Climate Change Impacts on Mining Value Chain: A Systematic Literature Review

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Abstract

Mining is becoming increasingly vulnerable to the effects of climate change (CC). The consequences of changing weather patterns, such as extreme weather events that can damage equipment, infrastructure, mining facilities, and operation interruption, are the source of the vulnerability. The new demand initiated by governments and international agreements put extra pressure on mining industries to update their policies to reduce greenhouse gas (GHG) emissions and adapt to CC, such as carbon pricing systems, renewable energy, and sustainable development. Most mining and exploration industries focus on reducing mining's impact and climate mitigation on CC rather than adapting to extreme weather events. Therefore, it is important to study and investigate the impacts of CC on the mining sector. This paper aims to study the challenges and strategies for adapting and mitigating CC impacts on mining using a systematic literature review (SLR). These results showed that most of the proposed models and strategies in the mining field are in the conceptual phase, and fewer are practical models.

Keywords: Climate change, Adaptation, Mitigation, Mining

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1- Introduction

Mining removes precious minerals or other geological elements from the Earth to fulfill various human desires and requirements. During several phases of the mining process, such as mineral exploration and mine development, resource extraction, material transportation, processing, manufacturing, and mine decommissioning, the economic benefits of mining become apparent. Remote mine sites in wilderness areas and mines in the urban-rural transition zone, mines reliant on climate-sensitive transportation networks (including ice roads), mines well-served by transportation infrastructure, mines situated in regions covered by land claims agreements, and operations such as mining base metals, aggregates, and gemstones are all examples of remote mine sites (Pearce et al. 2009). Also, looking from the lens of energy consumption, the mining and metal sector contributes 4–7% of greenhouse gas (GHG) emissions globally, which can be exacerbated by increased mineral production (increasing by more than 450% by 2050 t with the World Bank estimation (Hund et al. 2020)) (Mebratu-Tsegaye et al. 2021). On the other hand, stresses brought on by temperature variations, precipitation, harsh weather, and storms have in the past and do so now by impacting mining infrastructure and activities. Decisions should account for these uncertainties as "Climate Change (CC)". A change in the climate's mean and/or variability that lasts for a long time, generally for decades or longer, is called CC (Geneva 2013). Because each location will be affected differently, the relationship between CC and mine action activities may vary. The impact of CC will also be influenced by any program-based coping mechanisms that may already be in place. Several conflict-affected nations are situated in regions that are among the most susceptible to the effects of CC and must be ready to adapt and be resilient to the repercussions. Figure 1 outlines the two main climate-resilient actions: reducing emissions and managing climate risks:

- Climate adaptation: This entails planning for an uncertain future and taking action to lessen the effects of climatic changes (2018). Climate adaptation changes how we live, work, and behave to lessen our vulnerability to the unavoidable effects of CC caused by past and ongoing greenhouse GHG emissions (Cottrell and Stowe 2021). ISO 2019 defined CC adaptation as adjusting to the current and projected climate and its effects (ISO 2019).
- Climate mitigation: Lowering GHG emissions through improving energy management (such as efficiency and conservation), implementing renewable energy projects, and promoting a low-carbon economy (2018).

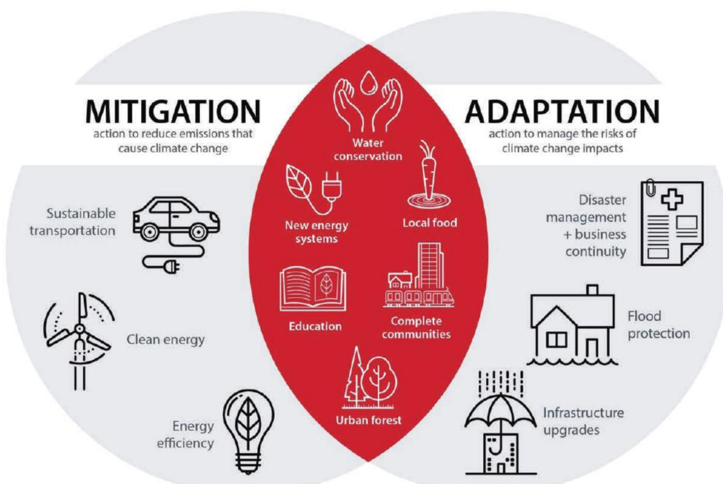

Figure 1: Climate mitigation and adaptation (2018)

In these definitions, the keyword in adaptation can be considered "vulnerability", which has been used in most water research. However, there is no acknowledged definition of CC vulnerability, and there are no measurements either (Luers et al. 2003). The vulnerability may be measured using various techniques, including proxy indicators, direct elicitations, etc. In addition to these challenges, vulnerability is considered a subjective phenomenon, dynamic in nature, and location-dependent (Adger 2006). The term "vulnerability" describes how vulnerable or helpless a mine infrastructure component is to CC. When a climatic variable interacts with mine infrastructure, vulnerabilities exist since such interaction may result in risk (MAC 2021).

Conversely, in a long-term perspective, as mitigation, CC is considered a serious uncertainty in the mining field. The mining industry is now adjusting to the recent developments. Additional mines are being developed, and they will soon start working. These mines will be operational until 2050 and 2070, respectively, during which CC is anticipated to continue. These mines will have to work in new climatic circumstances (Hodgkinson et al. 2010). White & Case's 2023 Mining & Metals market sentiment survey shows in Figure 2 that CC response/energy transition and managing supply chains/labor continue to dominate as the main priorities for the second year running.

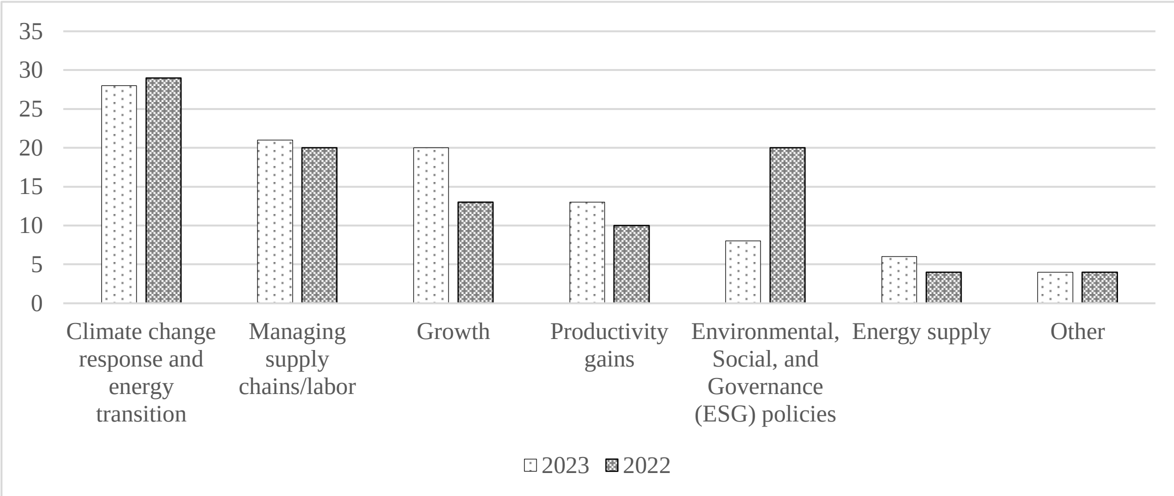

Figure 2. The main priority for the mining sector (Adapted from Source: White & Case 2023 Mining & Metals market sentiment survey) (Campbell et al. 2023)

In addition, the importance of this issue is fully evident in authentic scientific documents, so searching for documents in reliable scientific databases based on the keywords "Climate Change" and "Mining" has the following results:

- 7,310 publications selected from Web of Science (WoS)
- 4,579 publications selected from Scopus

Figure 3 shows results by year for WoS and Scopus Databases. Therefore, the issue of CC in the mining area in both databases has sharply increased since the year 2000, which shows the importance of this issue in the scientific community. This search indicates that study on the effects of CC on the mining sector is ongoing worldwide, primarily regarding the mining sectors of the United States, China, and Australia (WoS: 24.51%, 21.79%, 12.67%, and Scopus: 15.01%, 10.07% and 6.73% respectively)

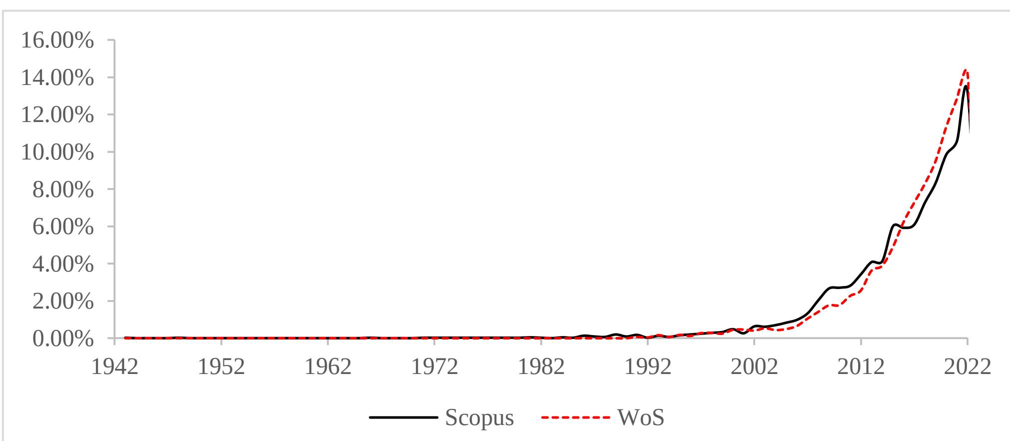

Figure 3: Document results for "Climate Change" and "Mining" keywords by year for WoS and Scopus (Elsevier 2023; WOS 2023)

Thus, CC has significant implications for sectors such as mining and regional and national economies. It is becoming more widely understood that stakeholders, practitioners, and regulators may adopt proactive measures to lessen future uncertainty. However, we still do not know much about how CC may affect important industrial processes, raising concerns about mining firms' capacity to maintain profitable operations. Companies that go above and beyond the conventional response to CC can develop an edge over uncertainty.(Jang and Topal 2020). In this regard, engineers, managers, and decision-makers in the mining field need a detailed understanding of the challenges and adaptation solutions. This paper presents findings of research on the CC impact on mining operations. A straightforward, systematic literature study may offer a thorough grasp of the CC, its limitations, and its uses. The systematic literature review uses a search methodology not often included in a literature review and offers a systematic approach. Consequently, this method boosts the precision and legitimacy of the findings by not choosing the research at random (Mallett et al. 2012). To investigate how CC is defined in the field of CC impact in Mining Operations (CCIMO), what types of CCIMO resilience have been used, what kinds of concepts affect CCIMO's resilience, and which approaches have been used for CCIMO resilience analysis, this paper implements a systematic literature review. The remainder of the essay is structured as follows: The steps of the systematic literature review approach are detailed in Section 2. The application of the CCIMO systematic review is shown in Sections 3 and 4. The discussion of the systematic review's findings is illustrated in Section 5, which also summarizes our conclusions.

2- Systematic Literature Review (SLR) Methodology for CCIMO

Researchers use a non-systematic (narrative/traditional) literature review approach to answer questions about a particular subject. They search for relevant articles and studies and summarize the results according to their previous ideas (Mallett et al. 2012). This strategy is unclear on the techniques used to discover and choose research (Jansen 2017). SLR is a systematic literature review approach that is repeatable and pre-arranged (Kitchenham 2004). SLR is a method for identifying, evaluating, and outlining all available literature, reducing the risk of skewed outcomes (Preidel et al. 2018; Paschou et al. 2020; Silva et al. 2020; Lavissière et al. 2020; Carroll et al. 2020; Chacón-Luna et al. 2020; Mottahedi et al. 2021). Afterward, this method was updated, and a directive was given to make it easier. According to the new approach in Figure 4, SLR may be divided into three phases: planning, conducting, and reporting the review (Kitchenham and Charters 2007).

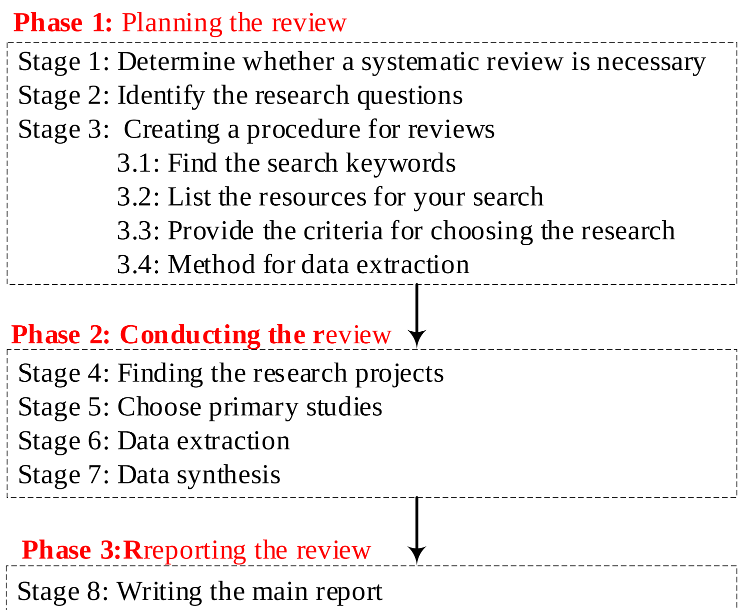

Figure 4: SLR process phases (Kitchenham and Charters 2007).

The research questions must be defined, and keywords must be specifically set to locate scientific papers in designated databases (Kitchenham and Charters 2007; Kitchenham et al. 2009). The data extraction strategy determines how data items are obtained (Kitchenham and Charters 2007). Phase 2 involves reviewing the scientific database to find potential documents and research. Primary studies are chosen based on inclusion and exclusion criteria. Data extraction synthesizes data to meet research objectives (Kitchenham and Charters 2007; Kitchenham et al. 2009). The outcomes of the earlier phases should be published after the review process.

3- SLR of CCIMO: Phase 1 and 2

The necessity for SLR should be supported, as was previously stated. The idea of CC must be thoroughly understood before it can be applied effectively. As mentioned, the mining sector's decision makers (and stockholders) must understand the CCIMO, its assessment methods, and elements to reduce mining production loss and facilitate a quick recovery.

After defining the necessity of CCIMO, the research question (RQ) must be created. The most important phase of the evaluation process is this phase. The study questions were created by the first author following the objectives of this work, and all writers then verified them. The following are the clearly stated research questions:

- *RQ1: How is CC perceived in the mining value chain? And what are the impacts (or challenges as risks and opportunities) of CC in the mining industry?*
  The scientific literature on CC effects and mining value chain modifications is developing. The mining value chain includes firms, service providers, utility and infrastructure providers, local and/or state government organizations, and community groups.(Loechel et al. 2013b).
- *RQ2: What models/approaches have been initiated to confront the challenges of CC?*
  Making the right decisions in the face of existing challenges requires specialized, comprehensive, and multifaceted approaches arranged from the macro to the micro level. Thus, the models and methodologies offered for this purpose should be recognized before planning and decision-making. Then, appropriate strategies and decisions can be adopted based on the output of these models (approaches).
- *RQ3: What approaches and strategies have the mining industry used to combat CC impacts, and how have climate adaptation and mitigation strategies been addressed?*
  The mining industry embraces CC adaptation and mitigation strategies, including energy efficiency, renewable energy sources, and sustainable mining practices. Also, depending on the type of mining operation, location, and resources available, the mining industry may employ various strategies to combat CC. Some tactics may be more successful than others but can provide long-term advantages. Therefore, the best strategies should be selected and developed based on reviewed strategies.

Creating a review procedure at the first stage requires identifying the search terms. Thus, based on the addressed research questions, search string terms are considered with Boolean operators (AND, OR) as: “climate change” **OR** “climate adaptation” **OR** “climate immigration” **AND** “mining” **OR** “mining operation”.

Then, the resources for your search were listed from well-known digital sources. The Multidisciplinary Digital Publishing Institute (MDPI), SpringerLink, Taylor & Francis, and Wiley Online Library are among them. Moreover, additional databases, including Web of Science and Google Scholar, can be used for the search process.

In the next stage, the criteria for choosing the research were provided as follows:

- The included document should be prepared in English
- Included studies need to be turned into a research paper and published.
- Unrelated research should be discarded based on title, keyword, abstract, and conclusion.
- The complete version of duplicated publications was included in the review process.
- The articles of the last two decades were examined based on the search statistics obtained from WOS and Scopus.

Finally, data extraction and synthesis forms were used to gather data to answer study questions. The following is a list of the items on the data extraction form:

- Research topic;
- Publication date;
- Presented definitions for CC and CC challenges for the mining sector;
- Type and explanation of the concepts determine the CCIMO;
- Type and description of the strategies used for CCIMO.

4- SLR of CCIMO: Phase 3

The search was done using search sources and the search string starting in 2000. Primary studies were 49 related studies of all one. The results of the reviewed articles explain the three main research questions:

4-1- Answer to RQ1: Impacts

The term "Climate Change" is used in the mining value chain to describe the long-term alterations in the planet's climate brought on by human activities such as the combustion of fossil fuels, deforestation, and industrial operations. These actions raise greenhouse gas emissions, which trap heat in the planet's atmosphere and negatively affect the ecosystem, including temperature increases, altered precipitation patterns, and sea level rise. Both as a contributor to and a potential victim of CC, the mining sector is both. Large amounts of energy are needed for mining activities, frequently produced by burning fossil fuels, increasing greenhouse gas emissions. At the same time, changes in the quantity and quality of mineral resources, rising water shortages, and extreme weather occurrences can pose physical threats to mining operations (Pearce et al. 2009). Irarrázabal, in 2006, looked into whether or not CC was a problem for the mining sector (Irarrázabal 2006). The mine production stage is likely to be the stage that is most at risk from climatic events and CC in the future. The majority of stages of mining (from pre-mine planning through planning and development, production, post-production and closure, and post-mining) are already influenced by climate and extremes (Hodgkinson et al. 2010). Figure 5 explored the effects of significant weather events and climatic variations on a general mining process.

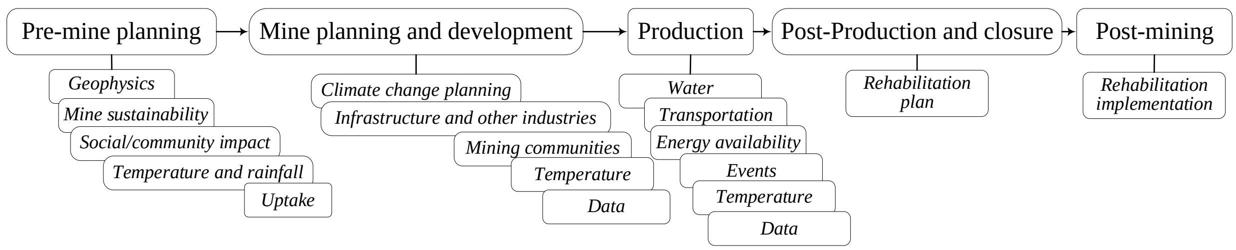

Figure 5: Potential impacts of climate and extreme weather on mining practices (Garnaut 2008)

Together, these projects will help define a program of further research to examine the risks and consequences of CC on mining communities and help develop strategies for adaptation and management of those risks. As shown in Figure 6, the impacts on mining and mining communities are closely related (Hodgkinson et al. 2010). Geological hazards (geohazards) are events linked to geological processes and features that risk human life, property, and the built-up and natural environments. For instance, rainfall is widely acknowledged as one of the primary triggers of mass movements (such as landslides, landfalls, and rockfalls) and is the focus of extensive research.

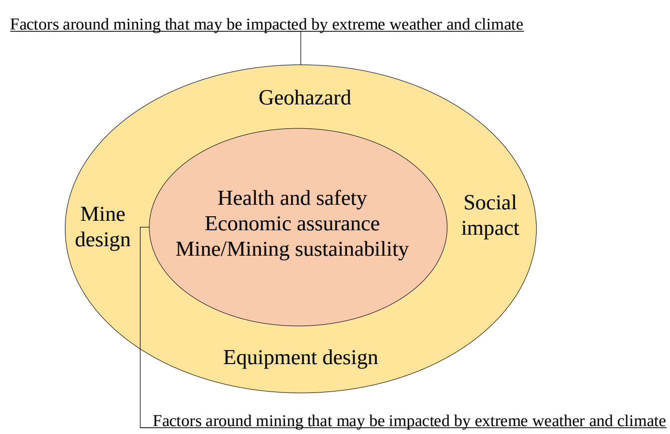

Figure 6: Some of the impacts and effects possible from extreme weather events and CC showing a link between technical and social impacts (Hodgkinson et al. 2010)

In general, the design of the mine and the equipment may be impacted directly or indirectly by extreme weather conditions and CC (Irarrázabal 2006; Hodgkinson et al. 2010):

- Primary (or direct) impacts: Physical effects such as flooding, erosion, landslides, debris flows, overflowing waste ponds, and threats to human life, property, revenue, and the environment would make up the majority of the direct effects.

- Secondary (indirect or 'knock-on') impacts: For instance, Mining access to land and labor can be affected by changes in population and resources. Local labor force shortage due to lack of water, electricity, dust, isolation, and tropical diseases.

These effects might have a favorable or negative influence on future mining assurance, economic stability, and health and safety conditions inside and around the mine (Hodgkinson et al. 2010; Janson et al. 2020). Also, Mining operations, labor, transportation, communication, building infrastructure, and mine decommissioning are all projected to be impacted by CC (Nelson and Schuchard 2011). The effective elements of the mining sector can be defined as follows:

- The processing operations: Because mining is frequently a "heavily water-dependent" sector, rising water scarcity is a major concern. Water shortage can influence various things, including production rates, dust suppression techniques, mine drainage makeup, and tailing pond covering. Heavy metals and hazardous minerals were discharged during mining operations into the land and water environment (Lemmen et al. 2007; Dontala et al. 2015).
- The site geography (condition of the property): There is a chance that steep slopes in permafrost overburden that have been exposed for a long time will damage the stability of open-pit mine walls. (Instanes 2006). Permafrost thaw is a problem in all northern locations, especially when containment buildings have not been built to endure the faster melting expected by CC or to allow for long-term maintenance (Furgal and Prowse 2007; Prowse and Furgal 2009). Flooding and intense precipitation also run the risk of exposing sinkholes and causing or escalating acid rock drainage, all of which might have negative effects on water supplies (Pearce et al. 2009).
- Challenges to environmental management: For instance, risks associated with greater rainfall include tailings dam collapse, polluted water flow into nearby communities, associated remedial costs, increased environmental responsibility, effects on community health and safety, and a large potential for reputational harm. (Pearce et al. 2009).
- Dryer conditions could decrease water intake capacity and expose tailings to sub-aerial weathering, underscoring the urgent need for new technologies to combat the effects of CC. This is due to the limited amount of climate modeling data and continued reliance on permafrost in the design of retention facilities (Smith 2013).
- It is essential that the planning for new mines and the closure and reclamation of existing ones consider the possible repercussions of CC as its effects become increasingly obvious (Smith 2013).
- Access to distribution and supply chains is evolving: Transportation services that provide products and services, transport people, transfer ore to processing facilities, and move ore to ports for export will be made possible or hindered by increasing sea levels, more precipitation, altering storm patterns, and temperature changes (Nelson and Schuchard 2011).
- Natural catastrophes provide immediate health and safety threats. At the same time, higher temperatures might impact employee hiring, retention, safety, and productivity by raising the likelihood of accidents, producing or worsening food and water shortages, and increasing the incidence of illness (Nelson and Schuchard 2011). (Adaptation)
- Changes in temperature, precipitation, and wind may all directly affect mines. For example, strong winds can damage electrical lines, high temperatures can lead to heat exhaustion in workers, and low precipitation can restrict water availability. These climatic factors also affect the intensity and frequency of natural hazards such as forest fires, avalanches, flooding, landslides, drought, and landslides (Nelson and Schuchard 2011).
- Water supplies, mine waste morphology, hydrogeologic/geochemical variables impacting water flow, geochemical reactions, and pollutant transport at mine sites will all be directly impacted by CC (Anawar 2013).
- Environmental systems are thus potentially seriously threatened by surface mining and CC. For instance, mining and CC's effects harm delicate ecosystems like wetlands (Phillips 2016).
- Transportation (roads, sea, and freshwater), containment (Tailings), buildings, energy (communications, powered facilities/equipment), and mine site drainage comprise the mining infrastructure. The Arctic Climate Impact Assessment (ACIA) highlights the potential impacts of permafrost thawing on transportation, infrastructure, and economic development (Instanes 2006; Nelson and Schuchard 2011).
- The impacts that a changing climate has on water management structures and activities, waste impoundment structures, and the hydrologic/ hydrogeologic/ geochemical conditions affecting the flow of water and contaminants at mine sites give rise to the CC risks associated with acid rock drainage and metal leaching

(when minerals containing metals and sulfur (sulfides: pyrite, arsenopyrite, and marcasite)) (Nordstrom 2009).

- Lack of guidance and misunderstanding about how to respond among employees; conflicting emergency response guidelines; a lack of contingency plans for worst-case scenarios; poor communication within and across organizations and departments; and limited awareness of sensitivity to climatic stresses are some of the issues that need to be addressed (Pearce et al. 2009).

In addition to the abovementioned situations, CC creates management difficulties in the following fields classified as non-climatic risks. Non-climatic risks can be defined as following points of view:

- Mining corporations are under growing pressure to look for ways to lower their emissions, such as through employing renewable energy, due to increased scrutiny of the industry's carbon emissions and recent progress in climate discussions (Rüttinger and Sharma 2016).
- Possibilities provided by CC (such as the opening of Arctic seaways, extended exploration seasons, and rising temperatures that will allow for exploration of the mineral-rich Arctic) may lessen the impact of other vulnerabilities (Nelson and Schuchard 2011).
- Major issues include the uncertain costs associated with addressing CC in connection to mining industry revenue and the nature of CC consequences, particularly regarding the lifespan of mines. This is an important concern because of the potential for long-lasting environmental implications following mining activities and the limited lifespan of mines. It may take hundreds of years, especially for massive mines, even though a single mining project might span between 20 and 50 years (Loechel et al. 2013b; Tolvanen et al. 2019).
- Uncertainty on the nature of the CC effects, particularly concerning miners' investment horizons (Loechel et al. 2013b).
- Big and obvious polluters (Large-scale mining) may be subject to more CC-related laws.
- Without sufficient industry participation, legislation that harms the mining industry may be created (Nelson and Schuchard 2011).
- Several challenges can hinder successful adaptation efforts, including sharing, defending, and fully accounting for adaptation costs, organizational cultural attitudes to learning and change, and inflexible company policies and/or government regulations (Loechel et al. 2013b).
- To reduce and adapt to CC, land use and land management are crucial to mine clearance operations and land release after clearance (Cottrell and Stowe 2021).
- By increasing complexity and modifying existing hazards, CC will multiply the risks associated with the mining supply chain, particularly in newly industrialized and developed nations (Rüttinger and Sharma 2016).

4-2- Answer to RQ2: Model and approaches

Climate impact assessment falls into two main categories: macroscopic and microscopic approaches. The macroscopic approach examines a predefined geographic area without considering specific assets and their failure behavior the size of the area, defined by features like maintenance zones or provinces. Climate parameters, like average temperature, are considered at a lower resolution. This approach is effective for assessing vulnerability and risk, such as identifying areas/assets prone to flooding across a large region. The second method is microscopic. Because of the diversity in asset types, adopting a macroscopic approach may introduce modeling inconsistencies, given the installation of various infrastructure/asset types within the mines. In the microscopic approach, climate parameters are considered at a higher resolution, focusing on a homogeneous group of assets for the assessment. Consequently, all features, including failure causes, failure modes, geographical locations, and local weather parameters at the asset level, are collected for the climate impact assessment (Kasraei et al. 2023). Table 1 provides the CC management methods and models in chronological order in this section, highlighting the crucial variables used in these approaches, such as risk management, vulnerability, and climate.

Table 1: Approaches in scientific papers for adaptation and mitigation in the mining sector

Researcher	Main approach, contributions	Category	Researcher	Main approach, contributions	Category

Auld and Maclver, 2006	"No regrets" and "Adaptation learning" (Conceptual) (Auld and Maclver 2006)	AD	Chavalala, 2016	Mixed-method (Analytical) (Chavalala 2016)	AD
Pearce et al., 2011	Vulnerability-based (Conceptual) (Pearce et al. 2011)	AD	Odell et al., 2018	Nature-society relationships (Conceptual) (Odell et al. 2018)	AD&MI
Riaza et al., 2007	Hyperspectral imaging (Analytical) (Riaza et al. 2007)	AD & MI	Hotton et al., 2018	Capillary barrier effects (Analytical) (Hotton et al. 2018)	MI
Garnaut, 2008	Vulnerability-based (Conceptual) (Garnaut 2008)	AD	Kosmol, 2019	Vulnerability based on Notre Dame Global Adaptation Country Index (Analytical) (Kosmol 2019)	AD
Pearce et al., 2009	Two-stage vulnerability-based (Conceptual) (Pearce et al. 2009)	AD	Nunfam et al., 2019	Contemporaneous mixed methods based on risk (Analytical) (Nunfam et al. 2019)	AD
Rayne et al., 2009	Risk of water quality (Conceptual-Analytical) (Rayne et al. 2009)	MI	Mavrommatis et al., 2019	Regional CC risks (Analytical) (Mavrommatis et al. 2019)	AD
Pearce et al., 2009	General Circulation Models (Conceptual) (Pearce et al. 2009)	MI	Mavrommatis and Damigos, 2020	Bottom-up survey-based (Analytical) (Mavrommatis and Damigos 2020)	AD&MI
Ford et al. 2011	Questionnaire for threats that CC (Analytical) (Ford et al. 2011b)	AD	Sun et al., 2020	Integrated climate risk index (CRI) based on return on total assets (Analytical) (Sun et al. 2020)	AD
Mason et al., 2013	Risk-based (Conceptual) (Mason et al. 2013)	AD	MAC, 2021	Adaptation measures (Conceptual) (MAC 2021)	AD
Loechel et al., 2013	Questionnaire for attitudes and actions about CC adaptation (Analytical) (Loechel et al. 2013a)	AD	Bresson et al., 2022	Risks and vulnerabilities (Analytical) (Bresson et al. 2022)	AD
Anawar, 2013	Acid mine drainage (AMD) (Analytical) (Anawar 2013)	AD	Xie and van Zyl, 2022	Revised the mine reclamation design (Conceptual) (Xie and van Zyl 2022)	AD&MI
Baisley et al., 2016	Risk-based (Analytical) (Baisley et al. 2016)	MI	Ngoma et al., 2023	The endogenous latent factors and exogenous latent variables in the partial least squares structural equation modeling technique (Analytical) (Ngoma et al. 2023)	AD&MI
Rüttinger and Sharma, 2016	Risk by iModeler and vulnerability (Analytical) (Rüttinger and Sharma 2016)	AD			
AD: Adaptation, MD: Mitigation, AD&MI: Adaptation-mitigation					

Mines need a two-pronged strategy to deal with the problems caused by CC, but only 20% of the methods assessed deal with adaptation and mitigation. Table 1 demonstrates that, according to the initiatives in the mining industry that have been studied, the majority (about 60 percent) are aimed toward adaptation, while just 16 percent are geared toward mitigation. The analysis of the currently used techniques demonstrates that most use an analytical mode. Even though these analytical techniques focus on particular CC effects, a holistic strategy has not yet been offered. In essence, it will take much development to produce a uniform standard for the currently used methodologies.

4-3- Answer to RQ3: Strategies

Mitigation and adaptation are essential and complementary methods to combat CC since they jointly reduce its hazards. Adaptation entails taking deliberate steps to lessen the negative effects of CC while seizing any favorable chances that may present themselves (OECD. Publishing 2009). Adaptation must become mainstreamed by incorporating adaptable methods into company planning and focusing on benefits independent of CC (Smit and Wandel 2006; Ford et al. 2011a). Instead of proactive measures based on scientific projections of expected future CC, adaptation is typically motivated by experience with recent occurrences brought on by CC or extreme weather (Garnaut 2008; Nelson and Schuchard 2011). Mitigation consists of activities that seek to prevent or capture GHGs before they are released into the atmosphere or sequester those already in the atmosphere by improving "sinks," such as forests, to decrease GHG emissions, either directly or indirectly. Such actions could involve, for instance, modifications to behavioral patterns or the creation and spread of technology (OECD. Publishing 2009). The key components of CC strategies (Nelson and Schuchard 2011):

- Include climate-compatible development in efforts for sustained local benefit from project operations.
- Develop practical measures for coping with the effects of CC with the host communities.
- Examine how enhancing local resilience through investments in ecosystem services
- Consult with stakeholders to comprehend their recent worries
- Launch industry-wide cooperation on regional adaption plans

Climatic adaptations and mitigation strategies in the mining sector can be provided by different researchers as follows:

Climate Mitigation Strategies:

- Accurate research and identification of CC-prone mining locations (Loechel et al. 2013b).
- Mines should be encouraged to use renewable energy through legislation, tax rebates, etc. (Mebratu-Tsegaye et al. 2021).
- Some mitigation measures could be implemented at the operational level (Mebratu-Tsegaye et al. 2021):
    - Fuel switching (Hybrid diesel, out of diesel)
    - Energy efficiency (Lighting, motors, pumps, conveyors)
    - Renewable energy (Procurement, PPAs, on-site)
    - Battery storage (Energy storage, electric vehicles)
    - Artificial Intelligence (Analytics, machine learning)
    - Digitization (Data processing, interfaces)
    - Low-carbon electricity (Renewables, CCS, SMRs)
    - Ore processing improvements (Bulk processing efficiency)
    - Hydrogen fuel cells (Electricity, machinery)
    - Other (RD&D, grade engineering)

Climate Adaptations Strategies:

- Information and communication technology (ICT) innovation adoption as part of adaption measures may lessen the susceptibility and exposure of the mining sector to CC catastrophe risks (Aleke and Nhamo 2016).
- Improved operational safety and resilience under projected future climate conditions through better planning, design, building, and maintenance (Loechel et al. 2013b).
- Mining contracts must consider CC concerns (national adaptation plans and climate adaptation guidelines), especially for areas highly vulnerable to the effects of CC (Mebratu-Tsegaye et al. 2021).
- The mining plan's tailings dam design must adhere to the most recent international safety requirements, and ongoing maintenance and clean-up procedures must be followed (Mebratu-Tsegaye et al. 2021).
- Applied engineering solutions can play a critical role in achieving climate resilience, which refers to the ability of communities and systems to withstand and recover from the impacts of CC (Loechel et al. 2013b).
- At the operational level, several adaptation activities could be carried out (Mebratu-Tsegaye et al. 2021):
    - Special pumps must be set up at the mine site to remove the water.
    - Mines open early if winters are short and close early if winters are long
    - Autonomous operations (Drilling, loading, haulage)
    - Fugitive emissions reduction (Ventilation Air Methane, CH_4 capture, and use)
    - Electrification (Mine processes, transport)
    - Tailings management (Emissions capture and mineral carbonation)
    - Water management (Treatment technologies)

Jointly for adaptation and mitigation Strategies:

- Governments could mandate that mining corporations account for all direct, indirect, and induced impacts on forests at every step of operations to limit forest conversion (Mebratu-Tsegaye et al. 2021).
- Governments should stipulate clearly when granting mining firms access to water (Mebratu-Tsegaye et al. 2021).
- At the project's start, closure plans incorporating climatic risks should be offered and submitted along with the environmental and social impact assessment.
- Use educational initiatives to raise knowledge of and capacity to address urgent threats, particularly in isolated communities, like rising flooding, bushfires, and diseases from mosquitoes (Loechel et al. 2013b).
- Impacts that have been identified cascading down, up, and across the supply chain (e.g., a higher frequency of intense rain events (in summer) may cause more transportation disruptions on the roads), which would reduce mining productivity at this time of year and have an impact on jobs and communities (Transport → mining → human resources → community)) (Loechel et al. 2013b).

4 – Discussion and Conclusion

This article streamlines the actions performed on climate mitigation and climate adaptation in the mining sector to address climate change challenges. The various climate mitigation and adaptation approaches and strategies in the mining sectors are presented. The review discovered that it is essential to independently understand the risks and uncertainties posed by the changes in each location to make informed decisions about CC. Once these risks have been identified, examining how each element or mineral will behave under the given circumstances is important. On the other hand, CC could pose a potentially serious risk to mines in the post-operational and closure stages of the mining life cycle. Simply put, CC will impact the entire life of the mine, and making the right decisions requires identifying these effects.

The first research question explored the impacts of CC on mining activities. The analyzed papers found that processing operations, mining and transportation infrastructure, and other essential mining activities are identified as particularly at risk from CC in the scientific literature. The challenges for mitigation and adaptation actions include low-level awareness of climate change impacts in mining, a lack of technical knowledge, high capital costs, and existing rules and regulations, necessitating a multidimensional approach to education and cultural advancement, encompassing political, legal, and practical aspects. A full analysis of the organizational obstacles to CC mitigation experienced by mining businesses, such as "employee attitudes, poor communications, historical practice, and weak top management leadership," is missing from this discussion. While climate change has detrimental effects, it is important to remember that there may also be some advantages. For instance, previously ice-covered areas might become accessible for mineral exploration, while rising temperatures might make some places more suitable for labor. Furthermore, greater accessibility to maritime transportation may create new business opportunities in coastal areas.

The second research question explored the current CC impacts and associated assessment methods. This section divided the survey into analytical and conceptual approaches. Our survey on climate adaptation and mitigation revealed a critical need for long-term planning in the mining industry. In addition, our analyses show that most mining and exploration industries focus on reducing mining's impact and climate mitigation action, and less attention has been paid to adapting the mining supply chain activities to extreme future weather events. Therefore, there is a need to emphasize climate adaptation action more to fulfill future demands and smoothen the transition toward sustainable mining development.

The answer to the third question involved a comprehensive review of the various solutions and strategies for CC adaption or mitigation utilized in the mining industry. Since some of today's mines have a short lifespan, there is a belief that they can delay climate change action when the most serious consequences of CC become apparent. Although, for the foreseeable future, it is expected that these mines will not change their current strategies to fulfill sustainability demands. However, the closest way to apply the necessary changes in the mining area can be a risk-based mine design plan. The mine’s risk management plans should incorporate environmental impacts, associated risks, and mitigation strategies to aid the CC adaptation. This plan for exploration mines should incorporate CC forecasts based on numerical data obtained via modeling and simulation to adopt a quantitative approach. Extractive mines, reduced emissions into the air and water, awareness of threats resulting from the reduced slope and shaft stability, and improved economic, social, and environmental advantages are all expected to result from implementing the mitigation plan.

Investigations showed that one of the most important tools for implementing mitigation and adaptation programs is awareness (learning) and sharing the importance of the issues in challenging areas such as mining. In this regard, the mining industry still requires extensive research to develop operational approaches to overcoming the challenges, despite the work reviewed in this article that helps people understand the significance of CC. As many proposed approaches and strategies for implementing mitigation and adaptation are still in their early stages (Although these increase awareness of different phases of mining activities and their associated value chain), decision-makers require an approach that can integrate macro-strategies with localized solutions (operational planning) for specific challenges, such as machinery issues and management decisions.

In this regard, the mining industry still requires extensive research to develop practical and operational approaches to overcoming the challenges. CC impacts on the mining value chain require a concerted effort to bridge the existing gap between conceptual frameworks and practical models in the future. This systematic literature review underscores the importance of translating theoretical ideas into practical strategies, given the industry's vulnerability to CC. A key element of this effort is the recognition that the operational phase plays a pivotal role, encouraging researchers and stakeholders to seamlessly incorporate climate considerations into the design and daily operations of mining operations. A critical facet of plans involves the enhancement of risk management, which advocates for the implementation of comprehensive plans incorporating not only environmental impacts and associated risks but also employing quantitative approaches through numerical data, modeling, and simulation techniques. A proactive risk management approach includes emissions control, stability assessments, and economic, social, and environmental considerations. It is through education and cultural advancement that low awareness, lack of technical knowledge, high capital costs, and existing regulations can be overcome. Fortifying the mining industry's overall preparedness for CC impacts requires a multidimensional approach that encompasses political, legal, and practical dimensions. Long-term planning is essential to sustainability. Mines, especially those with shorter lifespans, should take proactive measures to combat CC, emphasizing the possible long-term advantages. To effectively implement CC mitigation and adaptation initiatives and develop a culture of learning and information exchange, there must be a continuous commitment to raising awareness and sharing expertise within the mining industry. This helps researchers, industry stakeholders, and policymakers work together to translate theoretical knowledge into practical measures that improve the mining industry's ability to adapt. To put it briefly, the proposed mining value chain plan takes a multifaceted, holistic approach that integrates theoretical advances with real-world tactics, stressing the critical importance of operational considerations and teamwork in strengthening the sector against the many threats posed by CC.

Declarations

Conflict of interest There are no conflicts of interest declared by any of the authors.

Human participants and/or animals Human Participants and/or Animals are not involved in this research.

Informed consent was obtained from all individual participants included in the study.

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