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Fish mortality associated to volcanic eruptions in the Canary Islands

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The Canary Islands are an active volcanic archipelago. In the last decade, volcanic activity has occurred twice on the youngest and western most islands: El Hierro (submarine eruption) in 2011-12, and La Palma (subaerial eruption) in 2021. 70 fish specimens of different species from El Hierro volcano and 14 from La Palma were necropsied. A notable high and early mortality of fishes was registered during the submarine eruption of El Hierro. In most of them, generalized congestion in the gills, liver, spleen, kidney, heart and rete mirabile of the swim bladder was observed. Some specimens also presented exophthalmia, gastric eversion, ocular haemorrhages, over-inflation of swim bladder and gas bubbles mainly on the skin and cornea. The eruption of La Palma volcano was characterized by the emission of large amounts of lava flows and pyroclastic deposits (mainly ash in size) both, on land and sea. Lava flowed on land and eventually reached the sea, forming lava deltas in the coastline of La Palma. This event was also associated with an increase in fish mortality in locations near to the lava deltas. Fishes presented ash particles in opercula/oral cavities and gills. In addition, several fishes presented an intense intestinal impaction composed of volcanic material including ashes and hyaloclastites fragments. To our best knowledge this study describes, for the first time, pathological findings in dead fishes associated with two different styles of recent volcanic eruptions in the Canary Islands.

KEYWORDS

volcanic eruption, El Hierro, La Palma, decompression syndrome, gas bubbles, ashes, hyaloclastites, impaction

Introduction

The Canary Islands are an active volcanic archipelago developing over Jurasic oceanic lithosphere as a result of the eastward movement of the African plate over a mantle hotspot (e.g., Carracedo et al., 1998). They consist of eight main islands in the central eastern Atlantic Ocean, close to the Saharan coast of Africa. The geological stages and ages of the islands decrease from East to West. El Hierro and La Palma islands are the youngest and, because of that, the most volcanic active (e.g., Carracedo et al., 1998). This has led to two volcanic eruptions with different eruptive styles derived from the location of the vents: submarine in the case of the 2011-12 eruption of the Tagoro volcano on the island of El Hierro; subaerial in the case of the 2021 eruption of the Tajogaite volcano on the island of La Palma (Figure 1).

There are few studies on the effects of volcanic eruptions on fish stocks. In a recent review, Carrillo and Díaz-Villanueva (2021) have summarized the impacts of volcanic eruptions in freshwater environments and organisms mainly focused on the assessment of the density or behaviour alterations in fish populations. Among these studies, it can be highlighted the effects after the 1912 Mt Katmai (USA) eruption that produced a delay in the arrival of migratory salmonids by obstruction of access, leading to a reduction in recruitment of young sockeye salmon (*Oncorynchus nerka* Walbaum) (Eicher and Rounsefell, 1957). Similarly, Bisson et al. (2005), described a massive habitat loss because of the eruption of Mount St. Helens (USA; 1980) which led to an overall reduction in fish population densities. More recently, Di Prinzio et al., (2021) reported how, 21 months after the 2008 Chaitén eruption (Chile), fish assemblages were greatly affected by the volcanic effects on the habitat. Most of these studies have been carried out after volcanic eruptions to assess the disturbances or the recovery of the aquatic ecosystem. However, to our knowledge, there are not available studies about the causes of fish death, directly, due to volcanic eruptions.

The submarine eruption on the island of El Hierro began the 10th of October 2011, announced by the recording of more than 10,000 earthquakes during three previous months. The eruption was fed by a fissure located at the submarine prolongation of the Southern rift of the island between 350-400 m depth. It built a main volcanic cone (later named Tagoro volcano) nested inside a submarine canyon that reached a height of more than 200 m, with successive morphological reconfigurations of its flanks and craters. Pyroclastic materials, mainly lapilli and bombs in size, was accumulated close to the vents. Lava flows were emitted from different craters and flowed along the canyon for more than 3 km (e.g., Perez-Torrado et al., 2012; Carracedo et al., 2015). The eruption ended in the first days of March 2012, being the second longest eruption in the Canary Islands after Timanfaya eruption (1730-36) on the island of Lanzarote. In the first 20 days, many fishes appeared dead floating on the sea surface of the volcano area (Mendoza et al., 2022).

The subaerial eruption on the island of La Palma began the 19th of September 2021, with seismic precursors extended since 2017. As well as the El Hierro eruption, it was fed by a fissure located on the western flank of the Cumbre Vieja rift. Its main eruptive style was strombolian with the construction of a main volcanic cone (recently named as Tajogaite volcano) of about 200 m maximum height, emission of a large amount of pyroclastic deposits (mainly ash in size) and lava flows (mainly a'a on morphology). The eruption ended the 13th of December, being the longest (85 days) historical eruption of La Palma and the most destructive consequences in the last century in Europe (e.g., Instituto Geográfico Nacional, 2021; Carracedo et al., 2022). Lava flowed initially on land to the sea, where its entrance created new land know as lava deltas, with changes on the lava morphology (from a'a to pillow lava) and formation of a new type of volcanoclastic material named as hyaloclastites. The first entrance into the sea of the subaerial a'a lava flows was the 29th of September.

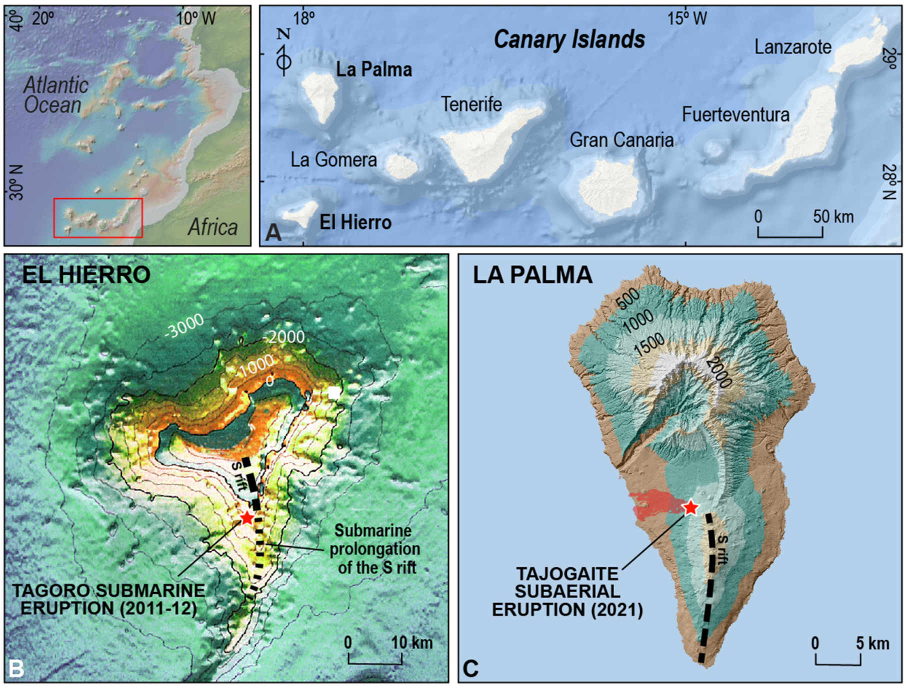

FIGURE 1
Location of the Canary Islands in the framework of the Central Atlantic Ocean **(A)**. Location of the Tagoro eruption in the submarine prolongation of the S rift of the island of El Hierro **(B)**. Location of the Tajogaite eruption in the western flank of the S rift (Cumbre Vieja rift) of the La Palma island. The perimeter of the lava field with the entrance to the sea is marked in red **(C)**.

Successive entrance of the lava flows generated a lava delta that reached a final surface of about 43 Ha. On 22th November a new lava delta, located north to the previous one, began to form, reaching a final surface of about 5 Ha (e.g., Instituto Geográfico Nacional, 2021; Carracedo et al., 2022). Around these lava deltas, fishes were found dead but to a lesser extent compared to El Hierro eruption.

Here, we report the results of pathological studies of fish found dead during the two volcanic eruptions in the Canary Islands. To our best knowledge, this is the first study showing the details of necropsies of dead fishes during these two different explosive episodes when volcanic ashes, lava flow and gas are injected into the oceanic environment.

Materials and methods

Fishes collected

Although 70 dead fishes were collected on the 11th,19th, 26th and 28th of October 2011 in the coastline of El Hierro, near to the submarine volcano eruption (Figures 2A and B), only 49 specimens were considered acceptable to perform the necropsy and the histopathological study. The remaining specimens were not included in the study due to a severe and advanced process of autolysis. In the case of La Palma volcano, 14 dead fishes were collected the 7th and the 28th of October of 2021, at the coastline area of the new formation of the lava delta (Figure 2C). Fish collection was provided, as a field opportunity, by the specialized emergency authorized personnel, which was allowed to access to the volcano area under the necessary permits an authorizations, and only when their lives were not under risk. This logically affects the total number of collected specimens.

All the different species of the dead specimens were identified following the Guidelines of the Canary Islands Marine Biodiversity (Espino et al., 2018) and listed in Table S1 (Supplementary material).

Necropsy and histopathological studies and procedures

The necropsies were performed at the Fish Pathology Unit of the Institute of Animal Health and Food Safety (IUSA) of the ULPGC, through a systemic approach and observation of external and internal organs (Meyers, 2009; Roberts, 2012). Gross morphological changes were identified, and samples of gill, heart, swim bladder, digestive tract, liver, spleen, anterior and posterior kidney, gonads, muscle,

FIGURE 2
(A). Ocean surface of the Mar de Las Calmas (El Hierro) indicating a submarine eruption (on Oct. 12th, 2011) (see details in Carracedo et al., 2015). **(B)** High mortality of fishes in the coastline of El Hierro Island (on Oct. 20th, 2011). **(C)**. The lava flow in contact with the ocean created the first lava delta (La Palma island) (on Sep. 30th, 2021) (see details in Caballero et al., 2022).

eyes, skin and central nervous system were taken from each specimen and fixed in 10% neutral buffered formalin for the histopathological examination. After fixation, the tissue samples were placed into cassettes and processed. Processing of the tissues included dehydration through ascending grades of alcohols, clearing in xylene and finally paraffin wax imbibition. Paraffin blocks were sectioned at 4 µm and sections stained with hematoxylin and eosin (H&E). The slides were mounted and examined with a light microscope (Olympus BX51TF, Japan).

The digestive content of four fish (3 parrotfish (*Sparisoma cretense*), 1 planehead filefish (*Stephanolepis hispida*) from La Palma volcano was extracted, air-dried and examined under scanning electron microscopy of the Advanced Confocal and Electronic Microscopy Service (SIMACE) of the ULPGC.

Results

Volcano of El Hierro Island

Macroscopic and microscopic findings

The necropsy findings of the fishes analysed are shown in Table 1. Specimens of *Helicolenus dactylopterus* and *Hoplostethus mediterraneus* collected on the 11th and 19th of October (first week after the beginning of the eruption) presented gastric eversion within the oral cavity, with a notable blood congestion of the stomach walls (Figure 3A). Specimens of *Antigonia capros* collected on the 11th of October (first day of eruption) showed unilateral exophthalmia. This finding was also seen in specimens of *Serranus atricauda* collected on the 26th and the 28th of October (after 16 days post-eruption) (Figure 3B). The presence of gas bubbles and hemorrhages in the cornea were observed in specimens of *Anthias* and *Chromis limbate* collected during the first week. Similarly, gas bubbles in the eyes (Figure 3C) and the skin (Figure 3D) were found in a specimen of *Grammicolepis brachiusculus*, usually adapted to live in deep oceanic waters (500-700m; source:FishBase). Many of the fishes (physoclistous species) collected also during the first days of the eruption, presented over-inflation of the swim bladder (Figure 3E) and severe congestion of the rete mirabile (Figure 3F).

Microscopically, severe congestion was confirmed in rete mirabile of the swim bladder (Figures 4A and B), gill, liver (Figure 4C), spleen, kidney and heart. In the heart ventricle, gas bubbles were observed in the specimen of *Grammicolepis brachiusculus* (Figure 4D).

TABLE 1 Necropsy findings reported in dead fishes from El Hierro volcano eruption.

Necropsy findings	% fish affected
Swim bladder congestion	18/49 (36.7%)
Gill, liver and heart congestion	13/49 (26.5%)
Gastric eversion	10/49 (20.4%)
Gas bubbles in cornea	10/49 (20.4%)
Ocular hemorrhages	7/49 (14.2%)
Exophthalmia	4/49 (8.2%)
Gas bubbles in the skin	1/49 (2.0%)
Gas bubbles in the heart	1/49 (2.0%)

Volcano of La Palma Island

Macroscopic and microscopic findings

The necropsy findings of dead fishes collected during the eruption of La Palma volcano are shown in Table 2.

The results of the necropsy of the animals found dead one week after the beginning of the formation of the lava delta (7th of October, 2021), showed the presence of volcanic material inside the oral and opercula cavities (Figure 5A) and between the gill lamellae. This material was composed by black small particles (≈1 mm) not found within internal organs or tissues. Nevertheless, those specimens analysed three weeks after the beginning of the formation of the lava delta (28th of October, 2021) together with abundant accumulation of small black particles in the gills (Figure 5B), showed a notable intestinal impaction composed by the presence of volcanic material within the digestive system (Figures 5C and D). In the digestive content (Figure 6A) presence of hyaloclastites (formed by quench fragmentation of lava flow surfaces when entered into the sea) and ashes were detected (Figure 6B). Under scanning electron microscope, the hyaloclastites are identified as angular and low-vesiculated fragments, while vesiculated particles are identified as ashes (Lindqvist et al., 2011).

Comparative summary of results

Table 3 summarizes the most significant oceanographic data together with the main lesions described for the two different volcanic scenarios. These results offer an overall perspective that could help for the diagnosis of fish mortality related to volcanic activity and/or eruptions.

Discussion

A volcanic eruption is an instantaneous and powerful geological event. In the last decade, this extraordinary phenomenon has taken place twice on the Canary Islands: El Hierro (submarine eruption, start date 10th of October, 2011), and La Palma (subaerial eruption, start date 19th of September, 2021). The effects of these two volcanic eruptions on the marine and terrestrial ecosystems were extensively monitored and coordinated by Special Plan for Civil Protection and Emergency Care due to Volcanic Risk in the Canary Islands (PEVOLCA) during the period of active eruptions.

In both recent volcanic eruptions in the Canary Islands the marine ecosystem was affected in two clearly differentiated ways. In the case of the underwater eruption in El Hierro, a high fish mortality rate was observed during the first days of the eruption around the volcanic area, with many dead fishes found floating near to the coastline related mainly to the important physical-chemical perturbations of the sea water. In the case of La Palma volcano, the rate of dead fishes was reduced in number and longer in time when compared with El Hierro eruption. Deaths were mainly associated to

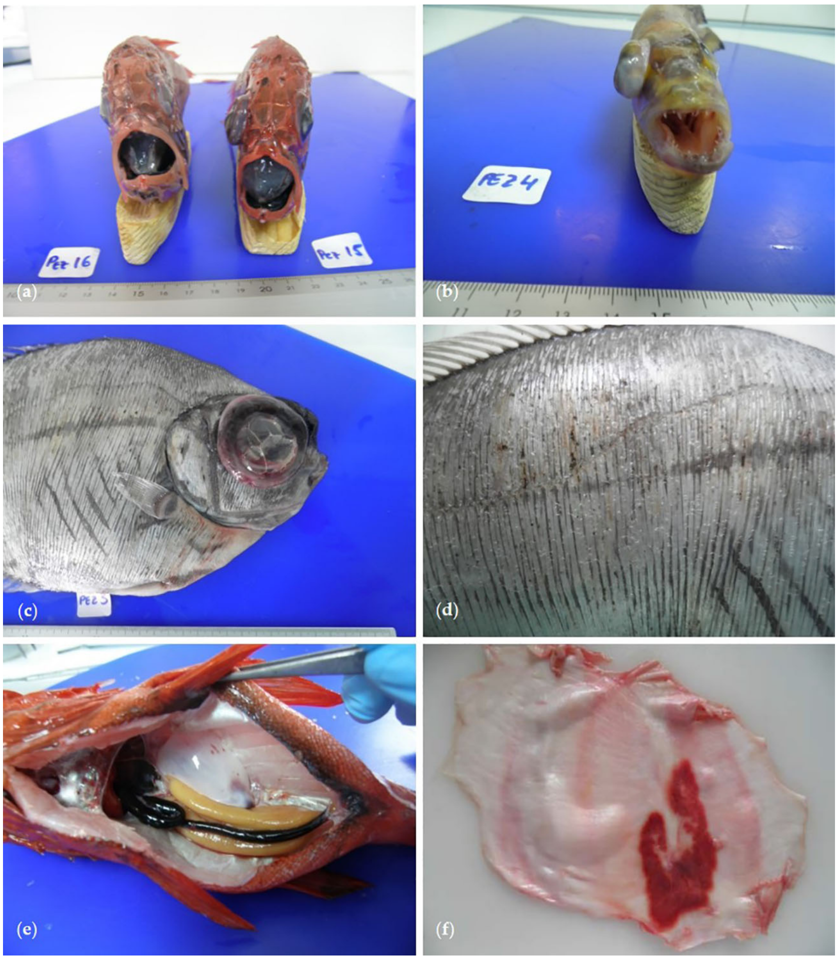

FIGURE 3
Macroscopy findings in fishes from El Hierro volcano. **(A)** Gastric eversion in two specimens of *Hoplostethus mediterraneus*. **(B)** Exophthalmia unilateral in a specimen *Serranus atricauda*. **(C)** Gas bubbles in cornea in a specimen of *Grammicolepis brachiusculus*. **(D)**. Gas bubbles in skin in a specimen of *Grammicolepis brachiusculus*. **(E)** Over-inflation of the swim bladder and hemorrhages in a specimen of *Hoplostethus mediterraneus*. **(F)** Severe congestion of the rete mirabile in a specimen of *Balistes carolinensis*.

the creation of the new lava delta, at the arrival of the lava flow to the sea 10 days after the beginning of the eruption (IGN, 2021), and associated also to the production of large amounts of volcanic ashes that eventually reached the ocean.

There are few studies reporting the impact of volcanoes on different environments (see review Carrillo and Díaz-Villanueva (2021)), however pathological studies describing the findings on dead animals, as a result of the extreme environmental conditions, during volcanic eruptions, are even scarcer.

In the present study, high and early mortality, severe congestion of the gills and internal organs was observed in all the dead fishes collected during the first days of the submarine eruption of El Hierro island. It has been reported that congestion is a common lesion associated to anoxia and temperature stress in fish (Bagherzadeh Lakani et al., 2013; Bowden et al., 2014). During El Hierro volcano several authors reported high temperatures, and a drastic decrease in pH and oxygen levels in the oceanic waters of the area, during the first weeks of the eruption. For example, González-Vega et al., (2022) reported conditions close to anoxia during initial stages of the eruption in the first 250 m of water column, with concentration of dissolved oxygen as low as 7.71 μmol Kg^{-1}, representing -96% depletion respect to normal conditions. Fraile-Nuez et al., (2012) reported temperature anomalies of +3°C at 80 m depth from the volcano with a maximum temperature of +18.8°C observed over the crate at 210 m depth. Finally, the pH of the seawater column in the volcanic area drastically decreased below 6, with a lowest registered in 2.9, as consequence of the emissions of CO_2, SO_2 and H2S/HS- (Santana-Casiano et al., 2013; Santana-Casiano et al., 2016). All these authors agreed that these extreme physical-chemical perturbations of the water column could be directly associated with the high mortality of the fishes seen in the El Hierro volcanic eruption.

In addition to generalized congestion, other internal damages were found in dead fishes from El Hierro. These damages include over-inflation of swim bladder with severe congestion of the rete mirabile, gastric eversion, exophthalmia, gas bubbles and hemorrhages in the eyes. The pathogenesis of these lesions could be associated to both, depressurization effects from rapid movements towards the surface and/or with gas oversaturation of the environmental surrounding waters. "Decompression syndrome" (Rummer and Bennett, 2005; Morrisey et al., 2005) or "barotrauma" (Munday et al., 2015), happens when a fast ascent from deep to superficial ocean waters drastically decrease water

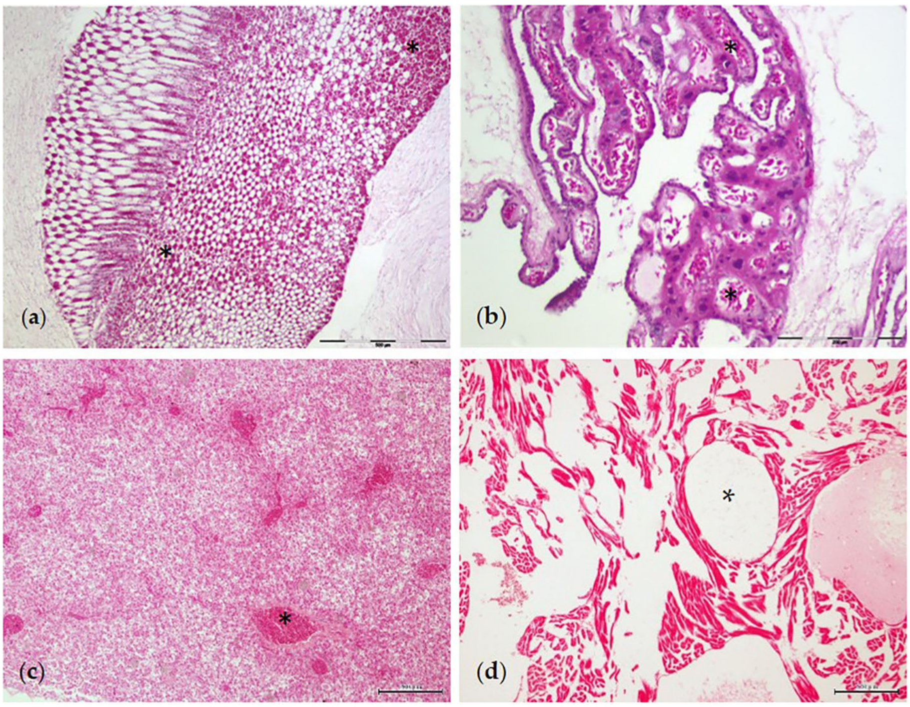

FIGURE 4
Microscopy findings in fishes from El Hierro volcano. Severe congestion (*) of the rete mirabile in a specimen of *Balistes carolinensis* (**A**, H&E, bar=500µm) and *Helicolenus dactylopterus* (**B**, H&E, bar=200µm). Liver congestion (*) in a specimen of *Hoplostethus mediterraneus* (**C**, H&E, bar=200µm). Gas bubble (*) in the heart ventricle in a specimen of *Grammicolepis brachiusculus* (**D**, H&E, bar=200µm).

TABLE 2 Necropsy findings reported in dead fishes from La Palma volcano eruption.

Necropsy findings	% fish affected
Intestinal impaction with volcanic material	6/14 (42.8%)
Presence of volcanic particles in oral/opercula cavity and gills.	6/14 (42.8%)
Presence of volcanic particles in stomach	3/14 (21.4%)
Gill congestion	3/14 (21.4%)

pressure causing an exponential increase in gas volume. Associated lesions described by the literature include overexpansion of the swim bladder, bulging of the eyes, oesophageal eversion and protrusion of the intestine very similar to those reported in the present study. In addition, literature on the environmental effects of underwater explosions have also reported the swim bladder as the most frequently damaged organ, together with extensive lesions on the kidney, liver and spleen, possibly related to the rapid contraction and overexpansion of the swim bladder (Kearns and Boyd, 1965; Christian, 1973; Falk and Lawrence, 1973; Yelverton et al., 1975; Linton et al., 1985).

Furthermore, Pribyl et al., (2011) also described microscopically emphysema (gas bubbles) in the heart ventricle, like the one described in the present study, as a consequence of barotrauma. In our case, a specimen of *Grammicolepis brachiusculus*, known as a deep ocean species, also presented gas bubbles in the skin. The presence of gas bubbles in the skin has not been documented in the process of decompression or barotrauma so far. However, Santana-Casiano et al., (2013) reported a notably increase of ocean water gas saturation in the first weeks of the volcanic eruption in El Hierro. It is well known, on fish populations, that any gas oversaturation of the environmental water will lead to oversaturation of the animal tissues and, consequently, the formation of intra- and extravascular gas bubbles; (Marking, 1987; Speare, 1991; Velázquez-Wallraf et al., 2022), that could also explain the results showed in the present study.

The recent studies of La Palma volcano eruption have reported notable changes in the properties of the water quality in the area, especially, in the turbidity, due to the entrance into the sea of the lava flows and falling of ash particles from the eruptive column developed about the volcanic vents (Caballero et al., 2022). Despite these conditions, fish mortality was low and only occurred sporadically associated with the creation of the lava delta. In the present study, we describe the deposition of ash particles in the oral and opercula cavities, and between gill lamellae of dead fishes, without any other histopathological damages associated. In addition, we also reported a severe impaction of volcanic material in the lumen of the intestine of 42.8% of the analysed fishes. The material found in the digestive content was mainly composed of hyaloclastites and ashes. Based on our findings, we think that although the water conditions in the area affected by the lava delta were less lethal to fish populations than El Hierro volcano, the presence of ashes in the water column, as well as the newly formed lava delta, facilitated the entry of the volcanic material into the fishes being a possible cause of death. Despite the lack of previous pathological studies, some authors have reported similar results. In this sense, Newcomb and Flagg (1983) described a

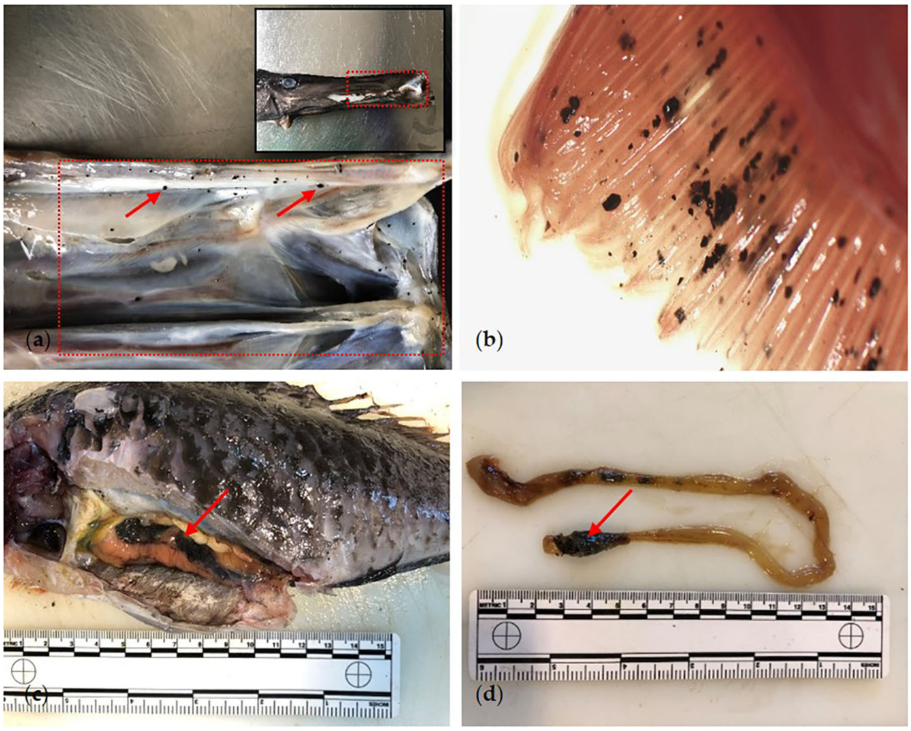

FIGURE 5
Macroscopic findings in fishes from La Palma volcano. **(A)** Volcanic particles (→) in the oral cavity in a specimen of *Aulostomus strigosus*. **(B)** Severe deposition of volcanic particles in the gill from a specimen of *Stephanolepis hispida*. **(C)** Presence of volcanic material (→) in the intestine of *Sparisoma cretense*. **(D)** Severe impaction of volcanic material (→) in the intestine of *Stephanolepis hispida*.

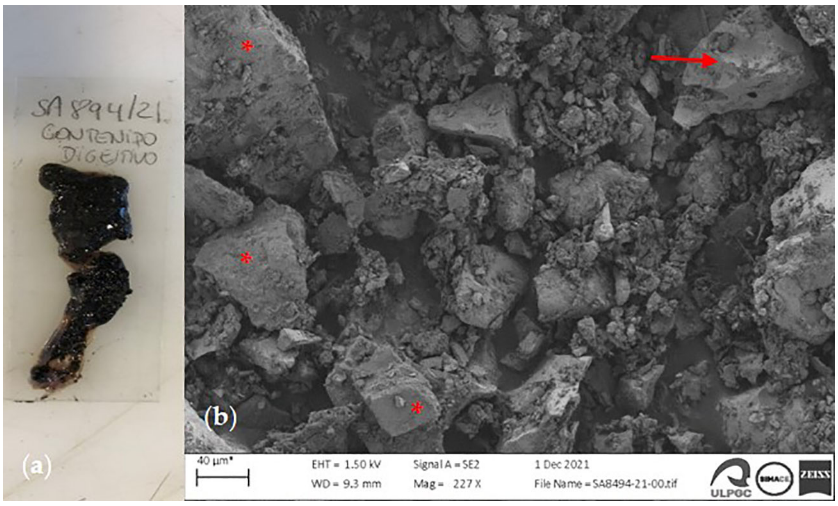

FIGURE 6
(A) Digestive content from a *Sparisoma cretense*. **(B)** Digestive content under the scanning electron microscope. (*) presence of angular and low-vesiculated fragments derivated of the fragmentation of the lava flows when entered to the sea (identified as hyaloclastites). (→) presence of vesiculated particles, falling into the sea-surface from the dispersion of the subaerial eruptive column (identified as ashes).

severe congestion in the gills of sockeye salmon due to deposition of ash particles from the 1980 Mt. St. Helens volcano (USA), suggesting disruption of oxygen exchange as the main cause of death. Similarly, and more recently, Lallement et al., (2016), reported how the eruption of the Puyehue-Cordon Caulle (in Chile, 2011) produced an important decline in fish densities in the most western streams associated to the deposition of ashes.

Conclusions

The extensive sea surface area and the water column affected during El Hierro volcano produced as result, a lower capacity of escape for the fishes in the zone. These conditions resulted in high and early mortality of the fish population during the first stage of the underwater eruption. The corresponding lesions were severe organ

TABLE 3 Summary of the most significant oceanographic data together with the main lesions described for the two different volcanic scenarios.

	El Hierro volcano	La Palma volcano
Start of eruption	October 10th, 2011 (submarine 300 m depth up to 88 m below surface)	September 19th, 2021 (first lava delta formed on September 30th, 2021)
Relevant water conditions		
Date and area measurements	5-Nov-11; 17 Nov-11 (464 km^2, at 1.8km offshore of the southern coast of El Hierro)	*1st-3rd October 2021 (near the lava delta, 344 km^2)
Temperature (°C)	¥Increase up to +3°C	*Increase up to + 4-5°C
pH_T (PH units)	$Decreasing (5.134-5.201 vs 8.045 control area)	*Decreasing (7.2473-7.8896 vs 7.9516 control area)
O_2 (μmol/kg)	$Decreasing (112.9 vs 217.2 control area)	Not published yet
CO_2 (μmol/kg)	¥High content in surface waters	*High content in surface waters
pCO_2 (uatm)	¥150,000 at the seawater surface (strong gas oversaturation with respect to atmospheric CO_2 level)	*595-2538 at the seawater surface (notably higher than the atmospheric measurements)
Assessed fishes		
Mortality	High and early	Low and delayed
Date of dead fish collected	From 11 to 28 October, 2011	From 7 to 28 October, 2021
Lesions on collected fishes	Severe tissue congestion in gill, liver, spleen, kidney, swimbladder. Gastric eversion. Exophthalmia Ocular hemorrhages. Gas bubbles in skin and cornea.	Deposition of ashes in the external organs in gill and oral cavity. Impaction of ashes and hyaloclastites in the intestine.

¥ Data from Fraile-Nuez et al., (2012) water samples were taken two weeks after the start of the eruption (5-Nov-11; 16-20 Nov-11). $Data from Santana-Casiano et al., (2013) water samples were taken two weeks after the start of the eruption (5-Nov-11; 17 Nov-11). * Data from Román et al., (2022), water samples were taken near the lava delta on 2th October 2021.

congestion and physical injury such as exophthalmia, gastric eversion, ocular hemorrhages, over-inflation of swim bladder and the presence of gas bubbles in eyes and skin. These findings are related to the dramatic changes in the reported physical-chemical water conditions (severe anoxia, increased temperature, decreased pH) and to the potential development of decompression and/or gas oversaturation syndromes. In La Palma volcanic eruption, the lava flow aroused gradually and slowly to the coastal water, creating the lava delta. The fishes in the area could have opportunity to escape to the extreme changes of the water conditions described. However, this eruption produced a huge amount of ashes and volcanic particles. These conditions together with the formation of the new delta had a lower and gradually impact on fish populations in terms of mortality. The corresponding lesions were the result of the entry of this volcanic material and particles into the fishes, affecting the respiratory and digestive systems. The results of the present study described for the first time two different injury patterns on fish mortality directly related to different volcanic eruptions occurred in the Canary Islands.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, MC. Methodology, AV-W, MB. Investigation, MC, FP-T, AC-A. Resources, AF. Writing-original draft preparation, MC. Writing-review and editing, AC-A and FP-T. Supervision, MC. Visualization, AC-A. Project administration, A.F. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.999816/full#supplementary-material

References

Bagherzadeh Lakani, F., Sattari, M., Sharifpour, L., and Kazemi, R. (2013). Effect of hypoxia, normoxia and hyperoxia conditions on gill histopathology in two weight groups of beluga (Huso huso). *Caspian J. Env. Sci.* 11, 77–84.

Bisson, P. A., Crisafulli, C. M., Fransen, B. R., Lucas, R. E., and Hawkins, C. P. (2005). "Response of fish to the 1980 eruption of mount st. helens," in *Ecological responses to the 1980 eruption of mount st. helens*. Eds. V. H. Dale, F. J. Swanson and C. M. Crisafulli (New York, USA: Springer), 163–182.

Bowden, A., Gardiner, N., Couturier, C., Stecyk, J., Nilsson, G., Munday, P., et al. (2014). Alterations in gill structure in tropical reef fishes as a result of elevated temperatures. *Comp. Biochem. Physiol. Part A: Mol. &amp Integr. Physiol.* 175, 64–71. doi: 10.1016/j.cbpa.2014.05.011

Caballero, I., Román, A., Tovar-Sánchez, A., and Navarro, G. (2022). Water quality monitoring with sentinel-2 and landsat-8 satellites during the 2021 volcanic eruption in la palma (Canary islands). *Sci. Total Environ.* 822, 153433. doi: 10.1016/j.scitotenv.2022.153433

Carracedo, J., Day, S., Guillou, H., Rodríguez Badiola, E., Canas, J., and Pérez Torrado, F. (1998). "Hotspot volcanism close to a passive continental margin: the canary islands," in *Geological magazine*, vol. 135. (Geological Magazine Production Unit Cambridge University Press), 135, 591–604. doi: 10.1017/s0016756898001447

Carracedo, J. C., Troll, V. R., Day, J. M. D., Geiger, H., Aulinas, M., Soler, V., et al. (2022). The 2021 eruption of the cumbre vieja volcanic ridge on la palma, canary islands. *Geol. Today* 38.3, 94–107. doi: 10.1111/gto.12388

Carracedo, J., Troll, V., Zaczek, K., Rodríguez-González, A., Soler, V., and Deegan, F. (2015). The 2011–2012 submarine eruption off El hierro, canary islands: New lessons in oceanic island growth and volcanic crisis management. *Earth-Sci. Rev.* 150, 168–200. doi: 10.1016/j.earscirev.2015.06.007

Carrillo, U., and Díaz-Villanueva, V. (2021). Impacts of volcanic eruptions and early recovery in freshwater environments and or-ganisms. *Biol. Rev.* 96, 2546–2560. doi: 10.1111/brv.12766

Christian, E. (1973). *The effects of underwater explosions on swimbladder fish. defense technical information center*. National Technical Information Service U. S. Department of Commerce 5285 Port Royal Road, Springfield Va. 22151. NOLTR 73-103. doi: 10.21236/ad0767019

Di Prinzio, C., Penaluna, B., Grech, M., Manzo, L., Miserendino, M., and Casaux, R. (2021). Impact of chaitén volcano ashfall on native and exotic fish recovery, recolonization, and abundance. *Sci. Total Environ.* 752, 141864. doi: 10.1016/j.scitotenv.2020.141864

Eicher, G., and Rounsefell, G. (1957). Effects of lake fertilization by volcanic activity on abundance of salmon. *Limnol. Oceanogr.* 2, 70–76. doi: 10.4319/lo.1957.2.2.0070

Espino, F., Boyra, A., Fernández-Gil, C., and Tuya, F. (2018). *Guía de biodiversidad Marina de canarias* (Oceanográfica press: Divulgación, Educación y Ciencia S.L).

Falk, M. R., and Lawrence, M. J. (1973). Seismic exploration: Its nature and effects on fish. *Can. Fish. Mar. Serv. Tech. Rep.* CEN/T-73-9, 51.

Fraile-Nuez, E., González-Dávila, M., Santana-Casiano, J., Arístegui, J., Alonso-González, I., Hernández-León, S., et al. (2012). The submarine volcano eruption at the island of El hierro: physical-chemical perturbation and biological response. *Sci. Rep.* 2, 486. doi: 10.1038/srep00486

González-Vega, A., Callery, I., Arrieta, J., Santana-Casiano, J., Domínguez-Yanes, J., and Fraile-Nuez, E. (2022). Severe deoxygenation event caused by the 2011 eruption of the submarine volcano tagoro (El hierro, canary islands). *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.834691

Instituto Geográfico Nacional (2021) *Informe mensual de vigilancia volcánica IGN*. Available at: https://www.ign.es/web/resources/volcanologia/html/CA_noticias.html (Accessed July 15, 2022).

Kearns, R. K., and Boyd, F. C. (1965). The effect of a marine seismic exploration on fish populations in British Columbia coastal waters. *Can. J. Explor. Geophys.* 1, 83–106.

Lallement, M., Macchi, P., Vigliano, P., Juarez, S., Rechencq, M., Baker, M., et al. (2016). Rising from the ashes: Changes in salmonid fish assemblages after 30 months of the puyehue–cordon caulle volcanic eruption. *Sci. Total Environ.* 541, 1041–1051. doi: 10.1016/j.scitotenv.2015.09.156

Lindqvist, H., Nousiainen, T., Zubko, E., and Muñoz, O. (2011). Optical modeling of vesicular volcanic ash particles. *J. Quantit. Spectrosc. Radiat. Transf.* 112 (11), 1871–1880. doi: 10.1016/j.jqsrt.2011.01.032

Linton, T. S., Landry, A. M., Buckner, J. E., and Berry, R. L. (1985). Effects upon selected marine organisms of explosives used for sound production in geophysical exploration. *Texas J. Sci.* 37, 341–353.

Marking, L. (1987). *Gas Supersaturation in Fisheries: Causes, Concerns, and Cures*. Washington DC: US Department of the Interior, Fish and Wildlife Service.

Mendoza, J. C., de la Cruz-Modino, R., Dorta, C., Pablo Martín- Sosa, P., and Hernandez, J. C. (2022). Ecosystem modeling to evaluate the ecological sustainability of small-scale fisheries: A case study from El hierro, canary islands. *Ocean Coast. Manage.* 228, 106297. doi: 10.1016/j.ocecoaman.2022.106297

Meyers, T. R. (2009). *Standard necropsy procedures for finfish. 3rd ed* (Alaska, USA: The Alaska Department of Fish and Game), 1–10.

Morrisey, M., Suski, C., Esseltine, K., and Tufts, B. (2005). Incidence and physiological consequences of decompression in smallmouth bass after live-release angling tournaments. *Trans. Am. Fish. Soc.* 134, 1038–1047. doi: 10.1577/t05-010.1

Munday, E., Tissot, B., Heidel, J., and Miller-Morgan, T. (2015). The effects of venting and decompression on yellow tang (*Zebrasoma flavescens*) in the marine ornamental aquarium fish trade. *PeerJ* 3, e756. doi: 10.7717/peerj.756

Newcomb, T. W., and Flagg, T. A. (1983). Some effects of mt. st. helens volcanic asch on juvenile salmon smolts. *Mar. Fish. Rev.* 45, 8–12.

Perez-Torrado, F. J., Carracedo, J. C., Rodriguez-Gonzalez, A., Soler, V., Troll, V. R., and Wiesmaier, S. (2012). La erupción submarina de la restinga en la isla de El hierro, canarias: octubre 2011–marzo 2012. *Estud. Geol* 68, 5–27. doi: 10.3989/egeol.40918.179

Pribyl, A., Kent, M., Parker, S., and Schreck, C. (2011). The response to forced decompression in six species of pacific rockfish. *Trans. Am. Fish. Soc.* 140, 374–383. doi: 10.1080/00028487.2011.567858

Roberts, R. J. (2012). *Fish pathology*. *4th ed* (Oxford, UK: Wiley-Blackwell). doi: 10.1002/9781118222942

Román, A., Tovar-Sánchez, A., Roque-Atienza, D., Huertas, I. E., Caballero, I., Fraile-Nunez, E., et al. (2022). Unmanned aerial vehicles (UAVs) as a tool hazard assessment: The 2021 eruption of cumber vieja volcano, la palma island (Spain). *Sci. Total Environ.* 843, 157092. doi: 10.1016/j.scitotenv.2022.157092

Rummer, J., and Bennett, W. (2005). Physiological effects of swim bladder overexpansion and catastrophic decompression on red snapper. *Trans. Am. Fish. Soc.* 134, 1457–1470. doi: 10.1577/T04-235.1

Santana-Casiano, J., Fraile-Nuez, E., González-Dávila, M., Baker, E., Resing, J., and Walker, S. (2016).). significant discharge of CO2 from hydrothermalism associated with the submarine volcano of El hierro island. *Sci. Rep.* 6, 25686. doi: 10.1038/srep25686

Santana-Casiano, J., González-Dávila, M., Fraile-Nuez, E., de Armas, D., González, A., Domínguez-Yanes, J., et al. (2013). The natural ocean acidification and fertilization event caused by the submarine eruption of El hierro. *Sci. Rep.* 3, 1140. doi: 10.1038/srep01140

Speare, D. (1991). Endothelial lesions associated with gas bubble disease in fish. *J. Comp. Pathol.* 104, 327–335. doi: 10.1016/s0021-9975(08)80044-8

Velázquez-Wallraf, A., Fernández, A., Caballero, M., Arregui, M., González Díaz, Ó., Betancor, M., et al. (2022). Establishment of a fish model to study gas-bubble lesions. *Sci. Rep.* 12, 6592. doi: 10.1038/s41598-022-10539-8

Yelverton, J. T., Richmond, D. R., Hicks, W., Saunders, K., and Fletcher, E. R. (1975). *The relationship between fish size and their response to underwater blast* (Defense Nuclear Agency). Topical Report DNA 3677T.