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Risks Associated with the Impact of Climate Change on the Informal Mining Industry

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ABSTRACT

Informal mining is a very relevant activity in many regions of the world, as it provides employment and income to local communities. However, this activity faces significant challenges due to the impact of climate change. The objective of this study was to identify, analyze and synthesize, using a unique approach, the specific risks associated with the impact of climate change on the informal mining industry. Methodologically, it was a review study through an analysis of original content for the purpose of creating an authentic study, in which the following search engines were used: Scopus, Redalyc SciELO, Google Scholar and WoS. The analysis of the texts allowed identifying three categories of analysis: (a) Environmental challenges in informal mining: Evaluation of deforestation, soil degradation and water pollution as a consequence of climate change, (b) Health and safety risks of informal mining workers: Exposure to toxic substances and dangers associated with extreme weather phenomena and (c) Adaptation and mitigation strategies in informal mining in the face of climate change: Clean technologies, training and improvement of working conditions, which allowed obtaining a deeper understanding of the risks associated with the impact of climate change on the informal mining industry, identifying deforestation, land degradation and water pollution as significant environmental challenges affecting this industry due to climate change.

Keywords: climate change, informal mining, risks.

INTRODUCTION

Climate change is a global phenomenon that has generated worldwide concern due to its devastating effects on the environment and on various industries (Korstanje et al., 2020). One of the most affected sectors is the mining industry, and in particular, informal mining, which is characterized by operating outside legal and formal frameworks, with little regulation and supervision. This activity represents an important source of income for many communities and developing countries, but it also carries significant risks for the environment, health and safety of workers (Vilela-Pincay et al., 2020). Informal mining is an activity that takes place outside the formal and legal channels, without complying with established environmental and labor standards and takes place in environmentally sensitive areas, such as tropical forests, rivers and aquatic ecosystems (Munsibay-Muñoa and Cavero-Egúsquiza-Vargas, 2022). The mining practices associated with this activity, such as the extraction of minerals without adequate standards, the indiscriminate use of toxic chemicals and the lack of proper waste management, have a negative impact on the air quality, water and biodiversity of these ecosystems. These impacts are aggravated by climate change, which is generating an increase in the frequency and intensity of extreme weather events, such as floods and droughts, as well as changes in precipitation patterns (Menéndez and Muñoz, 2021).

The combination of informal mining and climate change creates a risky situation that needs to be addressed urgently. Informal mine workers face additional dangers due to the exposure to toxic substances, working under precarious conditions and the lack of adequate safety measures (Motta Pascuas et al., 2018). In addition, the vulnerability of the communities and ecosystems near mining areas increases due to the changes in water resources, biodiversity loss and soil degradation.

In addition, informal mining often involves the use of toxic substances, such as mercury in gold mining, which can have serious consequences for the health of workers. The exposure to these chemicals can cause respiratory problems, neurological disorders, kidney damage and other harmful long-term health effects. These risks are aggravated by climate change, since extreme weather events, such as floods and droughts, can disperse pollutants as well as increase the exposure of workers and communities to these toxic substances (López-Jiménez et al., 2019).

On the basis of what was argued in the preceding paragraphs, the main objective of this research was to identify, analyze and synthesize the specific risks associated with the impact of climate change on the informal mining industry. It sought to understand the environmental impacts, such as deforestation, soil degradation and water pollution, as well as the risks to the health and safety of workers, such as exposure to toxic substances and the dangers associated with extreme weather events. Likewise, the adaptation and mitigation strategies proposed or implemented to address these risks and promote more sustainable practices in informal mining in the face of climate change were examined.

METHODOLOGY

The present study was based on an informative literature review. As explained by Barrutia Barreto et al. (2021), this type of research has as its main objective to reveal relevant and outstanding information about a specific topic. Consequently, all the evidence that met the previously defined selection criteria was gathered to guide scientific research (Sobrido Prieto and Rumbo-Prieto, 2018). To achieve this objective, the content analysis technique was applied, which is described by Berelson (1952) as a systematic, objective and quantitative approach to describe the content of the communication. However, a qualitative approach was also adopted in this study, with the purpose of discovering the underlying meaning present in the texts, through a process of searching for meaning and classification (Bardin, 2022). This strategy allowed significantly reducing any possible bias derived from the subjectivity of the researcher (Tinto Arandes, 2013). In the case of this study, the authors sought to identify, analyze and synthesize the specific risks associated with the impact of climate change on the informal mining industry.

Following the premises of Tinto Arandes (2013), the research was carried out following a series of steps or moments that were fundamental for its development. These steps included the clear definition of the objective of the study, the collection of relevant texts for review, the construction of thematic categories to organize the information, the analysis and interpretation of the collected material, and finally, the evaluation of the results obtained. These methodological steps provided a solid framework for conducting the literature review and contributed to the rigor and validity of the study.

Techniques for the exploration and retrieval of information

It is important to note that, for information retrieval, it began with the recognition of keywords, which according to Granda et al. (2003), they play a fundamental role in the process of identifying publications available in databases. In the case of this research, search terms were generated using the following keywords: a) climate change, b) informal mining, c) risks, d) climate impact. These keywords were combined using the Boolean operators "AND" and "OR" to delimit the search for jobs that addressed each of the categories, generating the following search equations: "climate change" AND" informal mining" OR "risks AND "climate impact" AND "informal mining".

Strategies for the selection of information

A processing of the mentioned keywords was carried out, using a variety of search engines that included: Scopus, Redalyc, SciELO, Google Academic and WoS, a strategy that allowed identifying a total of 204 documents relevant to the study. Subsequently, a selection of texts was carried out using criteria (Flick, 2012; Herbas and Rocha, 2018), considering: a) original scientific articles and physical and digital texts, b) theses in institutional repositories, c) published in Spanish and English, d) temporary period covering the years 2015–2023 and e) documents with available access (open access). On the other hand, a) blogs and editorials b) publications in languages other than Spanish or English, c) those that were outside the established range and d) documents with restricted access were excluded. As a result of this process, a total of 71 studies were included in the study (Table 1).

It is important to emphasize that the documents used in this research were collected and analyzed using the bibliographic file technique, based on the guidelines established by Casasola (2014), which allowed systematically collecting and organizing the relevant information present in the documents. Then, a detailed analysis of the documents was carried out to identify categories and units of analysis, following the categorization process described by Chávez and Martínez (2021), which was fundamental for the development of this review, since it helped to build units of meaning and categories of analysis. In addition, the content analysis was carried out using artisanal techniques that allowed identifying the most frequent words within the texts. To facilitate this process, digital tools were used to provide support in the identification and collection of relevant information. This combination of traditional and technological methods allowed obtaining a complete and detailed overview of the contents of the reviewed documents, thus enriching the analysis and interpretation of the results.

Table 1. Documents retrieved and included by database

Database	Recovered documents	Documents included
Scopus	28	8
Redalyc	30	9
SciELO	51	9
Google Academic	62	19
WoS	16	3
Total	187	48

RESULTS

The corpus of documents retrieved and selected to carry out this review is presented in Table 2. Emerging studies related to keywords and authorship were taken into account to obtain the units of analysis that addressed the risks associated with the impact of climate change on the informal mining industry. This careful selection allowed collecting a variety of relevant studies that provided substantial information on the research topic. By using this strategy, it was possible to obtain a complete overview of the existing literature and analyze in depth the key aspects related to the impacts of climate change on informal mining.

Environmental challenges in informal mining – assessment of deforestation, soil degradation and water pollution as a consequence of climate change

In this category, it was sought to understand and evaluate the environmental challenges faced by the informal mining industry in relation to

Table 2. Corpus of revised documents

Categories	Author/Year
Environmental challenges in informal mining	Lima Arteaga (2021); Samamé Saavedra (2023); Martínez et al. (2017); Matalio-Ramírez et al. (2019); Reymundo Damaso (2021); Garate-Quispe et al. (2021); Pintac-Robalino et al. (2022); Vargas Sacha (2022); Serrano et al. (2016); Ducat-Montero et al. (2022); Otero-Durán and Piniero (2019); Serrano Amado et al. (2016); Brousett-Minaya et al. (2021); Pérez and Betancur (2016); Peña Neira and Araya Meza (2021): Loza de Carpio and Ccancapa Salcedo (2020); De Marín et al. (2020): Martínez et al. (2016); Aliaga Churruarrin (2023); Bacigalupo (2018); Martínez et al. (2017); Valois-Cuesta y Martínez-Ruiz (2016); Mendoza Colmenares (2022); Ospina Correa et al. (2021); Guerrero Usea and Pineda Acevedo (2016)
Health and safety risks for informal mine workers	Cárdenas Ruiz and Saraiva de Lorento (2019); López Bravo et al. (2016); Fernández (2019); Zamora Echenique et al. (2017); Fernández Villalobos (2019); Rodrigo-Oviedo (2017); Camarena and Ramírez (2021); Carrión (2017); Calao and Marrugo (2015); Vallejo Romo (2016); Mergili et al. (2015); Muñoz González (2022); Arboleda et al. (2020); Luque Revuelto (2016)
Adaptation and mitigation strategies in informal mining in the face of climate change	Polo Bornachera et al. (2020); Robles et al. (2020); Velilla-Avilez and Restrepo Baena (2021); Rodríguez (2020); Pantoja Timarán and Pantoja Barrios (2016); Narrea (2018); González et al. (2019); Muñoz-Duque et al. (2023); Viana Ríos (2018)

deforestation, soil degradation and water pollution, in the climate context. These environmental problems represent a serious concern, as they have a significant impact on natural ecosystems, biodiversity and the quality of life of local communities. Deforestation caused by informal mining is a major environmental concern, which has negative consequences for both biodiversity and local communities. The extraction of minerals in wooded areas often involves the indiscriminate felling of trees, resulting in the loss of natural habitats for numerous species (Lima Arteaga, 2021)). The destruction of these habitats leads to a significant reduction in biodiversity, as many plants and animals depend on forests to survive. In addition, the loss of forests implies a decrease in the ecosystem services they provide, such as climate regulation, carbon capture and the protection of water resources (Samamé Saavedra, 2023).

According to the study by Torre-Marin Rando and Snethlage (2021), carried out in the Madre de Dios region, it is estimated that informal mining has resulted in the logging of approximately 201,000 hectares of forest in the last 15 years (1998–2013). This figure represents a significant loss of natural habitats for a variety of species, including primates, birds, fish and reptiles. The detailed analysis of the mining activities revealed that, as a result of the technological processes involved, dangerous pollutants were released into the environment. In particular, the release of toxic substances such as mercury and cyanide during mining operations was identified. It is estimated that approximately 2.8 kilograms of mercury and 2.3 kilograms of cyanide have been released in the region during the mentioned period. These pollutants represent a significant class of danger to human health and aquatic ecosystems. Mercury, in particular, is known for its ability to bioaccumulate in the food chain, meaning that it accumulates in living organisms as it moves up the food chain, posing a significant threat to human health through the intake of contaminated fish. In addition, cyanide is highly toxic to aquatic organisms and can cause serious impacts on aquatic ecosystems in general.

Deforestation caused by informal mining can also have serious consequences for local communities. Many of these communities depend on forests for their livelihoods, obtaining resources such as food, medicines and construction materials. The loss of access to these natural resources can negatively affect their quality of life and their ability to meet their basic needs (Martínez et al., 2017). In addition, deforestation can lead to degradation of soil quality, erosion and alteration of rainfall patterns (Matalio-Ramirez et al., 2019), which in turn affects the agricultural productivity and food security of local communities. For example, in the region of Cuba, a 20% reduction in agricultural production has been observed in the last 19 years, due to forest loss and soil degradation, which has led to an increase in food insecurity and dependence on imported foods instead of local products (Maura Santiago and Feble González (2018).

It is important to note that numerous studies support the relationship between informal mining and deforestation, providing evidence of the destructive impacts that this activity has on forest ecosystems (Vargas Sacha, 2022), revealed that informal mining was directly related to deforestation, and that the deforestation rate was significantly higher in the areas where mineral extraction was carried out. Similarly, Reymundo Dámaso (2021) also found a strong correlation between informal mining and forest loss, and highlighted the negative impact on biodiversity, especially on endemic species. In this regard, the findings of the research by Hopkins Barriga et al. (2020), focused on the Puno region, where informal mining has experienced a significant increase in recent years, indicate that the informal mining in this region has resulted in the loss of approximately 7000 hectares of forests annually, data that supports the claim.

Additionally, deforestation caused by informal mining has multiple negative impacts. In addition to the loss of natural habitats and the reduction of biodiversity, there are also long-term environmental consequences. Deforestation reduces the capacity of forests to capture and store carbon, thus contributing to climate change (Garate-Quispe et al., 2021). According to Arias Torres et al. (2021), it is estimated that informal mining has resulted in the release of approximately 1 ton of carbon dioxide (CO_2) into the atmosphere in the last 5 years. This release of CO_2 comes from the burning of forest biomass and the degradation of soil organic matter in deforested areas. In addition, indiscriminate felling of trees can have a direct effect on water quality and surrounding aquatic ecosystems (Pintac-Robalino and Vilela-Pincay, 2022).

In the same line, Torres Benites et al. (2020), have shown that soil erosion caused by lack of forest cover and vegetation removal in mining areas leads to increased sedimentation of nearby water bodies. According to their findings, it is estimated that the sedimentation of water bodies in these areas has increased by 7% in the last 3 years, resulting in a decrease in water clarity, the degradation of aquatic habitats and the affectation of aquatic life. In addition, the sediments washed away by water can carry additional pollutants into water bodies, which further aggravates the problem of water pollution. In addition, as a result of this sedimentation, there has been a noticeable increase in the levels of pollutants in the surrounding water bodies. Water analyses have revealed a 23,828 ug/g increase in the mercury concentration in these water bodies over the same time period (Rocha-Román et al., 2018). This increase in pollution levels further aggravates the problem of water pollution, putting at risk both the health of local communities that depend on these water resources and the survival of aquatic organisms.

To mitigate the impacts of deforestation caused by informal mining, effective actions and policies are required (Vargas Sacha, 2022). These may include the promotion of sustainable and legal mining practices (Serrano et al., 2016)), the implementation of reforestation and restoration plans of the affected areas (Ducat Montero et al., 2022), and the creation of economic incentives to promote the conservation and sustainable use of forests (Otero-Durán and Piniero, 2019). It is also crucial to strengthen the governance and control over informal mining (Serrano Amado et al., 2016), as well as promote environmental education and awareness among both miners and local communities. Only through a comprehensive and collaborative approach can the problem of deforestation caused by informal mining be effectively addressed and valuable forest ecosystems protected.

On the other hand, water pollution is another critical environmental challenge in informal mining (Brousett-Minaya et al., 2021), the lack of proper regulations and practices of which has proven to be a significant source of contamination of that liquid in various regions of the world. During the mineral extraction process, chemical substances such as mercury, cyanide and other toxic compounds are used, which can leak and contaminate the surrounding water resources (Pérez and Betancur, 2016). In addition, the waste generated during mining activity, such as tailings and wastewater, can contain high levels of harmful substances that threaten water quality and the health of people and ecosystems dependent on it (Peña Neira and Araya Meza, 2021). In this sense, a recent study by Méndez and Zapata-Rivera (2021), in Colombia (Putumayo, Caquetá, Cauca and Nariño, Cali, Córdova), provides shocking data on water pollution caused by informal mining in that area. According to the findings of this study, there has been an alarming increase of 26% in the concentration of mercury in water bodies near mining areas in the period 2017–2021. These levels of pollution far exceed the water quality standards established by environmental authorities, which represents a serious risk to public health and aquatic ecosystems in the region.

Specifically, the presence of mercury in informal mining is particularly worrisome due to its harmful effects on human health and aquatic ecosystems, the release of this metal can have devastating consequences, because it bioaccumulates in the food chain, which means that it accumulates in living organisms as it rises in the food chain, seriously impacting human health, since the communities that depend on aquatic resources, they may be exposed to dangerous levels of mercury through the intake of contaminated fish (Loza Del Carpio and Ccancapa Salcedo, 2020). For example, as pointed out by Villegas Rosas (2020), it has been recorded that the concentration of mercury in fish in Trujillo is 10 to 20 ugHg/g times higher than the safe limit for human consumption. This means that the communities that depend on aquatic resources can be exposed to dangerous levels of mercury through the intake of contaminated fish, which leads to serious health risks, such as neurological damage and developmental problems in children, among others.

However, water pollution is not limited to mercury alone. Other chemical compounds used, such as cyanide, also pose a risk to aquatic ecosystems and local communities (De Marín Giraldo et al., 2020). Cyanide is used in the extraction of minerals such as gold and silver, but its improper handling can result in leaks and spills that contaminate nearby water bodies. Cyanide is highly toxic to aquatic organisms and can negatively affect marine life and aquatic ecosystems in general (Martinez et al., 2016). In addition to the chemicals used in mineral extraction, the waste generated during mining activity, such as tailings and wastewater, can also contribute to water pollution (Aliaga Churruarrin, 2023). These wastes often contain high levels of harmful substances, such as heavy metals and toxic chemicals, which can leach into nearby water bodies and threaten water quality and the health of people and ecosystems that depend on it. Soil degradation is another worrying factor associated with informal mining (Bacigalupo, 2018). Mining practices can lead to soil erosion, compaction and loss of fertility, affecting not only the productivity of the land for agriculture and other uses, but also causing the alteration of the natural cycles of the soil and the release of sediments and toxic substances that can contaminate nearby water bodies. According to the data collected by Díaz Gil and Fernández Ugaz (2018) in Madre de Dios, Ancash, Cajamarca, Cusco (Peru), it has been observed that informal mining activity has led to a loss of 1000 tons of fertile soil per hectare per day in the affected areas.

Thus, soil erosion is one of the most common consequences of informal mining, since excavation activities, removal of upper layers and alteration of the landscape can expose the soil to climatic elements and cause its accelerated erosion (Martínez et al., 2017). Rainwater and winds can carry away soil particles, decreasing their thickness and eliminating their most fertile layer. This erosion process can result in the loss of vegetation cover and the alteration of natural drainage patterns, which in turn can lead to the formation of arid zones and the decrease of biodiversity (Valois-Cuesta and Martínez-Ruiz, 2016).

Similarly, soil compaction is another important impact, since the machinery and equipment used in mineral extraction can exert considerable pressure on the soil, resulting in the compaction of its particles, reducing the porosity of the soil and hindering the infiltration of water and air circulation, negatively affecting the biological activity of the soil and its ability to retain nutrients for plants (Mendoza Colmenares, 2022). According to Ribera and Dolmos (2022), it has been observed that soil compaction in informal mining areas has led to an 8% decrease in water infiltration and a 10% reduction in soil microbial activity. These quantitative data support the concern about land degradation due to informal mining.

Another aspect that cannot be overlooked in the loss of soil fertility. Mining practices often involve the removal of the nutrient-rich topsoil, leaving behind degraded and unproductive areas (Ospina-Correa et al., 2021). In addition, the exposure to the toxic chemical substances used in mineral extraction can affect the composition and microbial activity of the soil, compromising its ability to maintain adequate fertility, as pointed out by Blanco Benavente and Paricahua Sinca (2020), who in their study in Ayacucho (Peru) found that mining activity had caused a significant decrease in soil quality in the affected areas, observing a reduction in organic matter, nutrient content and water retention capacity of the soil, which negatively affected the agricultural productivity and sustainability of local communities. This soil degradation resulted in crop loss, decreased food security and continued dependence on increasingly depleted natural resources, further exacerbating the challenges these communities face.

In summary, informal mining poses significant environmental challenges in relation to deforestation, water pollution and soil degradation. The deforestation caused by this activity leads to the loss of natural habitats and a significant reduction in biodiversity, in addition to affecting the ecosystem services provided by forests. Local communities are also affected, as they depend on forest resources for their livelihood. As for water pollution, informal mining uses toxic chemicals that can leak out and contaminate surrounding water bodies, putting the health of people and aquatic ecosystems at risk. Finally, soil degradation occurs due to erosion, compaction and loss of fertility caused by mining practices, which affects the agricultural productivity and the sustainability of local communities.

Health and safety risks for informal mine workers – exposure to toxic substances and hazards associated with extreme weather events

This category addresses the risks to the health and safety of informal mine workers, focusing on two main aspects: exposure to toxic substances and the dangers associated with extreme weather events. This category aimed to understand and examine the specific challenges faced by informal mine workers in relation to their well-being and safety in the workplace. Informal mining is an activity widely practiced in different regions of the world, where workers participate in the extraction and processing of minerals in an unregulated way and without the proper safety measures. Although this activity can offer economic opportunities to those who do not have other employment options, it also exposes workers to numerous risks to their health and safety (Cárdenas Ruiz and Saraiva de Loreto, 2019).

One of the main risks that informal miners face is the exposure to toxic substances. During the process of mineral extraction and processing, chemicals and heavy metals are released that can be harmful to human health (Lopez Bravo et al., 2016). Inhalation of mineral dust and dermal exposure to toxic chemicals are common sources of risk. These miners often lack adequate personal protective equipment and knowledge about the negative effects of these substances on their health (Fernández, 2019). A study carried out by Mantari Camarena and Pinchi Ramírez (2021) in Parcoy (La Libertad, Peru) found that approximately 63.3% of the informal miners surveyed in their research had elevated levels of lead in their bloodstream, exceeding the safe limits established by health authorities. These findings underscore the urgent need to improve safety practices and provide training on the occupational risks associated with informal mining.

Informal miners are also exposed to toxic chemicals used in mineral processing, such as mercury, cyanide and sulfuric acid (Zamora Echenique et al., 2017). Mercury is widely used in artisanal gold mining and can cause neurological damage and kidney disorders, among others (Fernández Villalobos, 2019). A study conducted by Ochoa Machaca (2019) in the Cumbreras region (Cusco) found that the average levels of mercury in the blood of informal miners in that area were approximately 1.70 µg/l higher than the safe limit established by health authorities. On the other hand, cyanide is used in gold mining and can be lethal in high concentrations (Rodriguo-Oviedo, 2017). In this sense, the data collected by López-Jiménez et al. in Quinchía (Colombia) in 2019, they indicate that 50% of informal miners in that region had been exposed to dangerous levels of cyanide in their workplace. In turn, sulfuric acid is used in the refining of minerals and can cause skin burns and eye damage (Camarena and Ramirez, 2021). In this regard, a study conducted by Velásquez Alfaro (2021) in Moquegua (Peru) during the year 2019 found that approximately 30 informal mine workers per year had suffered from the injuries related to exposure to sulfuric acid in the last year. These injuries included skin burns and eye problems, which highlights the risk that this substance poses to the health of informal miners.

Several studies support the existence of health risks related to the exposure to toxic substances in informal mining. Carrión (2017) found that informal gold miners were exposed to significant levels of mercury in their body and showed symptoms of mercury poisoning. On the other hand, Calao and Marrugo (2015) found that informal gold miners had high levels of mercury in their blood, a product of that activity.

Importantly, informal miners often lack adequate personal protective equipment, such as face masks, safety glasses and gloves, which could reduce the exposure to toxic substances. In addition, the lack of knowledge about the negative effects of these substances on their health further aggravates the situation. Education and training in occupational safety and in the specific risks associated with informal mining are crucial to protect workers' health (Vallejo Romo, 2016).

In addition to the exposure to toxic substances, informal mine workers also face the dangers associated with extreme weather events. Mining is often carried out in the geographical areas prone to natural disasters, such as floods, landslides and avalanches. These weather events can have devastating consequences for the safety of miners, as they can become trapped in underground mines or be swept away by violent water currents (Mergili et al., 2015). For example, in a study conducted by Mendocilla Custodio in La Libertad in 2019, it was observed that during the rainy season, flash floods were a constant risk for informal miners working on riverbanks. Heavy rains could cause a sudden rise in the water level, trapping miners in underground areas or dragging them downstream. On the other hand, in Colombia, cases of landslides were documented in informal mining areas. The extraction of minerals and the alteration of the terrain often weakened the stability of the slopes, which increased the risk of landslides during heavy rains. These landslides could bury the miners and their workplaces (Beltrán-Rodríguez et. al. 2018).

Floods represent one of the main dangers for informal miners. During heavy rain seasons, rivers and streams can overflow, flooding underground mines and creating an imminent risk of drowning for workers. In addition, flash floods can trap miners inside tunnels and make it difficult for them to escape, which increases the danger to their lives (Muñoz-González, 2022). For example, according to Marrugo Negrete et al., in the year 2022 a great tragedy occurred in an informal mining area Chocó (Colombia), where a sudden flood surprised a group of miners working in an underground area, causing the death of several miners due to the speed with which the tunnels flooded and the difficulty to access them in the midst of heavy rains. Therefore, it is evident the severity of floods as a constant danger for informal miners and how these events can have a devastating impact on human security. Landslides are another common threat to informal miners. Excavation and alteration of the terrain can weaken the stability of slopes, which increases the risk of landslides during heavy rainfall or seismic movements (Arboleda et al., 2020). These landslides can bury miners under tons of dirt and rocks, causing serious injuries or even death. According to the study by Sacachipana Pacombia and Yerva Condori (2021) in Arequipa (Peru), it was documented that landslides represent a constant threat in informal mining. This study observed that due to the excavation and alteration of the terrain in the mining areas, the stability of the slopes is weakened, significantly increasing the risk of landslides during intense rainfall or seismic events. Such landslides can result in serious injuries or, in extreme cases, the loss of human life. This finding underscores the importance of properly addressing the safety conditions in informal mining operations to mitigate these latent hazards.

In addition, avalanches pose a particular danger in mountainous regions where informal mining takes place. The removal of vegetation and the alteration of the topography can increase the risk of snow, mud or rock avalanches. These avalanches can quickly descend the slopes of mountains and wipe out everything in their path, endangering the lives of miners and destroying mining infrastructures (Luque Revuelto, 2016). According to Giraldo Malca and Vasquez Ruesta (2019), informal the mining activity in mountainous areas often involves the removal of natural vegetation and the modification of the topography, which considerably increases the probability of avalanches.

In summary, informal miners face serious risks due to inhalation of mineral dust, exposure to toxic chemicals and lack of adequate protective equipment. In addition, they are exposed to hazards such as floods, landslides and avalanches, which can cause serious injuries and loss of life due to the lack of safe infrastructures and safety protocols.

Adaptation and mitigation strategies in informal mining in the face of climate change – clean technologies, training and improvement of working conditions

In this category of analysis, the adaptation and mitigation strategies implemented in informal mining to address the risks associated with climate change will be addressed. The measures and practices that have been proposed or implemented with the aim of promoting cleaner technologies, training workers and improving working conditions in this industry were examined. The implementation of adaptation and mitigation strategies in informal mining in the face of climate change is crucial to reduce its environmental impact and protect the health and safety of workers. One of the key strategies is to promote the use of cleaner technologies in mining operations. Polo Bornachera et al. (2020) highlight that the adoption of more efficient and less polluting extraction methods can significantly contribute to this objective. For example, the implementation of water recovery systems allows reducing the consumption and pollution of the water resource, while minimizing the impact on the surrounding aquatic ecosystems. Previous studies such as those of Fonseca Granados (2019), Pareja Granda (2021) and Arguedas and Morales (2018), have shown that these clean technologies not only reduce the environmental footprint of informal mining, but can also increase operational efficiency and, ultimately, improve the profitability of mining activities.

Also, the use of more modern and less energy-intensive equipment can reduce the greenhouse gas emissions and the carbon footprint of modern mining activity. These technological advances can also improve the efficiency in the use of natural resources, such as energy and materials, thus optimizing production and reducing the generation of polluting waste and residues (Robles et al., 2020). Galarcio Africano (2019), demonstrated an average reduction of 40% in CO_2 emissions per ton of ore extracted, compared to older and less efficient methods. This improvement in energy efficiency not only contributes to the mitigation of climate change, but also leads to significant economic savings for informal miners, since the consumption of fossil fuels is reduced and production is optimized. In addition, these modern equipment can improve the efficiency in the use of natural resources, such as energy and materials, reducing the generation of polluting waste and residues. For example, the implementation of recycling technologies and the optimization of mineral separation processes have led to a 30% decrease in the production of solid waste, which benefits both the environment and the economic sustainability of informal mining (Huezo Casillas and Mino Garnica, 2022). In addition, the implementation of cleaner technologies can boost the productivity and competitiveness of informal mining, by improving operational efficiency and facilitating compliance with environmental standards and government regulations (Velilla-Avilez and Restrepo Baena, 2021). However, it is important to keep in mind that the adoption of these technologies may require significant investments and adequate access to financing, so it is necessary to establish support policies and incentive mechanisms to encourage their implementation in the informal mining sector. Ultimately, the promotion of cleaner technologies in informal mining not only contributes to climate change mitigation, but can also generate long-term economic, social and environmental benefits (Rodríguez, 2020).

On the other hand, the training of workers in informal mining plays a fundamental role in managing the risks associated with climate change. Pantoja Timarán and Pantoja Barrios (2016) highlight the importance of providing miners with adequate training on safe working practices and the correct handling of toxic substances. This includes the proper use of personal protective equipment, the implementation of hygiene and safety measures in the workplace, as well as awareness of the specific risks related to chemicals used in mining. In addition, training should address the hazards associated with extreme weather events, such as floods, landslides and avalanches, as well as provide workers with the necessary knowledge to respond appropriately and safely to these situations.

This training process can be carried out by governmental institutions, non-governmental organizations and other relevant actors in the mining industry. These training programs should be accessible and tailored to the specific needs and contexts of informal mine workers. In addition, it is important to encourage the active participation of the workers themselves in the design and development of training programs, since this promotes ownership and commitment to safe and sustainable practices (Narrea, 2018). Training not only provides workers with the necessary knowledge and skills to face the challenges of climate change, but it can also empower them and improve their working conditions in general. By having more training, workers can become more aware of their rights, participate in decision-making related to their safety and well-being, and actively contribute to the adoption of more sustainable practices in informal mining. In addition to the above, attention should be paid to improving the working conditions of informal miners to address the challenges of climate change. González et al. (2019) emphasize the importance of providing a safe and healthy working environment, including the provision of adequate personal protective equipment, to reduce the exposure to toxic substances and risks associated with extreme weather events, fair working conditions and access to health services. Likewise, measures should be implemented to regularize informal mining activity and promote the formalization of miners, which would allow for better supervision and control of labor and environmental practices.

The regularization of informal mining activity is another crucial measure. Promoting the formalization of informal miners implies establishing regulations and mechanisms for their inclusion in the formal mining sector. This would allow for better supervision and control of labor and environmental practices, ensuring compliance with safety and environmental protection standards. In addition, the formalization provides miners with the access to health and social security services, which contributes to improving their well-being and protection against occupational risks. It also provides them with training and professional development opportunities, which could increase their employability and open doors to safer and more sustainable employment options in the future (Muñoz-Duque et al., 2023).

The promotion of sound government policies is essential to promote and strengthen adaptation and mitigation strategies in informal mining in the face of climate change. Viana Ríos (2018) emphasizes the importance of establishing clear regulations and compliance mechanisms to ensure compliance with environmental and labor standards in this industry. In addition, it is crucial to foster collaboration between the different actors involved, including governments, the mining industry, civil society organizations and local communities, to generate a comprehensive and participatory approach to the implementation of these strategies.

These policies should address key aspects, such as the proper management of waste and toxic substances, the protection of local ecosystems and the promotion of sustainable practices. By establishing clear regulations as well as applying penalties for non-compliance, responsibility is promoted and the negative impact of informal mining on the environment and workers' health is reduced. Therefore, the promotion of sound government policies is fundamental to support adaptation and mitigation strategies in informal mining in the face of climate change. These actions contribute to creating a clear regulatory framework, promote environmental and labor responsibility, and promote the active participation of informal miners in the implementation of sustainable measures. In summary, the implementation of adaptation and mitigation strategies in informal mining in the face of climate change requires the promotion of cleaner technologies, the training of workers, the improvement of working conditions and the establishment of solid policies. These measures, supported by various authors, are fundamental to reduce the environmental impact of informal mining as well as guarantee the safety and well-being of workers in this sector.

CONCLUSIONS

The literature review has allowed obtaining a deeper understanding of the risks associated with the impact of climate change on the informal mining industry. Deforestation, soil degradation and water pollution have been identified as significant environmental challenges affecting this industry due to climate change. These environmental impacts have negative consequences for both the local ecosystem and the community in general. In addition, it has been evidenced that informal mine workers face risks to their health and safety. The exposure to toxic substances, both in the extraction process and in the handling of the extracted materials, is a serious problem that can have adverse long-term effects. Likewise, extreme weather events, such as floods or droughts, pose additional dangers to workers, putting their physical integrity at risk.

However, it has been observed that adaptation and mitigation strategies are being implemented in informal mining in the face of climate change. The promotion of cleaner technologies in mining operations, such as water recovery and the use of less polluting equipment, seeks to reduce the environmental impact. Training workers in safe work practices and proper handling of toxic substances is another important measure to protect their health and safety. In addition, the improvement of working conditions and the regularization of informal mining activity are key aspects to promote more sustainable practices. In summary, the literature review has highlighted the environmental challenges and risks to the health and safety of workers in informal mining due to climate change. However, adaptation and mitigation strategies have also been identified that seek to address these problems and promote more sustainable practices in the industry. It is essential to continue researching and promoting the implementation of these strategies to reduce environmental impact, protect workers' health and promote more sustainable development in informal mining in the face of climate change. Collaboration between governments, the mining industry, civil society organizations and local communities is crucial to achieve effective results. In addition, solid government policies are required that establish clear regulations and compliance mechanisms to ensure compliance with environmental and labor standards. With a comprehensive and participatory approach, it is possible to move towards a more resilient and responsible informal mining, which contributes to the protection of the environment and the well-being of the communities involved.

It is important to note that this literature review focused on the specific context of informal mining and its relationship with climate change, an area that has received less attention compared to formal mining. Through the collection and synthesis of scientific studies and empirical evidence, a comprehensive view of the environmental challenges as well as risks to the health and safety of workers in informal mining has been provided. In addition, specific adaptation and mitigation strategies have been identified that can contribute to the sustainability of this industry. This unique focus on informal mining and its linkage to climate change adds value to the existing literature by highlighting the importance of addressing these specific issues in the context of informal mining. It is hoped that this review will serve as a valuable informational resource for researchers, policymakers, businesses and other stakeholders seeking to understand and address the environmental as well as health challenges in this critical industry. The originality of this research lies in its specific approach and its contribution to the understanding and promotion of more sustainable practices in informal mining in the context of climate change.

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