Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Biological, physicochemical, and social impacts resulting from the rupture of the Fundão Dam

ARTICLES doi:10.4136/ambi-agua.3045

Received: 29 Oct. 2024; Accepted: 05 Apr. 2025

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ABSTRACT

Mining is essential to Brazil's economy; however, the collapse of the Fundão Dam on November 5, 2015, due to the improper deposition of tailings, released approximately 50 million cubic meters of tailings into the environment. This disaster, the largest in the Brazilian mining sector and one of the most significant globally, affected the Doce River and its ecosystem across over 650 kilometers to the Atlantic Ocean, causing extensive damage to biodiversity and contaminating the Atlantic Forest, estuaries, and coastal areas, with the risk of extinction for some species. Water quality was severely compromised, with increased levels of heavy metals and significant impacts on microbiota, flora, and aquatic fauna. The social and economic consequences were also severe, affecting mental health, fishing, and agriculture within local communities. Accordingly, this review article seeks to address the identified knowledge gaps by comprehensively examining the biological, physicochemical, and social impacts of the Fundão Dam collapse. The review also highlights the differences between pre- and post-disaster and discusses the inadequacy of the containment measures adopted. The conclusion is that mitigation efforts were insufficient and delayed, resulting in lasting and severe consequences for both the environment and the population, underscoring the need for more effective environmental protection in the mining sector.

Keywords: contamination, environmental impacts, mining.

Impactos biológicos, físico-químicos e sociais decorrentes do rompimento da Barragem de Fundão

RESUMO

A mineração é essencial para a economia brasileira, contudo o rompimento da barragem de Fundão, em 5 de novembro de 2015, devido à deposição inadequada de rejeitos, lançou cerca de 50 milhões de metros cúbicos de resíduos no meio ambiente. Esse desastre, o maior do setor no Brasil e um dos maiores globalmente, afetou o Rio Doce e seu ecossistema por mais de 650 km até o Oceano Atlântico, com danos extensivos à biodiversidade e contaminação da Mata

Atlântica, estuários e áreas costeiras, além de riscos de extinção para algumas espécies. A qualidade da água foi severamente prejudicada, com aumento de metais pesados e impactos significativos na microbiota, flora e fauna aquáticas. As consequências sociais e econômicas também foram graves, afetando a saúde mental, a pesca e a agropecuária das comunidades locais. Desta forma, este artigo de revisão visa preencher lacunas no conhecimento ao abordar de forma abrangente os impactos biológicos, físico-químicos e sociais do rompimento da barragem de Fundão. A revisão destaca também as diferenças entre os períodos pré e pós-desastre e discute a insuficiência das medidas de contenção adotadas. Conclui-se que os esforços mitigadores foram insuficientes e aplicados tardiamente, resultando em consequências duradouras e severas para o meio ambiente e a população, evidenciando a necessidade de uma proteção ambiental mais eficaz no setor de mineração.

Palavras-chave: contaminação, impactos ambientais, mineração.

1. INTRODUCTION

Mining has played a crucial role in the economy of the Brazilian state of Minas Gerais, with the steel industry emerging as one of the key economic drivers in the region (Segura *et al.*, 2016). The Samarco mining company, located in the municipality of Mariana in southeastern Minas Gerais, is widely recognized for its prominence in mineral extraction (Wanderley *et al.*, 2016). The operations of this mining company have brought Brazil significant international recognition, making it the country with the highest rates of development and exportation of iron ore in the world, as well as generating substantial revenue from other minerals (Silva *et al.*, 2021). Tailings are typically stored in dams, which perform well when properly constructed. However, poor design and construction can lead to failure (Carvalho *et al.*, 2017).

On November 5, 2015, the Fundão Dam, located in the subdistrict of Bento Rodrigues, approximately 35 km from the center of Mariana, collapsed under the management of Samarco, due to pressure from the improper deposition of large quantities of iron ore tailings (Bottino *et al.*, 2017). This disaster resulted in the release of approximately 50 million cubic meters (m^3) of iron ore tailings into the environment (Gomes *et al.*, 2021). One year after the dam failure, over 43 million m^3 of tailings continued to cause environmental damage (Gabriel *et al.*, 2020). These tailings breached not only the Fundão Dam but also the Santarém Dam, flowing intensely as a slurry into the Doce River (Segura *et al.*, 2016; Carmo *et al.*, 2017), traversing the river system for over 650 km before reaching the Atlantic Ocean (Rudorff *et al.*, 2018; Duarte *et al.*, 2021).

The volume of pollutants and the extent of the affected ecosystems reached unprecedented levels, impacting the Brazilian Atlantic Forest, estuarine, coastal, and marine environments (Carmo *et al.*, 2017). This event is widely recognized as the largest environmental disaster in the history of mining in Brazil and one of the most significant globally (Andrade *et al.*, 2018). From an environmental perspective, the slurry composed of water and iron ore tailings resulting from the collapse destroyed villages and aquatic ecosystems, compromising essential areas for the reproduction of various species. As a consequence, several animal species may have gone extinct, with recovery of the affected watersheds estimated to take decades (Lacaz *et al.*, 2017). This disaster resulted in numerous casualties, affecting various municipalities in Espírito Santo and Minas Gerais that are part of the Doce River Basin, leading to significant psychological, social, material, and financial losses (Freitas *et al.*, 2019; Esteves *et al.*, 2020). Moreover, the environmental consequences are immeasurable due to the vast extent of the damage. Notable impacts include harm to reproductive biology and histological changes in the gonads of fish (Merçon *et al.*, 2021), alterations in microbial communities (Cordeiro *et al.*, 2019), physiological changes in algae (Costa *et al.*, 2019), as well as effects on benthic macrofauna

(Gomes *et al.*, 2017) and fish larvae (Bonecker *et al.*, 2019). Additionally, histopathological changes in the liver (Weber *et al.*, 2020) and the accumulation of heavy metals such as aluminum (Al), iron (Fe), manganese (Mn), and zinc (Zn) in the muscle tissue of fish exposed to contaminated water from the Doce River (Dos Santos Vergilio *et al.*, 2021) have also been detected.

Despite the significant visibility and attention generated by the Mariana disaster, just over three years later, a new tragedy emerged in Brumadinho/Minas Gerais (Almeida *et al.*, 2019). This incident involved a smaller volume of released tailings, but the proportion of fatalities was nearly fifteen times greater, overshadowing the discussion surrounding the Mariana disaster, which had gradually lost prominence and was being mentioned less frequently (Duarte *et al.*, 2021).

Although the Mariana disaster has received extensive scientific and media attention, existing studies address its impacts in a fragmented manner, considering biological, physicochemical, and social aspects separately, often without an integrated and in-depth analysis. Moreover, many of these investigations explore these topics superficially, failing to fully assess the consequences for ecosystems and local populations. Given this gap, the present study aims to consolidate and expand knowledge on the impacts on flora and fauna, as well as changes in water quality and the psychosocial aspects related to the disaster. Additionally, this study highlights the differences between the pre- and post-disaster periods and contributes to a more comprehensive understanding of the adverse effects that arose as a consequence of the catastrophe, enabling a better assessment of the interactions among ecological, physicochemical, and human factors.

2. MATERIAL AND METHODS

This article is a literature review aimed at consolidating and analyzing the existing literature on the biological, physicochemical, and social impacts of the Fundão Dam rupture. A comprehensive search was conducted across several academic databases, including PubMed, SciELO, Science Direct, Scopus, Web of Science, and Google Scholar. As inclusion criteria, we focused exclusively on published and peer-reviewed articles from 2012 to 2024, resulting in the inclusion of 70 articles, to ensure both methodological rigor and scientific reliability. The review primarily focuses on peer-reviewed journal articles, while also incorporating select technical reports, government agency documents, and book chapters/e-books. The inclusion of these diverse sources aims to provide a more comprehensive and multidisciplinary perspective on the subject matter. This selection was based on their scientific impact, methodological quality, and direct contribution to understanding the biological, physicochemical, and social consequences of the Fundão Dam rupture. As exclusion criteria, annal abstracts, thesis, dissertations, non-government documents or websites weren’t included in narrative review.

3. RESULTS

3.1. Physicochemical and microbiological changes in water

The physicochemical changes in aquatic ecosystems resulting from the release of iron ore waste have a significant impact on biogeochemical cycles, as well as on the dispersion of essential elements and pollutants in the affected area (Viana *et al.*, 2020). These pollutants were transported along the Doce River through the tailings slurry, as illustrated in Figure 1.

A study conducted seven days after the rupture of the Fundão Dam, followed by an analysis two years later, in 2017, showed that there was a significant change in redox potential, while the pH remained neutral (Queiroz *et al.*, 2021). Six months after the rupture of the Fundão Dam, the levels of the metals chromium (Cr), nickel (Ni), cadmium (Cd), and mercury (Hg) in the sediments were found to be in concentrations exceeding the limits established by the *National*

Oceanic and Atmospheric Administration (Dos Santos Vergilio *et al.*, 2021). Furthermore, analyses revealed that both the water and sediment of the Doce River exhibited cytotoxic, genotoxic, and mutagenic effects (Dos Santos Vergilio *et al.*, 2021). In another study conducted 34 months after the dam rupture in two rivers and six watersheds regarding the quantification of non-biotic parameters, a decrease in temperature, conductivity, and pH measured in the water of all sampling stations during the dry period was observed (Almeida *et al.*, 2023). The temperature varied between 24.7ºC to 28.7ºC in the dry season and 28.2ºC to 33.5ºC in the rainy season, as recorded at most sampling points. The concentration of dissolved oxygen was higher during the dry period in most stations, except for the samples from the Doce River-Linhares and Lagoa Monsarás, where the opposite was observed (Almeida *et al.*, 2023).

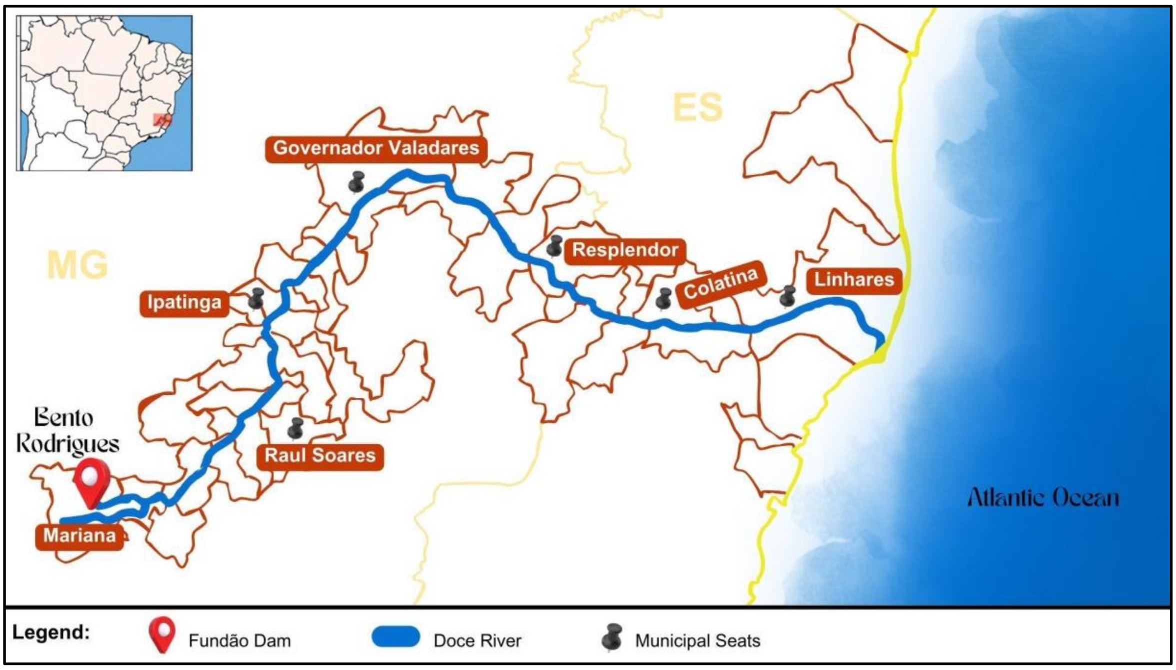

Figure 1. Map indicating the path taken by the tailings slurry.
Source: Prepared by the authors.

Due to its geographical proximity to the city of Mariana, the Gualaxo do Norte River Basin, situated in the São Bento district, was also impacted by the flow of mining waste. In a study by Dos Reis *et al.* (2019), conducted between September and December during the spring season, it was observed that the turbidity of the basin increased significantly due to the higher velocity of water flow. This resulted in a severe impact on the aquatic ecosystem, with elevated levels of suspended particulate matter, including heavy metals such as iron (Fe), aluminum (Al), manganese (Mn), and titanium (Ti), as well as toxic metals like lead (Pb) and arsenic (As). These conditions culminated in adverse effects on both the health of local fauna and the surrounding human population (Vergilio *et al.*, 2020).

It is important to emphasize that the fluviometric, hydrographic, and hydrodynamic conditions of the Doce River are heavily influenced by the precipitation patterns within the river basin. This watershed exhibits two distinct seasonal periods: the rainy season, occurring from October to March, and the dry season, from April to September (RRDM, 2020). In this context, seasonal meteorological and oceanographic events at the mouth of the Doce River and the adjacent coastal region play a significant role. These phenomena have been shown to greatly influence the distribution and deposition of sediments, as well as mining debris resulting from the Fundão Dam collapse (Quaresma *et al.*, 2015; 2020).

The water flow and, consequently, the amount of sediment discharged into the marine zone adjacent to the Doce River mouth are largely influenced by the rainfall pattern of the watershed. This pattern is marked by seasonal variations characterized by increased river flow during the rainy periods and increased wave-associated energy during the dry period (Costa *et al.*, 2022). During flood periods, the sediments present in the sea are preferentially directed to the South and Southeast, parallel to the coast. As a consequence, there is an increase in turbidity and in the concentration of suspended particulate matter, as well as a reduction in surface salinity near the river mouth. In contrast, during dry periods, the river flow is directed toward the river mouth and North region, associated with the resuspension of seabed sediments due to the increased occurrence of higher-energy waves, raising turbidity and the concentration of suspended particulate matter (ICMBIO, 2024). The reduction in the surface density of bottom sediment makes it less resilient to resuspension processes and more susceptible to remobilization, resulting in a decline in water quality during the dry period (ICMBIO, 2024). Thus, changes in the direction of coastal currents modify the depositional and erosive patterns to the north and south of the Doce River mouth (Costa *et al.*, 2022). Based on this, it is evident that rainy conditions, river flow, and the direction and intensity of currents are elements that can induce temporal and spatial changes in sedimentation processes and the physicochemical characteristics of the water (RRDM, 2020).

Both the studies by Gomes *et al.* (2021) and Queiroz *et al.* (2021) suggested a correlation between excess metals and various health disorders, such as neurodegenerative diseases, cardiovascular toxicity, and liver damage. In the study conducted by Carvalho *et al.* (2017), it was found that the increase in Pb levels, three times higher than the maximum value allowed by CONAMA Resolution No. 357/2005, results in a range of health problems, both short and long-term, including irritability. In contrast, manganese (Mn) is generally not toxic, but when associated with iron (Fe), it becomes controlled by redox processes and potentially harmful to humans, and especially to animals, by impairing metabolism and cell growth (Gomes *et al.*, 2021). Furthermore, in a study conducted by Metcalf and Codd (2020), the importance of properly removing the element copper (Cu) after the water bloom process was elucidated, as despite being useful in eliminating cyanobacteria, its persistence in water can result in liver damage in both animals and humans. This is particularly concerning due to the coexistence of additional biological toxins that enhance hepatic effects, such as heavy metals, particularly Pb and Mn, along with pathogenic microorganisms.

In Brumadinho, Minas Gerais, between 2017 and 2020, there was a considerable increase in reports of diseases transmitted via the fecal-oral route, resulting from inadequate water supply (Trovão *et al.*, 2023). After studies with 313 volunteers aged 8 to 78 years from communities impacted by the Fundão Dam failure in the Doce River region (Espírito Santo, Brazil), it was found that the consumption of well water and water from the urban supply network, combined with higher exposure to aluminum (60 μg/L) and nickel (2.7 μg/L), contributed to increased problems related to fecal-oral diseases (Paulelli *et al.*, 2022). Furthermore, *Bacillus safensis* 3A, a Gram-positive, spore-forming bacterium, was identified in toxic sludge samples from estuarine sediments after the dam collapse. Known for its remarkable ability to colonize extreme environments, this species is characterized by its high tolerance and resistance to salts and heavy metals (Defalco *et al.*, 2021).

Thus, all the accumulated damage contributes to a heightened risk of new diseases and health issues (Silva *et al.*, 2020), leading to an overload on Brazil's healthcare system, which results in more hospitalizations and, consequently, overburdening hospitals (Freitas *et al.*, 2019).

3.2 Impacts on fauna

3.2.1. Impacts on the Zooplankton Community

A series of impacts resulting from the dam collapse have already been documented at various trophic levels of the food chain, including physiological changes in algae (Costa *et al.*, 2019), in the diversity of the zooplankton community (Fernandes *et al.*, 2020), in the benthic community (Bernadino *et al.*, 2019), and modifications in the microbial community (Cordeiro *et al.*, 2019). Studies evaluating fauna have shown high concentrations of elements after the disaster involving the Fundão Dam (Ferreira *et al.*, 2021; Gabriel *et al.*, 2020). Low diversity has been observed in the organisms that make up the zooplankton, which are at the base of the food chain and respond rapidly to environmental changes (Fernandes *et al.*, 2020).

Before the Fundão Dam collapse, the Doce River exhibited high levels of biodiversity within the zooplankton community (Petrobras, 2015). However, due to the tailings, there was an acute alteration, resulting in reduced biodiversity (Fernandes *et al.*, 2020). This phenomenon may indicate a possible impact associated with the increased concentration of heavy metals (Rocha *et al.*, 2015). In addition to natural factors that can affect the zooplankton community, such as salinity, temperature, and phytoplankton biomass (Jia *et al.*, 2019), it should be considered that sediment resuspension events increase the levels of metals disaggregated from particulate matter (Hatje *et al.*, 2017). This results in direct impacts on zooplankton, such as low nutrient quality, death by burial or asphyxiation (David *et al.*, 2005). Therefore, the importance of analyzing the zooplankton community is reinforced as a parameter for assessing ecosystem health. Data such as the increase in younger forms of certain species suggest that there is a population in the process of recovery after the environmental impact (Rocha *et al.*, 2015).

3.2.2. Impacts on Fish

Fish are frequently used for monitoring metal contamination because they are considered excellent models for assessing the quality of aquatic ecosystems. This is due to their characteristics, such as their presence in a wide range of environments, occupation of different levels in the food chain, ability to accumulate toxins in their tissues, and sensitivity to various types of contaminants (Martinez *et al.*, 2021).

The biological impacts on fish resulting from the release of tailings have been widely documented in the scientific literature. Previous studies have highlighted a variety of impacts on fish (Vergilio *et al.*, 2020), including damage to reproductive biology and histological alterations in the gonads of lambari fish (*Astyanax lacustres*) (Merçon *et al.*, 2021), histopathological changes in the liver (Weber *et al.*, 2020), and the accumulation of heavy metals such as aluminum (Al), iron (Fe), manganese (Mn), and zinc (Zn) in the muscle of fish (Dos Santos Vergilio *et al.*, 2021). These impacts are shown in Figure 2.

The evidence of metal accumulation in fish larvae raises the hypothesis that the contaminated sludge plays a significant role in inducing morphological changes. These changes include the degeneration of the digestive tract, as documented by Bonecker *et al.* (2019). Since metals do not undergo degradation or rapid elimination from the ecosystem, aquatic organisms exposed to these contaminants accumulate them through their gills or by ingestion along the food chain (Merciai *et al.*, 2014). This accumulation can influence metabolism in such a way that it can cause various damages and pathologies (Coppo *et al.*, 2018). As a result, there may be a significant reduction in fish diversity (Andrade *et al.*, 2020); morphological changes (Bonecker *et al.*, 2019); bioaccumulation of metals; biochemical changes and oxidative stress (Weber *et al.*, 2020). Heavy metals are capable of promoting changes in the metabolism of lipids and carbohydrates, either by inhibiting enzymes involved in the degradation or synthesis of these compounds or by activating apoptosis mechanisms, such as kinases and caspases, which are compromised with hepatic necrosis (Anvarifar *et al.*, 2018). There are studies that confirm a relationship between metal contamination and fat accumulation in the liver (steatosis) and hepatic necrosis in fish (Anvarifar *et al.*, 2018). Therefore, it is of utmost importance to evaluate the ecological systems in areas affected by the dam collapse disaster so that mitigation measures can be implemented, along with conducting studies on the impacts on fauna associated with the affected areas.

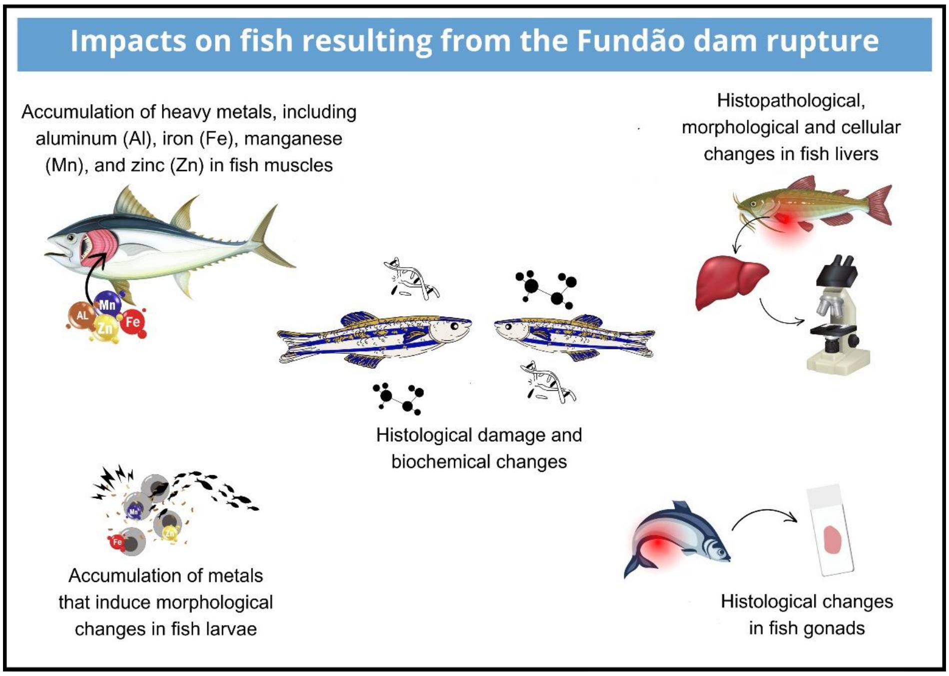

Figure 2. A schematic representation of the impacts resulting from the Fundão Dam rupture on the liver, muscle, gonads, and larvae of the fish.
Source: Prepared by the authors.

Weber *et al.* (2020) evaluated the impact caused on two fish species, *Hoplias intermedius* (traira) and *Hypostomus affinis* (catfish), which are widely distributed in the Doce River Basin and do not have migratory habits. These species are ecologically resilient to environmental changes, capable of surviving in impacted rivers, and are of commercial relevance to the riverine community of the Doce River Basin (Vieira *et al.*, 2015). In this study, the fish were collected in two regions during the dry (March) and rainy (June) periods of 2018: one region not affected by the tailings, located in the Piranga River, and another directly affected by the tailings from the Samarco Dam, in the Doce River. At the collection site affected by the mining tailings, both examined species exhibited several morphological, histopathological, and cellular alterations in the liver, as illustrated in Figure 2 below. These included flattened nuclei at the periphery, hyperemia, cytoplasmic vacuolization, and inflammatory infiltrate, indicative of stress and cell injury (Vieira *et al.*, 2015).

Metallothionein is a metal-binding protein widely present in the liver, playing an important role in the response of aquatic organisms to the presence of these metals. For this reason, the liver is a crucial organ for conducting analyses of metal contamination in aquatic environments (Marijić and Raspor, 2007). A study conducted by Vieira *et al.* (2015) revealed that the hepatic expression of metallothionein in catfish and traitor fish collected from the Doce River was significantly higher, about 3.8 and 2.5 times more, respectively, than the levels found in the same species collected in areas not contaminated by the tailings. Furthermore, additional research has established a correlation between increased concentrations of metals such as As, Ni, and Pb and elevated hepatic levels of metallothionein (Roy and Bhattacharya, 2006).

3.2.3. Impacts on Birds

Birds have been utilized in monitoring pollution caused by metals, thus enabling their tracking in ecotoxicological studies (Berglund, 2018). Tissues such as blood and feathers may serve as a less invasive method that does not negatively impact the quality of life of the birds (Croxall *et al.*, 2012). In the study conducted by Zebral *et al.* (2022), blood and feather samples were collected from birds during two distinct periods: the first collection took place in the winter of 2018, in September and October, while the second occurred in the summer of 2019, during January and February. The collections were made along the coast of Espírito Santo, an area affected by mining waste resulting from the collapse of the Mariana Dam. The results indicated elevated levels of heavy metals, including Pb, Hg, As, and Cd, in the tissues of the analyzed birds. A temporal variation was observed, with higher contamination levels detected in the winter samples compared to the summer samples. These elevated contamination levels during the winter collections, resulting by stronger winds and the arrival of cold fronts that enhance wave action and sediment resuspension, may suggest potential impacts on avian health, as levels of As, Pb, and Hg may disrupt the activity of certain enzymes (Mandal and Suzuki, 2002), lead to reproductive dysfunction (ATSDR, 2007), and potentially induce neurobehavioral alterations (Whitney and Cristol, 2018). However, it is recommended that more in-depth studies be conducted to confirm this hypothesis.

3.2.4. Impacts on Cetaceans

Unlike organic pollutants, metallic elements are not subject to accelerated elimination or degradation by ecosystems, which leads to their accumulation in organisms throughout food chains (Merciai *et al.*, 2014). Predatory cetaceans at the top of their food chains, such as dolphins, are profoundly affected by the bioaccumulative effect of chemical compounds (Bisi *et al.*, 2012). This marine species is considered vulnerable according to the International Union for Conservation of Nature’s Red List, and classified as critically endangered in the Brazilian Red Book of Threatened Fauna (Subirá *et al.*, 2018). A study involving the analysis of trace elements (As, Cd, Cu, Fe, Hg, Mn, and Zn) in the liver and muscle of franciscana dolphins (*Pontoporia blainvillei*) before and after the dam failure found an upward temporal trend for Hg and Zn in dolphin muscle and liver after the Fundão Dam rupture. This increase is attributed to higher concentrations and bioavailability of these metals in the water column and sediments of the Doce River. Additionally, decreasing trends were observed for As and Cu concentrations in muscle and liver, and Fe in the kidneys. These reductions are likely due to the reduced bioavailability of these metals, which were sequestered in the tailings mud accumulated along the riverbanks and suspended particulate matter (Manhães *et al.*, 2022).

3.3. Impacts on flora

Among the numerous biological groups affected by the incident, flora was one of the major casualties (Esteves *et al.*, 2020). Due to its extensive variety and diversity, the impact assessment was segmented into the following areas: (1) riverine ecosystems, (2) marine environments, (3) interface zones between marine and riverine environments (mangroves), and (4) terrestrial ecosystems adjacent to riverbanks.

In riverine areas, plant contamination was primarily impacted by mineral deposits, particularly due to the role of the Doce River as a channel for transporting extractive waste over more than 600 kilometers, leaving a trail of destruction along its path (Gabriel *et al.*, 2020). Numerous alterations resulted from the abnormal quantity of minerals in the water, changes which were also observed in the river’s resident fauna. In response, some algae, cyanobacteria, and other small plant species initiated a bioremediation process, effectively absorbing and removing heavy metals like Fe and Mn from the river, along with other toxic substances (Sood *et al.*, 2015). Larger plants, such as macrophytes, absorb small particles around their leaves and stems when submerged, using ion entry into the cytoplasm followed by deposition in the vacuole. Additionally, these plants produce chelating agents, substances capable of binding to metals, leading to inactivation or removal of these substances from the organic system (Bottino *et al.*, 2017). Although these processes contribute to water quality improvement, it is essential to recognize that direct exposure to various toxic compounds can cause significant damage. The accumulation of non-degradable materials in plant tissues can compromise their health and viability, leading to high bioaccumulation levels (Ali *et al.*, 2013). Consequently, reduced enzymatic function, decreased chlorophyll levels, and inhibited photosynthesis were observed, ultimately inhibiting development, growth, bud emergence, frequent leaf loss, and diminished biomass accumulation (Gomes *et al.*, 2021).

Regarding marine contamination, since the arrival of mining waste at the mouth of the Doce River, numerous metal depositions and resuspensions have occurred in the region (Coimbra *et al.*, 2020). This phenomenon, combined with the ease of dispersion via ocean currents and the transport of small and light silt and clay particles in the sediment, facilitates the spread of waste hundreds of kilometers offshore (Marta-Almeida *et al.*, 2016). The presence of heavy metals raises concerns about the safety of the entire ecosystem, especially in environmentally protected areas like the Abrolhos Archipelago (Gomes *et al.*, 2017). Generally, suspended particles and metals in the sea reduce light penetration, decreasing photosynthetic efficiency and lowering energy availability. In biodiversity-rich regions like Abrolhos, biological impacts are significantly intensified (Coimbra *et al.*, 2020). Additionally, due to decreased light availability for photosynthesis, a group of algae known as Zooxanthellae, which give corals their color, are dying, leading to coral bleaching (Smith *et al.*, 2005). This phenomenon results in substantial biological losses and adversely impacts the region's economic potential by reducing tourism associated with affected coral reefs (Coimbra *et al.*, 2020).

Concerning mangrove flora, it is important to recognize the bioma's role in sustaining marine life while noting its paradoxical territorial limitations and reduction, a process that began prior to the disaster in Mariana (Lovelock *et al.*, 2022). The dam failure exacerbated this situation, with heavy metals such as Fe, Mn, Zn, Pb and Cu accumulation in plants. Large trees facilitated the retention of mineral waste in the area due to friction with small metal fragments. The persistence of these particulate materials, especially iron and copper, within plants led to various adverse effects, including increased fluorescence, reduced photosystem efficiency, and lower chlorophyll concentration (Tognella *et al.*, 2022). Given these changes and the importance of mangroves for environmental regulation, it is crucial to restore, protect, and sustain these habitats (Lovelock *et al.*, 2022).

Both terrestrial plants and terrestrial vegetation are of great nutritional significance and are increasingly incorporated into human diets. Furthermore, certain types of vegetation, such as grasses consumed by livestock, are vital for local socioeconomic sustainability (Silva *et al.*, 2021; De Almeida *et al.*, 2022). However, vegetation along the Doce River was affected, with crops and pastures destroyed and contaminated by mineral waste. While typically beneficial, plant consumption becomes hazardous in high metal concentrations, potentially leading to health deterioration (Ferreira *et al.*, 2022). The most recurrent metals in plants post-disaster were Fe and Mn (De Almeida *et al.*, 2022). The presence of these elements within plants results in several deviations from typical flora behavior. In efforts to survive the hostile environment, plants adopt techniques like absorption control to limit the uptake of already excessive internal metals (Ferreira *et al.*, 2022). Additionally, the soil suffered numerous impacts, including a significant reduction in macropores due to increased density from sediment deposits. This resulted in reduced water infiltration, favoring leaching processes and increased particle runoff into the river's interior (Silva *et al.*, 2021).

3.4. Socioeconomic and psychosocial impacts

The collapse of the Mariana Dam precipitated a series of socioeconomic and psychosocial impacts, with extensive effects observed in adjacent communities. According to Mata-Lima *et al.* (2013), natural disasters engender deleterious socioeconomic effects, particularly within regions characterized by diminished social resilience. These effects are further exacerbated when compounded by the inherent vulnerabilities of local communities.

The arrival of tailings sludge led to notable alterations in the soil. Significant increases in soil compaction were observed, which subsequently reduced water and oxygen availability, as these elements lost space within the affected areas (Silva *et al.*, 2021), directly impacting agriculture. Nationally significant crops, such as corn, experienced adverse effects from increased soil resistance. The main implications include reduced root growth and decreased photosynthetic activity (Esteves *et al.*, 2020).

Fishing was among the most severely impacted sectors due to the Mariana disaster. Elevated levels of metals, exceeding Brazilian regulatory limits, were detected in fish and shrimp due to the sludge spill. Consequently, environmental oversight temporarily suspended fishing activities (Andrades *et al.*, 2020). Considering that fishing is vital for Indigenous communities and other populations residing along the Rio Doce, serving as an essential source of sustenance for the local economy due to its tourist appeal and because fishermen rely solely on their catch for income, the economic losses from this event are considered incalculable (Fernandes *et al.*, 2016; Esteves *et al.*, 2020).

Beyond fishing, livestock was also impacted. While no clinical diseases were observed, the excessive intake of metals by animals could alter their microbiota, leading to decreased milk production. Moreover, the presence of heavy metals renders the consumption of both meat and milk unviable, creating a deficit in the region's livestock sector (Gaeta *et al.*, 2020).

This landscape of loss led to considerable trauma and insecurity for individuals residing near the dam. Many lost both personal connections and material belongings to the sludge. Consequently, a collective disturbance of mental health and well-being emerged among the population (Tognella *et al.*, 2022). According to Dell'Aringa *et al.* (2023), research reported a sharp increase in the demand for mental health services in the public health system (SUS) of Mariana and eight other affected municipalities. Among those seeking help, the most common and sudden diagnoses were anxiety, depression, and suicide risk, respectively.

In addition to emotional instability, the general health of residents in the region was severely affected. Accompanying the arrival of the sludge, an outbreak of enteric viruses, known for causing diarrhea and hepatitis, became evident. The association between enteric viruses and the sludge is due to fecal-oral transmission methods and the fact that Mariana and surrounding cities discharge their sewage into the river (Fongaro *et al.*, 2019). Also, Fongaro *et al.* (2019) indicate that metals present in the sludge, such as iron (Fe), may enhance viral replication and potentially alter viral genomes, further promoting viral spread and prevalence. Other public health concerns, such as low birth weight, were also impacted by the Mariana disaster. In a study by Dos Reis *et al.* (2019) demonstrates that the conditions and environment of pregnant women directly influence fetal development. In this case, it was noted that the consumption of water from regions contaminated by mining tailings, combined with smoking and first-time pregnancy, constituted significant risk factors for the birth of underweight infants.

As a consequence of the disaster, the company Samarco faced a series of judicial actions aimed at reversing the resulting situation. Initially, there was considerable mobilization to rapidly implement corrective legal measures. However, concerning issues related to human and environmental impacts, as well as the awarding of compensation, these actions were often delayed, inadequate, or even absent (Primo *et al.*, 2021).

4. CONCLUSION

This review article discusses the biological, physicochemical, and social impacts resulting from the failure of the Fundão mining dam. Initially, the review provides a comprehensive and detailed analysis of the disaster's impacts on water, highlighting the physicochemical and microbiological changes in the Doce River. Subsequently, it describes the impacts on local fauna and flora, as well as on nearby communities, offering an in-depth understanding of the environmental, social, and economic aspects. Ultimately, the review aims to underscore the full spectrum of effects on water quality and the extensive damage inflicted on fauna, flora, and human populations by the devastating impact of the Fundão Dam collapse on the environment. Furthermore, a comparison was made between conditions prior to and after the dam failure, highlighting key differences and correlating the primary impacts that arose from this tragedy.

The Fundão Dam collapse triggered devastating mining-related effects in the absence of environmental protection measures. This event caused widespread environmental destruction, affecting not only local ecosystems but also the livelihoods and well-being of surrounding communities. The quality of the Doce River's water, as well as the region's fauna and flora, suffered irreparable damage. Based on the studies presented in this review article, it is concluded that the effects were significant and that the dam failure had profound consequences.

In relation to the impacts of the Fundão Dam collapse, notable physicochemical and microbiological alterations in the Doce River water were observed, including elevated levels of heavy metals and toxic elements. Furthermore, the fauna—including zooplankton communities, fish, birds, and cetaceans—was severely affected. Studies indicate reductions in biodiversity, morphological and physiological changes, as well as the accumulation of heavy metals in fauna, particularly in fish. The biodiversity and health of plant life were also gravely impacted by the contamination of riverine ecosystems, marine environments, mangroves, and adjacent terrestrial areas along the Doce River. Additionally, human health issues and negative impacts on local community life were reported, encompassing socioeconomic and psychosocial effects that have impaired the fishing industry, agriculture, and mental health within the population. Despite legal actions and initiatives aimed at mitigating human and environmental impacts, these responses were deemed insufficient and delayed in effectively addressing the problem.

This review article is significant, as it consolidates, contextualizes, and synthesizes scientific evidence related to one of the most catastrophic environmental disasters in Brazil's history. By addressing gaps in the existing literature and providing an interdisciplinary perspective on the biological, physicochemical, and social impacts of the Fundão Dam collapse, this study not only enhances academic understanding of the issue but also serves as a crucial reference for public policy and environmental risk management. The relevance of this work lies in its potential to inform future decision-making, facilitate the implementation of more effective mitigation and restoration strategies, and underscore the urgent need for stricter environmental oversight in the mining industry to avert similar tragedies.

5. ACKNOWLEDGEMENTS

We acknowledge the Espírito Santo Research Support Foundation (FAPES) for awarding the scientific initiation scholarship to Thiago de Souza Fernandes and Ana Ligia Fioroti Cescon. Additionally, we thank the Centro Universitário do Espírito Santo for providing a scientific initiation scholarship to Pedro Henrique Pegoreti Lima.

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