we utilised academic and scientific databases, including Scopus, Google Scholar, PubMed, and SciELO, among others, to retrieve peer-reviewed articles. Inclusion criteria were articles and studies published within the last 25 years (2000–2025) to ensure the information was relevant and up to date. Selected studies were analysed for methodological quality, the relevance of their results, and their applicability to the Chilean context. The information was synthesised through a critical and comparative analysis of the results, identifying the main conclusions, knowledge gaps, and recommendations for future research and public policy.

This approach provided a comprehensive and up-to-date view of the impacts of volcanic ash on health and the environment, contributing to a better understanding of the associated risks and the most effective mitigation strategies.

3. RESULTS AND ANALYSIS

3.1. Volcanoes in Chile

As mentioned above, Chile has a multitude of volcanoes scattered throughout its territory. To date, several active volcanoes have been recognised that can reach about one hundred under this condition. The Servicio

Nacional de Geología y Minería (SERNAGEOMIN) maintains an intensive surveillance programme on active volcanoes and issues different levels of alert for the population: “green alert”, “yellow alert”, “orange alert” and “red alert” (Table 1).

Table 1. Levels of volcanic alert of SERNAGEOMIN. Source: Servicio Nacional de Geología y Minería – SERNAGEOMIN – Red Nacional de Vigilancia Volcánica, 2025.

	Green alert (“Alerta verde”)	**Yellow alert (“Alerta amarilla”)**	**Orange alert (“Alerta naranja”)**	**Red alert (“Alerta roja”)**
Activity of volcano	Unchanged	Unstable	Significant variation	Expected development of an eruptive event
Phenomenon	Usual	Minor explosions, appearance of fumaroles, increase in monitoring parameters	Probable increase in activity (with respect to yellow alert)	Impending or ongoing major eruption
What to do?	No danger to the population	Keep informed through official channels of local and national authorities.	Stay informed, possible partial access restrictions to the volcano	Follow instructions from authorities, possible evacuation
Reports to community	Monthly	Every 15 days	Diaries	Daily or according to the evolution of the process

SERNAGEOMIN also maintains up-to-date information on its website about the characteristics of volcanic processes (Table 2), because volcanoes, during eruptions, can expel different types of volcanic products and processes.

Table 2. Volcanic processes. Source: Servicio Nacional de Geología y Minería – SERNAGEOMIN (2018).

Volcanic processes	**Characteristic**
Lava Flow	A viscous fluid consisting of molten rock, dissolved gases, of varying chemical composition. The flow velocity will depend on its composition.
Ash fall	Pyroclastic rain coming from eruptive columns. Its advance can reach thousands of kilometres from the source.
Gases	Corresponds to the gases dissolved in the magma, most of the gases are water vapor and carbon dioxide.
Volcanic avalanche	Avalanche of detritus produced by volcanic collapse, its speed of displacement is variable and can reach 300 km/hour, dragging a large amount of material.

This strategy allows the population adequate access to information. In addition, throughout Chile, a series of graphic information signs has been installed near volcanoes to inform and optimise evacuation if required. For example, volcanoes such as Villarrica (southern Chile) experience intense tourist activity in the surrounding area (Calder, 2004), which, during the summer season, can considerably increase the population and make evacuation tasks more difficult.

As of July 2025, according to the most recent update, SERNAGEOMIN classifies multiple volcanoes across the country into distinct risk categories (see Table 3).

Table 3. Volcanic hazard viewer. August 2025. Source: Servicio Nacional de Geología y Minería – SERNAGEOMIN (2025).

Category	Volcano
Category 1	Villarrica, Llaima, Calbuco, Nevados de Chillán, Puyehue-Cordón Caulle, Osorno, Mocho Choshuenco, Antuco, Carrán Los Venados, Cerro Azul Quizapu, Chaitén, Lonquimay, Hudson, Láscar.
Category 2	Michinmahuida, Yate, Sollipulli, Copahue, Grupo Descabezado Grande, Callaqui, Quetrupillán, Parinacota, Planchón-Peteroa, Hornopirén, Lanín, Complejo Antillanca, Laguna del Maule, Melimoyu, Tupungatito, Guallatiri.
Category 3	Maipo, San José, Apagado o Huailahué, Puntiagudo-Cordón Cenizos, Isla Decepción, Monte Burney, Taapaca, Huequi, Mentolat, Nevado de Longaví, San Pedro, Tacora, Reclus, Macá, Yanteles, Isla de Pascua, Irruputuncu, Corcovado, Olca-Paruma, Lautaro.
Category 4	Fui, Tatara-San Pedro, Cayutue-Ralún- Viguería, Tolhuaca, Grupo Volcánico Aysén, Tinguiririca, Socompa, Grupo, Puyuhuapi, Isluga, Ollagüe, Alto Palena, Grupo Caburgua, Barranco Colorado, Lastarria, Cay, Grupo Pali-Aike, Palomo, Aguilera, Licancabur, Aucanquilcha, Fueguino o Cook, Descabezado Chico, Cerro del Medio.
Category 5	Colachi, Ojos del Salado, Apacheta-Aguilucho, Escalante-Sairecabur, Putana, Chascón (Purico), Puntas Negras, Púlar-Pajonales, Nevado Tres Cruces, Chiliques, Caichinque, Nevado de Incahuasi, Palvitad, Acamarachi, Llullaillaco, Alítar, Cerro Bayo, Cordón del Azufre, Sierra Nevada.

Additionally, the characteristics of some volcanic eruptions are shown in Table 4 and Figures 1 and 2.

Table 4. History of volcanic eruption in Chile. Source: Servicio Nacional de Geología y Minería – SERNAGEOMIN (2018).

Year	Volcano	Description
1835	**Osorno**	Observed by Charles Darwin during his expedition. Coincided with a major earthquake in Concepción. Moderate eruption with ash emissions.
1864	**Calbuco**	One of the strongest eruptions of the 19th century. Reported with large ash emissions and lava flows. Nearby towns reported ashfalls for days.
1893–1895	**Villarrica**	A series of explosive eruptions. They triggered lahars (volcanic mudslides) that affected nearby areas. At least 15 deaths were reported from landslides and flooding.
1932	**Quizapu (Cerro Azul)**	Extremely explosive Plinian eruption. Considered the largest in South America in the 20th century. Fortunately, it occurred in an uninhabited area.
1948	**Llaima**	Violent eruption with lava flows and ash emissions. It affected agricultural areas in La Araucanía.
1960	**Puyehue-Cordón Caulle:**	Activation following the Valdivia megathrust earthquake. Long-lasting (several months), impacting transportation and agriculture.
1971	**Villarrica**	Major eruption with generation of lahars. Several deaths and damage to rural homes.
2008	**Chaitén**	A sudden eruption after more than 9,000 years of inactivity.

		Destruction of the town of Chaitén. Evacuation of more than 4,000 people.
2011	**Cordón Caulle (Complejo Puyehue)**	Huge eruptive column (>14 km). Affected southern Chile and much of Argentina. Air travel was disrupted, even in Australia.
2015	**Calbuco**	Three explosive eruptions in less than 24 h. More than 6,000 evacuated. Ash reached cities in Chile and Argentina.
2023	**Láscar**	Moderate activity with ash plumes up to 6 km high. Precautionary alert in San Pedro de Atacama.
2024	**Villarrica**	New eruptive phase with increased seismic activity and gas levels. Orange alert and constant monitoring remain in effect.

Figure 1. Satellite image of the Chaitén volcano (Chile) obtained by the EO-1 ALI satellite on October 20, 2009. Source: NASA Earth Observatory, data courtesy of the EO-1 team.

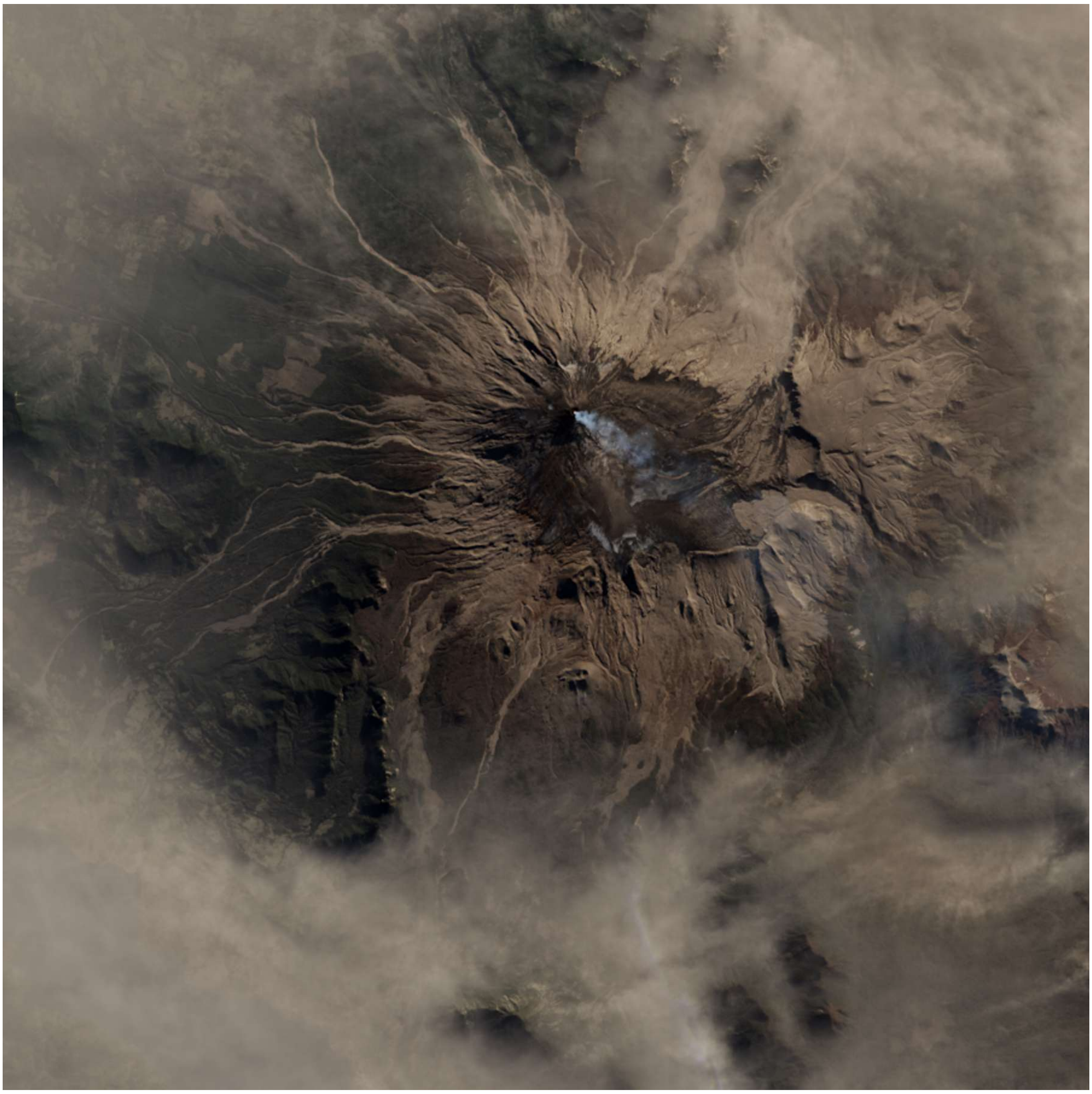

Figure 2. Column of ash from the Calbuco volcano (Chile) seen from the MODIS satellite, April 23, 2015. Source: NASA Earth Observatory / MODIS (Terra/Water). Image used with public permission; Spring NASA Earth Observatory.

3.2. Effects on human health

Volcanoes can have a variety of effects on human health through different means: mechanical (avalanches, earthquakes), thermal (lava and high-temperature gases), chemical (gases), and electrical and ionising radiation (Ortiz et al., 2022). Therefore, real-time monitoring is the most effective way to prevent harmful effects on health (Ortiz et al., 2022; Alvarado Celedón, 2006). These effects depend on the proximity of people to areas with volcanic activity, although the effect of the ash can occur several hundred kilometres away (Servicio Nacional de Geología y Minería - SERNAGEOMIN, 2018).

It is known that naturally occurring sources of air pollutants include soil erosion, seawater evaporation, forest fires, and volcanic eruptions (Jorquera González, 2015). Volcanic eruptions, in turn, can also trigger or intensify soil erosion and forest fires, and under certain conditions may contribute to seawater evaporation.

Exposure to gases is considered one of the most common, potentially causing severe acute illness and death. Gases can be composed of various substances: sulphur dioxide, carbon dioxide, hydrogen sulphide, carbon monoxide, among others (Ortiz et al., 2022; Alvarado Celedón, 2006). It is relevant to consider that these gases may also be present in geothermal areas. Immediate effects may include respiratory irritation, coughing, increased salivary secretion, shortness of breath, difficulty breathing, headache, exhaustion, nausea, impaired consciousness, and coma. In cases of acute exposure, it is important to stay away from the source of gases and seek specialised medical assistance.

Regarding the effects of chronic exposure, respiratory diseases such as chronic bronchitis (Cook et al., 2005; Vargas-Alfaro et al., 2024) and cancer of the lip, oral cavity, or pharynx (Navarro-Sempere et al., 2021) have been described. Likewise, the accumulation of inorganic mercury in the brain parenchyma and astrocyte dysfunction have been reported (Navarro-Sempere et al., 2021).

Ash can cause medium- and long-term effects. Prolonged exposure is a significant risk factor for lung disease. It is even possible to contaminate waterways at long distances, which can cause poisoning when ingested. The effects can be reduced by sealing windows in homes and cars, activating air recirculation inside vehicles, and wearing masks; however, these measures will not have a significant effect against toxic gases.

Significant effects on human health have also been described, beyond the acute situation. The impact on mental health following a natural disaster is also complex to quantify and requires a multidimensional approach. Volcanic eruptions can also have effects on mental health (Padrón-Armas & Trujillo, 2025). The impact is caused by the immediate emergency, which involves displacement, loss of property, and permanent injuries, including death, as well as by long-term effects, such as the loss of a place of residence, the death of loved ones, and the loss of material possessions.

3.3. Effects on animal health

The effects on animal health, across all species, can be catastrophic. Immediate death is common due to the release of toxic gases. These gases have similar effects on humans, given that they share a physiology based on oxygen-mediated cellular respiration.

Other important effects, although not entirely immediate, are related to the displacement and loss of natural habitats. Less domesticated animals, in particular, can suffer considerable harm, given their complex adaptation to other environments. Farm animals can usually be moved to different locations more safely.

Under laboratory conditions, various impacts on the respiratory tract have been observed in animals (Vargas-Alfaro et al., 2024). About fauna residing in volcanic regions, a study conducted in Spain identified neuroinflammatory responses in mice inhabiting volcanic environments. Nonetheless, such inflammation does not inherently imply a pathological or detrimental outcome (Navarro-Sempere et al., 2021).

Other effects on animal health are related to the loss of micronutrients from the soil, with a particular impact on grazing animals (Linhares et al., 2019).

3.4. Effects on environmental health

The effects on the immediate environment surrounding volcanoes have been widely described and often represent a profound socioeconomic impact (Vargas-Alfaro et al., 2024). These effects can, in turn, influence human and animal health due to the damage to ecological niches and the displacement of animal and plant species. The damage to the plant environment can be considerable and can even spread to distant areas due to the action of rivers (Major et al., 2013; Piña-Gauthier, 2013).

The emergency caused by the Chaitén volcano, for example, caused significant damage to areas as far away as 15 kilometres (Major et al., 2013), including damage to nearby areas, where pyroclastic flows of up to 300°C are estimated, causing carbonisation of vegetation (Major et al., 2013).

Damage to ecological niches can be permanent, and species recovery may even be impossible in some cases of significant destruction. While ash deposits can be fertile for some plant species (Linhares et al., 2019; Navarro-Sempere et al., 2021), the damage to animal species can be considerable and often irreparable.

Agricultural soils can be beneficial because some deposits can be considered fertile, such as manganese, copper, iron, magnesium, potassium, and zinc (Briceño et al., 2024). However, toxic compounds such as cadmium, lead, cobalt, nickel, and strontium can also accumulate there (Briceño et al., 2024). High concentrations can have effects on both soils and human and animal health. Some of these compounds can even have carcinogenic effects (Briceño et al., 2024). In agricultural soils formed from volcanic ash in southern Chile —such as volcanic brown soils, weakly developed volcanic soils, and weathered red soils— the adsorption of pollutants like herbicides is highly complex and poses environmental risks after eruptions. For the herbicide diuron, sorption kinetics indicate that volcanic brown soils rich in allophane and organic matter have faster and stronger adsorption. In contrast, weathered red soils show slower, time-dependent retention, increasing the risk of leaching into groundwater (Cáceres-Jensen et al., 2013). In the case of 2,4-D, organic matter has a relevant role in sorption and desorption processes, with volcanic brown soils showing greater retention capacity. The presence of hysteresis indicates irregular retention patterns, which may affect the environmental persistence of the compound (Cáceres-Jensen et al., 2021). These findings emphasise how the physical and chemical characteristics of volcanic soils influence pollutant mobility, highlighting the need for tailored environmental and agricultural management in recently ash-affected areas.

In summary, Table 5 provides an overview of the impacts of volcanic eruptions on human, animal and environmental health.

Table 5. Summary of the effects of volcanic eruptions on human, animal and environmental health.

Effects	Acute exposition	Chronic exposition
Human health	Acute gas poisoning. Burns caused by high temperatures or electric discharges. Traumatic injuries. Post-traumatic stress disorder. Mental health problems.	Chronic respiratory disorders. Cancer. Subclinical long-term intoxication.
Animal health	Acute gas poisoning. Burns caused by high temperatures or electric discharges. Species displacement.	Chronic inflammatory disorders.
Environmental health	Water pollution. Loss of ecological niches. Decline in plant species.	Depending on the mineralogical composition of the ash and the specific characteristics of each volcanic event, volcanic ash may lead to increased plant fertility in certain areas, while in other cases it may contaminate large swaths of soil with volcanic compounds.

3.5. *Health challenges in the case of volcanic alerts*

The intense surveillance carried out by SERNAGEOMIN, combined with the alert levels and a specific “disaster culture” among the Chilean population, allows for a more appropriate approach. Anticipation plays a key role, especially in the face of eruptions with little warning (Hall et al., 2004). SERNAGEOMIN has among its faculties the monitoring of volcanoes, in real time, with emphasis on the most active volcanoes in the country.

In general, the primary recommendation for human health care is self-care during volcanic risk situations. Residents in affected areas should have a pre-established action and evacuation plan, along with emergency kits containing first aid supplies; local governments can support them in these efforts.

The One Health approach represents a real challenge in addressing crises of this type, as is recommended for other crises (Cortés, 2025). One Health is a relatively recent approach to addressing the growing and complex problems related to health. It involves close cooperation between human and animal health professionals (Zinstag et al., 2018), moving beyond a human- or animal-centred approach. It is an integrative and unifying approach to optimise health strategies for humans, animals, and ecosystems (Manterola et al., 2023; González-Mena et al., 2025; FAO, UNEP, WHO, and WOAH, 2023). Infectious diseases are the primary practical example of the One Health approach (Manterola et al., 2023). This approach has been key, for example, during the COVID-19 pandemic, due to its zoonotic characteristics (Cortés, 2025). The One Health approach also has an impact on resource management, as it optimises resources, avoiding, for example, duplication of efforts. The One Health approach has been particularly successful in the case of interspecies infectious diseases (Zinstag et al., 2018). It has also expanded its scope to include natural disasters such as droughts (González-Mena et al., 2025). It is also being promoted by various international organisations such as the World Health Organization (WHO), the Food and Agriculture Organisation of the United Nations (FAO), the World Organization for Animal Health (WOAH), and the United Nations Environment Programme (UNEP) (González-Mena et al., 2025; FAO, UNEP, WHO, and WOAH, 2023).

In the case of the effects of volcanoes on health, the proposal is also to use the One Health approach (Figure 3), avoiding duplication of efforts to manage adequate human, animal, and environmental health, understanding the complex interrelationship of these components, understood as the human-animal-environment interface (Manterola et al., 2023). While the One Health perspective has been mainly studied in the case of infectious diseases, its application to the case of health affected by volcanoes appears promising, even if only from a theoretical perspective, as empirical evidence is necessary to determine its impact. However, the successful application of the One Health approach will depend on the adequate interaction of experts in human health, animal health, and environmental health, once the multifactorial impact of volcanoes is recognised.

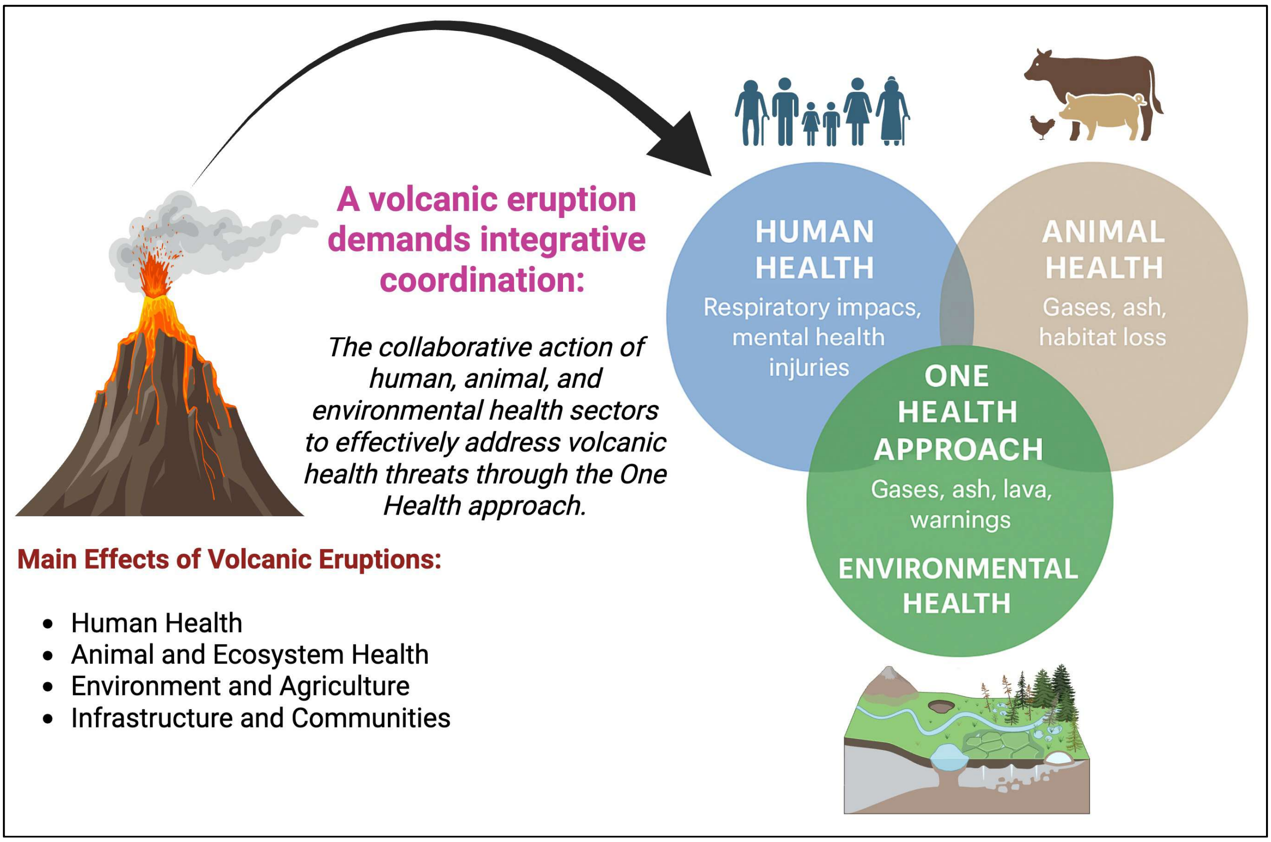

Figure 3. A conceptual diagram illustrating the One Health approach, highlighting the interconnections among human, animal, and environmental health in the context of volcanic eruptions. The figure emphasises shared vulnerabilities and the need for integrative coordination to manage gases, ash, habitat loss, and other health threats arising from volcanic activity. Created with *BioRender.com*.

The advantage is that volcanic crises generally occur in limited geographic regions, making it possible to limit the scope of the crisis and the resources required.

Advances in artificial intelligence, telemedicine, and digital health are essential for addressing the crisis (Cortés, 2025). The situation concerning local health action plans in volcanic risk zones requires particular attention. However, including specific content on health management may not be advisable; instead, curricular content focused on crises, crisis management, and network coordination is more suitable.

In the face of the crisis already underway, it is necessary to install field hospitals staffed with trained personnel to care for emergencies such as burns and respiratory tract injuries, and to be able to connect to highly complex centres via land or air vehicles.

Healthcare personnel must be prepared to face these types of situations, both during acute events and in long-term situations, for example, in volcanic areas that are tourist attractions.

3.6. *A Proposal Based on the Curriculum*

Consideration should be given to incorporating curricular content aimed at developing health competencies capable of more effectively addressing these types of problems, with the One Health approach as a central issue. Such curricular innovation would represent a genuine transformation across multiple healthcare disciplines, which will increasingly need to transcend their traditional professional boundaries in order to confront these emerging challenges. This need has already been suggested in relation to heat waves and forest fires, both of which may also be triggered by volcanic eruptions, thereby underscoring the urgent necessity for interdisciplinary preparedness in health education (Cortés et al., 2025). In this context, volcanic risk involves environmental exposure, respiratory vulnerability, and territorial impacts on populations, further reinforcing the need for interdisciplinary approaches within health education (Horwell & Baxter, 2006).

The challenges ahead should therefore focus on achieving a more comprehensive understanding of the effects of volcanic activity on human, animal, and environmental health, while simultaneously incorporating the One Health approach into such analyses. Although current strategies are primarily centred on the systematic monitoring of volcanoes through diverse technical tools —a responsibility largely undertaken by institutions such as SERNAGEOMIN— the emerging challenge lies in integrating these efforts across the broader health system.

More specifically, it is possible to propose an interdisciplinary curriculum for training in health and geological hazard management, based on a competency-oriented approach and encompassing topics such as One Health, disaster risk management, climate change, chronic exposure to ash and pollutants, post-disaster mental health, zoonoses and animal displacement, as well as environmental monitoring (Table 6). Expected learning outcomes would include the ability to recognise volcanic-related respiratory risks, interpret environmental and epidemiological information, and participate effectively in interdisciplinary preparedness and response actions.

Table 6. Proposal for health education and its integration into the curriculum.

	Description
General and specific competencies	Analyze the effects of acute and chronic volcanic activity on human, animal, and environmental health. Participate in public health response strategies for volcanic emergencies. Integrate approaches to epidemiological surveillance, environmental health, and One Health in disaster situations. Assess post-disaster mental health impacts. Apply triage and health management during mass evacuations. Identify the effects of water, forage, and soil contamination on domestic and livestock animals. Understand the dispersion of volcanic particulate matter and its ecosystem effects. Understand early warning systems and risk communication.
Thematic units	Unit 1. Chilean Volcanic Geography and Risk Context: The Pacific Ring of Fire; Volcanism in Chile; Major Historical Events. Unit 2. Effects on Human Health: Volcanic Ash and the Respiratory System; Air Pollution; Mental Health and Trauma. Unit 3. Impacts on animal health and ecosystems: Livestock and wildlife; Water pollution; Food security. Unit 4. Public health disaster management: Preparedness and response; Epidemiological surveillance; Intersectoral coordination. Unit 5. One Health and territorial resilience: Human-animal-environment integration; Community participation; Adaptation and resilience.
Levels of education	Undergraduate Programmes: Medicine, Nursing, Physical Therapy, Veterinary Medicine, Medical Technology, Psychology, Dentistry, Pharmacy, among others. Continuing Education: Environmental Health and Disasters, One Health, Health Risk Management, Disaster Epidemiology.
Methodologies	Problem-based learning, emergency simulations, analysis of historical cases, interprofessional collaboration, field-based learning, risk communication exercises.

Evaluation	Objective structured clinical examinations in disaster scenarios, case analysis, healthcare response plans, risk mapping, interprofessional assessment, and community-based simulations.

This proposal may be implemented through transversal courses, interdisciplinary modules, or continuing education programmes in the health sciences, particularly in territories exposed to active volcanism.

The integration of disaster risk management and environmental health content into health education has increasingly been promoted by international organisations and by countries exposed to geological and climate-related hazards. Through the Health Emergency and Disaster Risk Management (Health-EDRM) framework, the WHO emphasises the need to strengthen capacities for prevention, preparedness, response, and recovery within both health systems and professional education (WHO, 2019, 2020). Likewise, the Sendai Framework for Disaster Risk Reduction 2015–2030 explicitly recognises the strengthening of human and educational capacities as an essential component of disaster risk reduction, promoting intersectoral strategies and the development of community resilience (United Nations Office for Disaster Risk Reduction, 2015). In parallel, geography education has been identified as an appropriate curricular field for integrating disaster risk reduction, including preparedness and risk-awareness education on volcanoes and other natural hazards (Hawa et al., 2023).

Within this context, countries highly exposed to volcanic and seismic hazards, such as Japan, have developed university- and community-based programmes focused on disaster medicine, providing education and training to strengthen resilience while incorporating simulations, interprofessional training, and community-based work. In this regard, disaster education may improve preparedness, reduce vulnerability, and strengthen risk awareness when integrated into formal educational curricula (Hawa et al., 2023). Similarly, Iceland and New Zealand have strengthened interdisciplinary training in geological risk management and public health owing to their recurrent volcanic activity (University of Canterbury, 2026).

Consequently, the incorporation of content on volcanic risks and health into Chilean healthcare degree programmes aligns with international trends aimed at strengthening capacities in public health, territorial resilience, and comprehensive risk management. It is therefore proposed that Chilean universities incorporate such content through cross-cutting courses, interdisciplinary modules, or continuing education programmes, particularly in regions with high volcanic exposure, thereby strengthening competencies in health surveillance, disaster response, and territorial resilience under a One Health approach.

4. CONCLUSIONS

In conclusion, volcanic emergencies will inevitably affect human, animal, and environmental health. Therefore, it is necessary to draw on past experience and establish state policies to monitor these events and develop appropriate action plans. From this point of view, this macro action plan must originate with the country's central authorities as a permanent state policy that enables centralised coordination in terms of institutional arrangements and resource management. This action plan should focus on two main aspects. The first will relate to permanent preventive action when there is no crisis and will include the preparation of plans with interministerial coordination (Interior, Health, Defense, Public Works). The second will relate to specific actions for crisis management once a volcanic emergency occurs.

It is essential to have a population that is prepared to respond. Just as awareness and preparedness have been achieved for other natural disasters, such as earthquakes and tsunamis, in which Chile has extensive experience, similar efforts must be replicated for volcanic events, given their particularities and potentially devastating consequences.

The main challenges in health include adopting the One Health approach, effectively coordinating networks, preparing professionals to manage critical situations, and implementing local action plans, especially in Chilean areas at risk of volcanic activity. However, the One Health approach must originate from a central administration within the Ministry of Health, and the model must be part of both military and civilian training. Higher education institutions must therefore adopt this approach, with the enactment of legislation being one of the most effective ways to do so. As a result of Chile's extensive geography and volcanic history, the health professions, in keeping with the premise that they respond to social needs, must adapt the training of professionals to adequately address both this type of crisis and others arising from the country's geographical nature. In this regard, the incorporation of interdisciplinary curricular approaches centred on volcanic risk, environmental health, disaster preparedness, and One Health may represent a strategic opportunity to strengthen the education of healthcare professionals in geographically vulnerable territories.

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