



# From Sustainable Mining to Climate-Smart Mining; Lessons for Nigeria

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## Abstract

As Nigeria confronts the dual challenges of economic development and environmental sustainability, the mining sector emerges as a critical area for transformation. This study explores the transition from traditional sustainable mining practices to a more advanced paradigm known as climate-smart mining. The concept of climate-smart mining integrates climate resilience and mitigation strategies into mining operations, aiming to reduce the sector's carbon footprint while enhancing its contribution to sustainable development goals. The study begins by reviewing the current state of mining in Nigeria, identifying key environmental and social impacts, including deforestation, water contamination, and loss of biodiversity. It then examines global best practices and innovations in climate-smart mining, highlighting approaches such as energy-efficient technologies, waste reduction, and ecosystem restoration. Lessons from countries that have successfully implemented climate-smart mining strategies provide valuable insights for Nigeria. The study emphasizes the need for a comprehensive policy framework that incorporates climate-smart principles, alongside improved regulatory oversight and stakeholder engagement. It advocates for the adoption of advanced technologies and practices that align with Nigeria's environmental and economic objectives. By transitioning to climate-smart mining, Nigeria can achieve a more sustainable mining sector that supports both economic growth and environmental stewardship. This study serves as a guide for policymakers, industry stakeholders, and environmental advocates, offering actionable recommendations to facilitate Nigeria's shift towards a climate-smart mining future.

**Keywords:** Climate-Smart mining; Environmental impact; Mining policy; Nigeria and sustainable development

## Introduction

Mining plays a crucial role in the global economy, providing raw materials essential for industrial processes and technological advancements. However, the sector has long been associated with significant environmental degradation, including deforestation, water pollution, habitat destruction, and greenhouse gas emissions. These environmental challenges have spurred a growing recognition of the need to transition towards more sustainable practices in mining. Sustainable mining, as conceptualized, seeks to balance economic development with environmental protection and social equity. It emphasizes minimizing negative ecological impacts, enhancing resource efficiency, and ensuring that mining activities contribute positively to local communities. The concept aligns with the broader global sustainability agenda, including the

Sustainable Development Goals (SDGs) aimed at mitigating climate change and preserving ecosystems [1]. In recent years, climate-smart mining (CSM) has emerged as a more targeted approach within the sustainability framework, focusing specifically on reducing the mining sector's carbon footprint and increasing resilience to climate change. CSM integrates practices that lower greenhouse gas emissions, reduce energy consumption, and promote the use of renewable energy in mining operations. It also emphasizes the importance of resource recycling and waste reduction, which further contributes to the reduction of environmental impacts [2]. The concept of climate smart mining holds the potential of achieving the balance of sustainable mining and the achievement of sustainable development especially for populations that host mining operations. This shift from sustainable mining to climate-smart mining reflects a more urgent response to

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the growing climate crisis and aligns with global efforts to transition to a low-carbon economy. For Nigeria, this presents an opportunity for a mining and climate change dialogue [3]. Nigeria, a country endowed with abundant mineral resources, has a long history of mining. From tin and coal in the early 20th century to more recent extractions of gold, limestone, and bitumen, the mining sector has significantly contributed to the nation's economy. It provides employment opportunities and generates revenue through exports, supporting the industrial and manufacturing sectors [4]. In Nigeria, the mining sector holds immense potential for economic diversification. With over 44 solid minerals in commercial quantities across its 36 states and the Federal Capital Territory, Nigeria's mining sector promises to diversify its oil-dependent economy. However, this potential remains largely untapped, contributing a mere 0.3% to the GDP in 2020, a figure that starkly contrasts with the sector's capacity to contribute up to 10% of the GDP by 2026 according to government projections [5]. Despite its economic importance, mining in Nigeria faces significant environmental challenges. Deforestation, soil erosion, water contamination, and air pollution are common problems associated with mining activities in the country. Furthermore, the lack of adequate regulatory frameworks and enforcement mechanisms exacerbates these environmental issues, leading to unsustainable exploitation of natural resources [6]. Given the environmental impacts of mining, there is an urgent need for Nigeria to embrace the transition from sustainable mining practices to climate-smart mining. Such a shift would not only contribute to reducing the environmental footprint of the mining sector but also enhance its resilience in the face of climate change. This paper examines the potential for this transition in Nigeria, drawing lessons from global best practices and providing recommendations for policy and regulatory reforms.

## Statement of the Research Problem

Mining has historically been a cornerstone of economic development in resource-rich countries, including Nigeria. However, the environmental costs of traditional mining practices have raised concerns about their sustainability, particularly in the context of climate change. The process of extracting, processing, and transporting minerals often generates significant greenhouse gas (GHG) emissions, pollutes water bodies, degrades landscapes, and leads to biodiversity loss [7]. These adverse effects not only threaten local ecosystems but also exacerbate climate change, posing a significant challenge to sustainable development. While traditional sustainable mining practices have made strides in mitigating some negative effects, they are insufficient to address the growing challenges posed by climate change. Nigeria, with its vast mineral wealth, faces a growing imperative to transition from

traditional mining practices to approaches that are not only economically viable but also environmentally sustainable. This challenge is amplified by the country's commitment to global climate targets, including the Paris Agreement, which calls for a significant reduction in GHG emissions [8]. Despite efforts to promote sustainable mining practices, current strategies in Nigeria fall short of addressing the multifaceted impacts of mining on climate and environmental sustainability. Existing policies and frameworks lack the integration of climate-smart mining principles that prioritize the reduction of carbon footprints, efficient resource use, and the protection of ecosystems. Moreover, with Nigeria's economy heavily reliant on natural resources, there is an urgent need to reconcile economic growth with environmental stewardship [9]. The concept of climate-smart mining, introduced by the World Bank, advocates for mining practices that support the global transition to low-carbon energy while minimizing environmental and climate impacts [10]. Climate-smart mining involves the adoption of practices that reduce greenhouse gas emissions, enhance energy efficiency, and promote the sustainable use of resources throughout the mining value chain [11]. For Nigeria, adopting climate-smart mining practices can offer critical lessons in aligning mining activities with national and global climate goals. However, little research has been conducted on the practical implementation of climate-smart mining in Nigeria, highlighting a gap in both policy and practice. This research seeks to address this gap by exploring the necessity of shifting from sustainable mining to climate-smart mining in Nigeria. It will assess the limitations of current mining practices, evaluate the environmental and climate impacts, and draw lessons from international best practices in climate-smart mining. The study will also examine how integrating climate resilience into the mining sector can contribute to Nigeria's broader environmental sustainability goals.

## Aim and Objectives

The overarching aim of this study is to explore the need for a transition from sustainable mining to climate-smart mining practices in Nigeria. The study will draw lessons from international best practices and examine how such a shift can contribute to reducing environmental impacts, enhancing climate resilience, and promoting sustainable development in Nigeria's mining sector.

The specific objectives of the study are:

1. To assess the environmental and climate impacts of current mining practices in Nigeria.
2. To identify the key principles and practices of climate-smart mining.
3. To analyse the limitations of existing sustainable mining policies and practices in Nigeria.

4. To explore the potential benefits of adopting climate-smart mining practices in Nigeria
5. To provide policy recommendations for integrating climate-smart mining into Nigeria's mining sector
6. To draw lessons from international examples of climate-smart mining applicable to Nigeria

## Conceptual Clarification

### Sustainable mining

Sustainable mining refers to the practice of extracting minerals and other geological resources in a manner that ensures long-term environmental, social, and economic sustainability. The core idea behind sustainable mining is to minimize the negative impacts of mining activities while maximizing the benefits for current and future generations. It seeks to balance the need for resource extraction with the protection of ecosystems, local communities, and the broader environment [12]. Sustainable mining refers to mining practices that aim to meet the needs of the present without compromising the ability of future generations to meet their own needs. This concept integrates economic, environmental, and social dimensions to ensure that mining activities contribute to sustainable development [13]. Sustainable mining practices are designed to minimize environmental damage, ensure social responsibility, and promote economic viability. Sustainable mining has been defined as the process of carrying out mining activities that are environmentally sound, socially responsible, and economically viable. According to the International Council on Mining and Metals (ICMM), sustainable mining involves the "commitment to ensure that mining delivers benefits to host communities while minimizing environmental harm and ensuring economic development" [14]. The United Nations defines sustainable mining as a practice that ensures the "sustainable use of natural resources, preservation of ecosystems, and promotion of social welfare" [15].

### Key Principles of Sustainable Mining

1. **Minimizing Environmental Damage:** One of the most critical principles of sustainable mining is reducing the environmental footprint of mining activities. This includes minimizing habitat destruction, water pollution, and air pollution, as well as limiting the release of harmful chemicals and waste materials into the environment. Sustainable mining practices emphasize restoring mined land through reforestation and rehabilitation, aiming to preserve biodiversity and prevent soil erosion [16].
2. **Efficient Resource Use:** Sustainable mining advocates for the efficient use of natural resources, ensuring that mineral extraction is optimized, and waste generation is minimized.

This includes adopting technologies that maximize the extraction of valuable minerals while reducing energy and water consumption. By improving resource efficiency, the long-term sustainability of mining operations can be ensured [17].

3. **Social Responsibility and Community Engagement:** Social responsibility is a key component of sustainable mining. It requires mining companies to engage with local communities, ensuring that the benefits of mining are shared equitably. This includes providing employment opportunities, investing in local infrastructure, and ensuring that local populations are not negatively impacted by mining operations. Additionally, sustainable mining emphasizes respecting indigenous rights, ensuring safe working conditions, and fostering community participation in decision-making [18].
4. **Economic Viability:** For mining to be sustainable, it must also be economically viable. This involves ensuring that mining activities provide long-term financial benefits not only to the companies involved but also to host countries and communities. Sustainable mining encourages the reinvestment of mining revenues into local economies and the development of diversified economic activities to ensure economic resilience once mining operations cease [19].
5. **Governance and Transparency:** Effective governance and transparency are essential principles of sustainable mining. This includes adherence to legal frameworks, compliance with environmental and social regulations, and transparent reporting on mining impacts. Sustainable mining also involves accountability to both shareholders and stakeholders, ensuring that companies meet environmental, social, and economic standards [20].

While sustainable mining practices aim to reduce negative impacts and promote benefits, challenges remain, particularly in aligning mining operations with climate goals. The concept of climate-smart mining seeks to address this gap by specifically incorporating climate change mitigation and adaptation into the sustainable mining framework. This shift is particularly important for resource-rich countries like Nigeria, where mining plays a critical role in economic development but also contributes significantly to environmental degradation and climate change.

### Climate-Smart Mining (CSM)

Climate-smart mining (CSM) refers to a set of practices that aim to align the mining sector with the global climate agenda. Climate-Smart Mining (CSM) refers to mining practices that are designed to minimize the environmental and climate impacts of mining activities while ensuring the sustainable extraction and processing of minerals and metals. It is designed to reduce the negative

environmental and climate impacts of mining while ensuring that the sector continues to supply the raw materials necessary for the transition to low-carbon energy systems. The concept was introduced by the World Bank as part of its efforts to decarbonize industries, particularly in light of the increasing demand for minerals and metals required for renewable energy technologies like solar panels, wind turbines, and electric vehicles [10]. CSM focuses on minimizing the carbon footprint of mining operations, promoting resource efficiency, and enhancing the sector's climate resilience. It goes beyond sustainable mining by directly incorporating climate change mitigation and adaptation strategies into mining activities. This approach recognizes that the mining industry is both a contributor to and a victim of climate change; while mining processes emit significant greenhouse gases (GHGs), the sector is also vulnerable to the effects of climate change, such as extreme weather events and water scarcity [21]. The primary goal of CSM is to support the transition to a low-carbon economy by providing the raw materials needed for clean energy technologies, such as solar panels, wind turbines, and electric vehicles, in a manner that is environmentally responsible and socially inclusive [11].

## Goals of Climate-Smart Mining

The primary goals of CSM are to:

1. Reduce the environmental and carbon footprint of the mining industry.
2. Reduce Greenhouse Gas Emissions
3. Enhance resource efficiency and minimize waste generation.
4. Increase resilience of mining operations to climate-related risks.
5. Support the global transition to low-carbon energy systems by ensuring a sustainable supply of critical minerals and metals.
6. Promote Social and Environmental Responsibility:
7. Promote sustainable economic development while mitigating the impacts of climate change on mining communities and ecosystems.

## Key Pillars of Climate-Smart Mining

1. **Mitigation:** The mitigation pillar of CSM is focused on reducing the mining sector's contribution to climate change by lowering greenhouse gas emissions. This involves the adoption of energy-efficient technologies, transitioning from fossil fuels to renewable energy sources for mining operations, and improving the carbon efficiency of mineral processing. Mitigation also includes reducing methane emissions, which are prevalent in coal mining, and implementing carbon capture and storage (CCS) technologies to sequester emissions [10]. Efficient resource use is another crucial component of

mitigation. This involves the optimization of mining processes to extract more minerals with less energy, as well as the recycling and reuse of materials to reduce the demand for new mineral extraction [22].

2. **Adaptation:** Adaptation focuses on increasing the resilience of mining operations to the impacts of climate change. Climate-related risks, such as extreme weather events, floods, droughts, and temperature changes, can disrupt mining operations and supply chains, making it necessary for the industry to develop strategies to cope with these changes. Adaptation measures in CSM include the use of water-efficient technologies in water-scarce regions, constructing resilient infrastructure to withstand extreme weather, and diversifying energy sources to mitigate the risk of energy shortages [23]. Furthermore, adaptation involves addressing the vulnerabilities of mining communities and workers who are directly affected by climate impacts. This includes the development of early warning systems, disaster risk reduction strategies, and the incorporation of climate risk assessments into mining project planning [24].
3. **Resilience:** Resilience in CSM refers to the capacity of the mining sector to maintain its operations and supply chains in the face of climate-induced disruptions. Building resilience involves both physical and financial measures, such as investing in infrastructure that can withstand extreme weather, securing water resources in regions affected by drought, and developing financial mechanisms to buffer against climate-related economic shocks [25].

Additionally, resilience is linked to the social aspect of mining, emphasizing the importance of creating resilient communities that can adapt to changing environmental conditions. This includes promoting alternative livelihoods for communities dependent on mining, improving working conditions, and ensuring that the benefits of mining are equitably distributed to help buffer against economic downturns caused by climate change. The concept of climate-smart mining is a forward-thinking approach that integrates climate mitigation, adaptation, and resilience into the mining industry. While sustainable mining focuses on minimizing environmental impacts, CSM addresses the broader issue of aligning mining activities with global climate goals. In Nigeria, where mining plays a key role in economic development, transitioning to CSM practices can help the country meet its climate commitments under the Paris Agreement while ensuring the sustainable extraction of critical minerals.

## Methodology

This review paper employs a desk review methodology to examine the transition from sustainable mining to climate-smart mining,

focusing on lessons for Nigeria. Online databases, academic journals, government reports, and industry publications were systematically searched to identify relevant literature. Key terms used in the search included "sustainable mining," "climate-smart mining," "Nigeria," and "mining practices." The collected materials were critically analysed to extract insights into the challenges, opportunities, and best practices associated with this transition. Reference citations are provided throughout the paper to support the claims and arguments made.

## Result of Findings

### Empirical review of global best practices

The transition from sustainable mining to climate-smart mining is pivotal in ensuring that mining operations contribute to long-term economic growth while minimizing environmental damage. Sustainable mining involves balancing resource extraction with environmental stewardship and social responsibility. Climate-smart mining, on the other hand, integrates climate resilience into mining practices, focusing on reducing greenhouse gas emissions and adapting to climate change. This section examines global best practices in sustainable mining, focusing on environmental regulations, technology innovations, and social policies from key mining nations, including Australia, Canada, and South Africa, to draw relevant lessons for Nigeria.

### Sustainable Mining Practices: Case Studies from Australia, Canada, and South Africa

#### Australia: Leading in technological innovation and environmental regulations

Australia is a global leader in mining, with vast reserves of minerals such as iron ore, coal, and gold. The Australian government has implemented strict environmental regulations to mitigate the negative effects of mining. The Environmental Protection and Biodiversity Conservation Act (1999) requires mining companies to assess the environmental impact of their projects and implement biodiversity management plans. In addition, Australia's Mining for Sustainable Development framework emphasizes the importance of stakeholder engagement and minimizing water and energy use in mining operations [26]. Technological innovations are central to Australia's sustainable mining agenda. For example, BHP, a leading mining company, has implemented autonomous haulage systems in its Pilbara iron ore mines, which have reduced fuel consumption and lowered greenhouse gas emissions [27]. Renewable energy integration into mining operations is also gaining traction, with companies adopting solar and wind power to replace fossil fuels in remote

locations [28]. These practices ensure that mining operations are both efficient and environmentally friendly.

#### Canada: Fostering social policies and indigenous rights

Canada is recognized for its robust environmental regulations and progressive social policies in the mining sector. The Canadian Environmental Assessment Act (2012) mandates comprehensive environmental impact assessments before mining projects can be approved. In addition, the Canadian Minerals and Metals Plan (2019) emphasizes sustainable mining, encouraging companies to reduce carbon footprints, protect biodiversity, and improve energy efficiency [29]. A unique feature of Canada's mining practices is the inclusion of Indigenous communities in decision-making processes. Companies are required to consult with Indigenous groups, respecting their rights to land and resources [30]. The Impact and Benefit Agreements (IBAs) signed between mining companies and Indigenous communities help ensure that these communities receive economic benefits and job opportunities from mining projects. For instance, the Voisey's Bay nickel mine in Labrador has successfully implemented IBAs, leading to improved social outcomes for Indigenous populations [31]. Canada's approach to integrating social policies with environmental regulations offers important lessons for Nigeria, where local communities often face negative impacts from mining operations.

#### South Africa: Addressing environmental and social challenges

South Africa is rich in minerals such as gold, platinum, and diamonds, and has a long history of mining. However, the country has faced significant environmental and social challenges due to mining. In response, South Africa has strengthened its regulatory framework to promote sustainable mining. The Minerals and Petroleum Resources Development Act (2002) requires mining companies to submit environmental management plans and engage in community development initiatives [32]. South Africa has also adopted several initiatives to address the socio-economic impacts of mining on local communities. For example, the Mining Charter outlines requirements for mining companies to promote employment, training, and social investment in mining regions [33]. Companies are also encouraged to implement strategies that improve local infrastructure and promote sustainable livelihoods. However, despite these efforts, challenges such as mine closures and abandoned mines continue to pose environmental hazards [34].

### Environmental Regulations and Policy Frameworks

Environmental regulations are essential to mitigating the adverse impacts of mining on ecosystems and local communities. The case studies from Australia, Canada, and South Africa highlight the

importance of stringent regulatory frameworks that enforce environmental impact assessments, biodiversity protection, and water management in mining operations. These frameworks ensure that mining activities do not deplete natural resources or cause irreversible harm to the environment. In Australia, companies are required to implement rehabilitation plans for mined land, ensuring that ecosystems are restored after mining operations cease [26]. In Canada, companies must adhere to strict guidelines on tailings management and water quality to prevent pollution from mining waste [35]. South Africa's policy framework includes a focus on water management in mining areas, as water scarcity is a critical issue in many mining regions [32]. For Nigeria, adopting similar regulations could help mitigate the environmental degradation caused by mining activities. Strengthening existing policies, such as the Nigerian Minerals and Mining Act (2007), with clear guidelines on environmental impact assessments, land rehabilitation, and stakeholder engagement will be essential in advancing sustainable mining practices.

### **Technological Innovations for Sustainable and Climate-Smart Mining**

Technological advancements are critical to improving the sustainability of mining operations. In Australia, the use of autonomous vehicles, renewable energy, and digital technologies has significantly reduced the environmental footprint of mining. Autonomous vehicles, for example, have improved fuel efficiency and safety, while remote monitoring systems have enhanced operational efficiency [27]. In Canada, innovations in carbon capture and storage (CCS) are being explored to reduce emissions from mining activities [29]. Climate-smart mining also involves reducing energy consumption and minimizing greenhouse gas emissions. Transitioning to renewable energy sources, such as solar and wind power, for mining operations in remote areas is becoming more common in both Australia and Canada [28]. For Nigeria, investing in these technologies can help reduce the reliance on diesel generators in mining operations, thereby lowering carbon emissions and improving the sustainability of the mining sector.

### **Social Policies and Community Engagement**

The social impacts of mining are significant, particularly for local and Indigenous communities. Canada's emphasis on social policies, such as the inclusion of Indigenous communities in decision-making, is a global best practice that can be adapted to Nigeria. Nigeria's mining industry has often been criticized for its negative impacts on local communities, including land degradation, water pollution, and loss of livelihoods [36]. Adopting inclusive social policies that ensure community participation in mining projects and equitable distribution of benefits is critical for

achieving sustainable and climate-smart mining. The global best practices from Australia, Canada, and South Africa offer valuable lessons for Nigeria's transition from sustainable mining to climate-smart mining. These countries have demonstrated the importance of strong environmental regulations, technological innovations, and inclusive social policies in minimizing the negative impacts of mining while maximizing economic benefits. By adopting similar approaches, Nigeria can ensure that its mining sector contributes to long-term sustainability, reduces carbon emissions, and benefits local communities.

### **Climate-Smart Mining Practices: Global Perspectives**

The shift from sustainable mining to climate-smart mining (CSM) is essential for reducing the environmental impact of mining activities while meeting the growing demand for minerals critical to clean energy technologies. The transition is vital in addressing the global challenges posed by climate change while ensuring resource extraction continues to contribute to economic development. Climate-smart mining integrates renewable energy, carbon capture technologies, and circular economy principles to reduce the environmental impact of mining and improve its long-term sustainability. This section explores CSM implementation in key mining regions, focusing on Chile and Peru. The study also examines the integration of renewable energy, carbon capture technologies, and circular economy practices in mining operations, drawing lessons for Nigeria.

### **Climate-Smart Mining (CSM) Implementation in Key Mining Regions**

#### **Chile: Leading the Shift to Renewable Energy in Mining**

Chile is a global leader in copper production and has made significant strides in integrating climate-smart mining practices. The country's mining sector is responsible for a substantial portion of its greenhouse gas emissions, primarily due to its reliance on fossil fuels. However, in recent years, Chile has embraced renewable energy as part of its climate-smart mining strategy. The adoption of solar and wind energy has transformed the energy mix in Chile's mining sector, with renewable sources now accounting for approximately 20% of the energy used in mining operations [37]. The country has leveraged its abundant solar resources to power mining activities, significantly reducing greenhouse gas emissions. For instance, the Collahuasi mine has implemented solar power to meet a substantial portion of its energy needs. Additionally, Chile is exploring carbon capture and storage (CCS) technologies to further mitigate the environmental impact of mining. Chile's mining companies have invested in large-scale solar photovoltaic (PV) plants and wind farms, reducing their

dependence on imported fossil fuels and lowering carbon emissions. For instance, the Collahuasi copper mine has implemented a hybrid energy system that combines solar and wind power, reducing its greenhouse gas emissions by 30% [38]. The country's National Green Hydrogen Strategy, launched in 2020, also promotes the use of green hydrogen in mining operations, further enhancing Chile's position as a global leader in climate-smart mining [39].

#### **Peru: Advancing CSM through Carbon Capture and Renewable Integration**

Peru is another major player in the global mining industry, particularly in the production of copper, silver, and gold. The country has also recognized the need for climate-smart mining practices to ensure the long-term sustainability of its mining sector. Peru has focused on integrating renewable energy and exploring carbon capture technologies in its mining operations to address the sector's carbon footprint. One notable example is the use of renewable energy in the Cerro Verde copper mine, where solar energy and energy efficiency measures have been implemented to reduce emissions [10]. Moreover, Peru is exploring carbon capture and storage (CCS) technologies to further mitigate the environmental impact of mining. While CCS is still in its early stages, several pilot projects are being developed, with the potential to capture significant amounts of CO<sub>2</sub> emissions from mining operations [40]. These efforts demonstrate Peru's commitment to transitioning towards climate-smart mining practices, which can serve as a model for other countries, including Nigeria.

### **Integration of Renewable Energy in Mining Operations**

The integration of renewable energy is a cornerstone of climate-smart mining. Mining is energy-intensive, and the use of fossil fuels contributes significantly to greenhouse gas emissions. Shifting to renewable energy sources not only reduces the carbon footprint of mining operations but also enhances energy security and lowers operating costs. In Chile, the mining sector has embraced solar energy due to the country's favourable geographical conditions. The Atacama Desert, one of the sunniest places on Earth, provides an ideal location for large-scale solar power plants. Mining companies, such as Anglo American and BHP, have invested heavily in solar PV projects to power their operations. These initiatives have led to a substantial reduction in the sector's reliance on diesel generators, which previously accounted for a large portion of emissions [37]. Similarly, in Peru, renewable energy integration is becoming a critical part of mining operations. The Quellaveco copper mine, operated by Anglo American, plans to rely entirely on renewable energy for its operations by 2025, utilizing solar and hydropower to meet its

energy needs [41]. This shift aligns with global efforts to decarbonize mining and promote climate-smart practices.

### **Carbon Capture Technologies in Mining**

Carbon capture technologies are essential to achieving climate-smart mining by capturing and storing carbon dioxide emissions produced during mining operations. These technologies are particularly relevant in countries with significant fossil fuel use in mining or high levels of industrial emissions. Chile is actively exploring carbon capture and storage (CCS) as part of its climate-smart mining agenda. Several pilot projects aim to capture CO<sub>2</sub> emissions from industrial processes, including mining. For example, the "Carbon Capture at Source" project in Chile focuses on capturing CO<sub>2</sub> from copper smelting processes, where emissions are particularly high [42]. While still in the development phase, these projects demonstrate Chile's commitment to leveraging carbon capture technologies to reduce emissions. In Peru, the adoption of carbon capture technologies is also gaining momentum. The Ministry of Energy and Mines has initiated discussions on developing carbon capture pilot projects in collaboration with mining companies [40]. These efforts aim to position Peru as a leader in climate-smart mining practices by addressing both the energy and emissions challenges faced by the sector.

### **Circular Economy Principles in Mining**

The application of circular economy principles in mining is a key component of climate-smart mining, promoting the reuse, recycling, and repurposing of materials to reduce waste and enhance resource efficiency. By minimizing waste and extending the lifecycle of mining products, companies can reduce the environmental impact of mining and contribute to a more sustainable resource extraction model. In Chile, several mining companies are adopting circular economy strategies. The El Teniente copper mine, operated by Codelco, has implemented a zero-waste initiative that focuses on recycling mine tailings and reprocessing waste materials to extract additional valuable minerals [43]. This not only reduces the environmental burden of waste disposal but also increases the overall efficiency of resource extraction. The Chilean government has also introduced policies that encourage mining companies to adopt circular economy principles, such as reusing water in mining operations and recycling metals from old mining equipment. Peru is also making strides in incorporating circular economy practices into its mining industry. The country's National Strategy for the Circular Economy promotes waste reduction and the efficient use of natural resources, particularly in mining regions. Mining companies are encouraged to recycle materials, such as scrap metal, and to adopt

practices that reduce water consumption and pollution [44]. These efforts align with global trends towards a circular economy and offer valuable insights for Nigeria's mining sector. The global examples of climate-smart mining from Chile and Peru highlight the importance of integrating renewable energy, carbon capture technologies, and circular economy principles in mining operations. Both countries have demonstrated significant progress in reducing the environmental impact of mining through innovative technologies and policy frameworks. For Nigeria, the lessons from Chile and Peru provide a roadmap for transitioning to climate-smart mining, with a focus on reducing carbon emissions, improving resource efficiency, and promoting sustainable development in the mining sector.

## **Nigeria's Mining Sector: Current Practices and Challenges**

The Nigerian mining sector has historically played a pivotal role in the country's economic development. However, its contribution has declined significantly due to over-reliance on oil and the lack of sustainable practices in the industry. As Nigeria looks to revitalize its mining sector, there is growing recognition of the need to adopt sustainable and climate-smart mining practices to balance economic development with environmental stewardship. This section provides an overview of Nigeria's mining sector, its history and economic relevance, current sustainability initiatives, and the challenges that hinder the country's progress towards sustainable and climate-smart mining.

## **Overview of Nigeria's Mining Sector: History and Economic Relevance**

### **Historical context of mining in Nigeria**

Mining has been an integral part of Nigeria's economy since pre-colonial times, with local communities engaging in the extraction of gold, tin, and columbite. During the colonial era, Nigeria became a key exporter of minerals, particularly tin from the Jos Plateau, contributing significantly to the country's revenue [36]. By the 1960s, Nigeria was among the world's leading producers of tin and columbite, with the mining sector accounting for a substantial share of the national economy. However, following the discovery of oil in the 1950s and its subsequent commercialization in the 1970s, Nigeria's focus shifted towards the oil and gas industry, leading to the decline of the mining sector [45]. The neglect of mining led to the deterioration of infrastructure, loss of skilled labour, and an overall reduction in the sector's contribution to the gross domestic product (GDP). Currently, mining contributes less than 1% to Nigeria's GDP, despite the country's vast untapped mineral resources [46].

## **Economic relevance and potential of the mining sector**

Nigeria is endowed with over 44 different types of minerals, including gold, limestone, lead-zinc, coal, iron ore, and tantalite. These minerals are distributed across various states, presenting opportunities for economic diversification [47]. With the federal government's renewed interest in mining, the sector has the potential to drive economic growth, generate employment, and contribute to foreign exchange earnings.

The Nigerian Minerals and Mining Act (2007) and the Nigerian Mining Growth Roadmap (2016) outline the country's vision for developing a sustainable mining sector. These policies aim to attract foreign investment, improve transparency, and promote the efficient use of Nigeria's mineral resources. The government has also established the Solid Minerals Development Fund (SMDF) to support artisanal and small-scale miners, further enhancing the sector's potential to contribute to the economy [48].

## **Current Sustainability Initiatives in Nigeria's Mining Sector**

### **Environmental regulations and policy frameworks**

Sustainability in mining is increasingly becoming a priority for Nigeria's government. The Nigerian Minerals and Mining Act (2007) provides a legal framework for environmental management in the mining sector. The Act mandates that mining companies conduct environmental impact assessments (EIAs) before commencing operations and develop environmental management plans to mitigate adverse effects [49]. This legal provision is in line with global best practices for sustainable mining. In addition to the Mining Act, the National Environmental Standards and Regulations Enforcement Agency (NESREA) has developed regulations for mining activities, particularly in the areas of air and water pollution control, waste management, and land reclamation. The goal is to ensure that mining companies operate in a manner that minimizes environmental degradation (NESREA, 2020). However, these regulations are often not fully enforced, leading to widespread environmental issues, including land degradation, water contamination, and loss of biodiversity in mining regions [50].

### **Sustainable mining initiatives**

Nigeria has also initiated several sustainability programs aimed at promoting responsible mining practices. One notable initiative is the Safer Mining Project, launched by the Ministry of Mines and Steel Development (MMSD) in collaboration with international partners, such as the World Bank. This project focuses on reducing the use of harmful substances, such as mercury, in artisanal and small-scale mining (ASM), particularly in the gold mining sector

[51]. The project also promotes safer and more environmentally friendly mining techniques, which are critical for transitioning to sustainable and climate-smart mining. Furthermore, the Nigeria Mining Cadastre Office has implemented reforms to improve transparency and governance in the mining sector. The digitalization of mining titles and the establishment of an online cadastre system have helped to reduce illegal mining and promote responsible mining practices [52]. These initiatives align with global efforts to ensure that mining activities contribute to sustainable development while minimizing environmental and social impacts.

## Challenges Facing Nigeria's Transition to Climate-Smart Mining

### Environmental degradation and lack of enforcement

Despite the existence of environmental regulations, Nigeria's mining sector continues to face significant sustainability challenges. Unregulated artisanal and small-scale mining is a major contributor to environmental degradation, particularly in regions such as Zamfara and Osun, where illegal gold mining activities have resulted in widespread pollution and deforestation [36]. Additionally, mining activities in the Jos Plateau have left behind abandoned mine sites and degraded landscapes, with little effort made towards land reclamation or rehabilitation [47]. The enforcement of environmental regulations remains weak due to a lack of capacity, corruption, and inadequate funding for regulatory agencies. This has led to poor compliance by mining companies, especially smaller operators, who often disregard environmental impact assessments and pollution control measures [50]. Strengthening the enforcement of regulations and improving governance in the mining sector is critical for ensuring the sustainability of mining operations in Nigeria.

### Technological gaps and lack of innovation

Nigeria's mining sector has yet to fully embrace the technological innovations that are essential for climate-smart mining. In countries such as Chile and Canada, mining companies have integrated renewable energy sources, autonomous vehicles, and digital monitoring systems to reduce their environmental footprint (IRENA, 2020b). In contrast, Nigeria's mining industry relies heavily on outdated technologies and inefficient practices, leading to high energy consumption and greenhouse gas emissions [47]. To transition to climate-smart mining, Nigeria needs to invest in technology and innovation. This includes the adoption of renewable energy for mining operations, such as solar or wind power, and the use of digital tools for monitoring environmental impacts and improving resource efficiency. Collaboration with

international partners and the private sector could accelerate the adoption of these technologies.

## Socio-Economic Impacts and Community Engagement

Mining activities in Nigeria often have negative socio-economic impacts on local communities, including displacement, loss of livelihoods, and exposure to health risks from pollution. The lack of proper community engagement and benefit-sharing mechanisms has led to conflicts between mining companies and host communities [53]. In many cases, communities bear the brunt of the environmental and social costs of mining without receiving adequate compensation or economic benefits.

**Infrastructure Deficit:** Inadequate infrastructure, including transportation, power supply, and access to water, poses significant challenges to mining operations. Improving infrastructure is critical for reducing operational costs and making mining more attractive to investors.

**Security Concerns:** Security issues, including illegal mining activities and community conflicts, have created an unstable operating environment. Addressing these concerns through enhanced security measures and community engagement is vital for the sector's stability and growth.

### Limited Access to Finance

Access to finance remains a significant hurdle for both small-scale and large-scale mining operations. Financial institutions are often hesitant to provide loans due to perceived risks. Developing financial mechanisms and incentives to support mining investments is crucial for sector development.

To address these challenges, Nigeria must adopt inclusive social policies that prioritize community engagement, ensure fair distribution of benefits, and mitigate the negative impacts of mining on local populations. The establishment of community development agreements (CDAs) between mining companies and host communities, similar to those used in Canada's mining sector, could help improve relations and promote sustainable development in mining regions [54].

Nigeria's mining sector has the potential to drive economic growth and diversification. However, achieving this potential requires addressing significant challenges related to environmental degradation, technological gaps, and social impacts. Current sustainability initiatives, such as environmental regulations and safer mining projects, represent important steps in the right direction. However, stronger enforcement of regulations, investment in climate-smart technologies, and improved community engagement are essential for Nigeria to transition from sustainable mining to climate-smart mining. By adopting best

practices from global mining leaders and investing in innovation, Nigeria can create a mining sector that contributes to long-term sustainability and climate resilience.

## **Analysis of Existing Policies in Nigeria's Mining Sector**

### **Nigerian minerals and mining Act (2007)**

The Nigerian Minerals and Mining Act of 2007 remains the primary legislation governing the exploration, exploitation, and management of Nigeria's mineral resources. The Act aims to regulate the sector by promoting private sector investment, ensuring transparency in licensing, and setting out procedures for environmental management in mining operations [49]. The law mandates that mining companies conduct Environmental Impact Assessments (EIAs) and implement Environmental Management Plans (EMPs) before commencing operations. These requirements are designed to mitigate the adverse environmental impacts of mining activities. The Act also encourages community participation and the signing of Community Development Agreements (CDAs) between mining companies and host communities to ensure that local populations benefit from mining operations [53]. Additionally, the Act provides for the reclamation and rehabilitation of mined-out lands, reflecting the growing emphasis on sustainable mining practices.

### **National minerals and metals policy (2008)**

The National Minerals and Metals Policy of 2008 complements the Mining Act by providing a strategic roadmap for the development of the sector. The policy emphasizes economic diversification, the development of the solid minerals sector, and the promotion of local value addition. It also highlights the importance of environmental sustainability, focusing on the need for environmental safeguards, efficient resource use, and the minimization of mining-related pollution [48].

### **Environmental regulatory frameworks**

In addition to the Mining Act and the National Minerals and Metals Policy, several environmental regulations apply to Nigeria's mining sector. The National Environmental Standards and Regulations Enforcement Agency (NESREA) is responsible for enforcing environmental laws in the country. NESREA's regulations target air quality control, water pollution, hazardous waste management, and biodiversity conservation in mining areas (NESREA). The agency collaborates with the Ministry of Mines and Steel Development (MMSD) to ensure that mining activities are carried out in an environmentally responsible manner.

## **Gaps in Sustainable and Climate-Smart Mining Policies**

### **Lack of focus on climate-smart mining (CSM)**

One of the most significant gaps in Nigeria's regulatory framework is the lack of explicit provisions for climate-smart mining (CSM). While the Nigerian Minerals and Mining Act and other relevant policies promote sustainable mining practices, they do not specifically address the integration of climate mitigation and adaptation strategies into mining operations. This includes the use of renewable energy, carbon capture technologies, and the circular economy in mining activities. For example, countries like Chile and Canada have integrated renewable energy into their mining sectors to reduce carbon emissions, while Nigeria's regulatory framework does not mandate or incentivize the adoption of renewable energy solutions in mining [37]. Similarly, Nigeria's policies lack provisions for the application of carbon capture and storage (CCS) technologies, which could play a crucial role in reducing the environmental footprint of high-emission mining activities, such as coal extraction.

### **Weak Enforcement of Environmental Regulations**

Another critical gap in Nigeria's mining policy framework is the weak enforcement of existing environmental regulations. Despite the requirements for EIAs and EMPs under the Nigerian Minerals and Mining Act, many mining companies, particularly artisanal and small-scale miners, fail to comply with these regulations. This non-compliance is due in part to the limited capacity of regulatory agencies such as NESREA and the Mines Inspectorate Department (MID), which are often underfunded and understaffed [50]. The lack of effective enforcement mechanisms has resulted in widespread environmental degradation, including deforestation, land degradation, water pollution, and loss of biodiversity in mining regions [47]. This situation underscores the need for more robust regulatory oversight and capacity-building for enforcement agencies to ensure compliance with sustainability standards.

### **Limited integration of social and environmental considerations**

While the Nigerian Minerals and Mining Act includes provisions for CDAs between mining companies and host communities, the Act does not provide detailed guidelines on how to ensure equitable benefit-sharing or the effective mitigation of social impacts. In practice, many mining communities in Nigeria remain marginalized, with limited access to the economic benefits of mining activities [53]. Moreover, mining-induced displacement and loss of livelihoods are common issues that are inadequately addressed by the existing regulatory framework. To align with

global best practices, Nigeria's mining policies should integrate social sustainability into mining operations more effectively. For instance, Canada's mining regulations include provisions for Impact and Benefit Agreements (IBAs), which ensure that indigenous communities receive fair compensation and employment opportunities from mining projects [30]. A similar approach could be adopted in Nigeria to ensure that mining operations contribute positively to local communities.

### **Inadequate incentives for innovation and technology adoption**

Nigeria's mining policies currently lack adequate incentives to encourage the adoption of innovative technologies that can enhance sustainability and climate-smart practices. In countries like Peru and South Africa, governments provide financial incentives, tax breaks, and grants to mining companies that adopt green technologies, such as energy-efficient equipment, waste recycling systems, and renewable energy solutions [40]. In contrast, Nigeria's mining sector has yet to implement policies that encourage technological innovation. Without incentives for the private sector to invest in cleaner technologies, the transition to climate-smart mining remains slow. This gap highlights the need for Nigeria to introduce policies that promote research and development in sustainable mining technologies and offer financial support to mining companies that prioritize environmental sustainability.

## **Recommendations for Strengthening Nigeria's Mining Policy Framework**

### **Incorporating climate-smart mining into policy**

To close the gaps in Nigeria's regulatory framework, there is a need to explicitly incorporate climate-smart mining (CSM) strategies into existing policies. This could include introducing provisions that mandate the use of renewable energy sources, such as solar and wind power, in mining operations. Additionally, policies should promote the adoption of carbon capture technologies to reduce emissions from high-carbon mining activities. The government can also encourage the use of circular economy principles, which focus on reducing waste, recycling materials, and reusing water in mining processes. For example, Chile has implemented circular economy initiatives that recycle mine tailings and reprocess waste materials to reduce the environmental burden of mining [43]. Adopting similar practices in Nigeria could improve resource efficiency and reduce the environmental impact of mining.

### **Enhancing enforcement of environmental regulations**

Strengthening the enforcement of environmental regulations is critical to ensuring that mining activities in Nigeria are conducted sustainably. This could involve increasing funding and capacity-building for regulatory agencies, such as NESREA and the Mines Inspectorate Department. These agencies should also have access to modern monitoring technologies, such as remote sensing and satellite imagery, to track environmental changes in mining regions and ensure compliance with regulations [50]. Additionally, penalties for non-compliance should be made more stringent, and there should be clear mechanisms for holding mining companies accountable for environmental violations. Establishing an independent oversight body could also enhance transparency and accountability in the enforcement process.

### **Promoting social and environmental justice in mining**

To ensure that mining contributes to sustainable development, Nigeria's regulatory framework should place greater emphasis on social and environmental justice. This includes ensuring that mining communities receive a fair share of the economic benefits generated by mining operations. The government can introduce legislation that mandates the establishment of community development funds, which mining companies would contribute to as part of their corporate social responsibility (CSR) initiatives. Furthermore, the framework should include detailed guidelines for the negotiation of CDAs, with a focus on equitable benefit-sharing, community engagement, and compensation for any negative social or environmental impacts. Nigeria's mining policy and regulatory framework provides a foundation for sustainable mining, but it requires significant enhancements to align with climate-smart mining practices. Existing policies, such as the Nigerian Minerals and Mining Act, focus on environmental sustainability, but they lack specific provisions for integrating climate-smart technologies and practices. Weak enforcement of regulations and the limited focus on social and environmental justice also present challenges. By incorporating global best practices, strengthening enforcement mechanisms, and incentivizing innovation, Nigeria can create a mining sector that balances economic growth with environmental and social sustainability.

### **Lessons from global experiences: pathway for Nigeria**

The global mining industry is undergoing a significant transformation, with a shift towards more sustainable and climate-smart mining (CSM) practices. Countries such as Chile, Canada, and Australia have made substantial progress in integrating renewable energy, reducing carbon emissions, and enhancing energy efficiency in their mining sectors. For Nigeria, which is rich in mineral resources but faces significant environmental and socio-economic challenges in its mining sector, these global experiences provide valuable lessons. This section explores the integration of

climate-smart mining practices in Nigeria, the feasibility of renewable energy use in Nigerian mines, and opportunities for reducing carbon emissions and enhancing energy efficiency.

### **Integration of climate-smart mining practices in Nigeria**

Climate-smart mining (CSM) practices encompass the adoption of low-carbon technologies, the use of renewable energy, resource efficiency, and the reduction of environmental impacts such as water and land use. The global mining industry has begun to embrace CSM strategies, driven by international climate commitments and the need to reduce the environmental footprint of mining activities [10]. Nigeria, however, has been slower to adopt these practices due to regulatory gaps, technological limitations, and financial constraints.

### **Global Best Practices in Climate-Smart Mining**

Countries like Chile, Canada, and Australia have taken significant steps toward integrating climate-smart practices in their mining sectors. For instance, in Chile, the mining sector has increasingly incorporated solar energy into its operations to reduce reliance on fossil fuels and cut down on carbon emissions [37]. The Collahuasi Copper Mine in Chile is a prime example of renewable energy integration, as it runs a significant portion of its operations on solar power, reducing its carbon footprint while maintaining productivity.

In Canada, mining companies are utilizing electric vehicles (EVs) for underground operations, which not only reduces greenhouse gas (GHG) emissions but also improves worker safety by reducing harmful diesel emissions underground [35]. The country has also invested heavily in carbon capture and storage (CCS) technologies to reduce emissions from mining activities, particularly in the oil sands sector.

These global examples demonstrate that the transition to CSM is not only feasible but can also enhance operational efficiency, reduce costs in the long term, and improve environmental outcomes. Nigeria can leverage these lessons to integrate CSM practices into its own mining sector.

### **Current Efforts and Challenges in Nigeria**

While Nigeria has not yet fully embraced CSM, some initiatives signal a shift towards more sustainable practices. The Safer Mining Project, for example, has promoted mercury-free gold mining in artisanal and small-scale mining (ASM) operations [51]. However, Nigeria's mining sector remains heavily reliant on traditional methods, and there is little investment in renewable energy or advanced technology solutions.

Challenges such as limited access to finance, weak regulatory enforcement, and insufficient technological capacity have hindered

the large-scale adoption of CSM in Nigeria. Additionally, the lack of incentives for mining companies to adopt green technologies remains a significant barrier [49]. Addressing these challenges will require stronger policy support, investment in technological innovation, and the development of public-private partnerships to promote climate-smart solutions.

### **Feasibility of Renewable Energy Use in Nigerian Mines**

One of the critical components of CSM is the use of renewable energy in mining operations. Globally, the mining sector has turned to renewable energy sources, such as solar, wind, and hydroelectric power, to reduce dependence on fossil fuels and lower carbon emissions. The feasibility of renewable energy in Nigerian mines depends on several factors, including geographic potential, investment costs, and policy support.

### **Global Examples of Renewable Energy in Mining**

In regions like Latin America, the integration of renewable energy into mining has seen significant success. For instance, in Peru and Chile, solar energy is extensively used in copper mining operations, which are energy-intensive and have traditionally relied on coal and diesel power [55]. The development of large-scale solar farms near mining sites has not only reduced emissions but also provided a more stable and cost-effective energy supply. In Australia, the DeGrussa Copper-Gold Mine became the first mine in the country to incorporate a solar power and battery storage system to meet a substantial portion of its energy demand. The project has reduced diesel consumption by over 5 million liters annually, significantly cutting down emissions [56].

### **Potential for Renewable Energy in Nigeria**

Nigeria is well-positioned to harness renewable energy for its mining sector, given its abundant solar resources. The northern region of Nigeria, where much of the country's mining activities are concentrated, receives an average solar radiation of about 5.5–6.5 kWh/m<sup>2</sup> per day [57]. This makes solar energy a viable option for powering mining operations in states such as Zamfara, Kano, and Kaduna, which are rich in gold, tin, and other minerals. However, the adoption of renewable energy in Nigerian mines is currently limited due to the high upfront capital costs and lack of supportive infrastructure. Most mining companies rely on diesel generators for energy, which is both expensive and environmentally harmful [50]. To make renewable energy more feasible, Nigeria needs to provide financial incentives, such as tax credits or grants, for mining companies to invest in solar power systems. Additionally, partnerships between the government and

international development agencies could help finance the construction of renewable energy infrastructure near mining sites.

### **Policy Support for Renewable Energy in Mining**

The Nigerian government's National Renewable Energy and Energy Efficiency Policy (NREEEP)(2015) sets the stage for promoting renewable energy across sectors, including mining. The policy aims to increase the share of renewable energy in the national energy mix and promote the use of decentralized renewable energy solutions. However, specific guidelines and incentives for the mining sector are still lacking. To accelerate the adoption of renewable energy in the mining sector, the government should introduce targeted policies that encourage the integration of solar and wind energy into mining operations. These policies could include feed-in tariffs for renewable energy generated at mining sites and subsidies for solar equipment.

### **Opportunities for Reducing Carbon Emissions and Enhancing Energy Efficiency**

Reducing carbon emissions and enhancing energy efficiency are critical components of climate-smart mining. Global experiences demonstrate that mining companies can significantly lower their carbon footprints through technological innovations, such as energy-efficient equipment, electric vehicles, and carbon capture and storage (CCS) technologies. For Nigeria, there are several opportunities to reduce emissions and improve energy efficiency in the mining sector.

### **Energy Efficiency in Mining Operations**

Energy efficiency measures, such as the use of energy-efficient grinding and milling technologies, can substantially reduce energy consumption in mining operations. In South Africa, energy-intensive mines have adopted high-efficiency motors and automated systems to monitor and control energy use, leading to reductions in both energy costs and emissions (Chamber of Mines of South Africa). In Nigeria, energy consumption in mining operations remains high due to outdated equipment and inefficient processes. Upgrading to more energy-efficient technologies can reduce operational costs and improve competitiveness in the mining sector. The government can play a role in facilitating access to energy-efficient equipment by offering low-interest loans or grants to mining companies that invest in upgrading their machinery.

### **Carbon Capture and Storage (CCS)**

Carbon capture and storage (CCS) technologies offer a promising solution for reducing emissions from mining operations, particularly those that involve the extraction of high-carbon

minerals such as coal. Canada has been a leader in this area, with several mining companies adopting CCS technologies to capture and store carbon dioxide emissions generated during extraction and processing [35]. For Nigeria, CCS technology could be particularly beneficial in coal mining, which contributes significantly to the country's carbon emissions. However, the adoption of CCS requires substantial investment and technological expertise, both of which are currently lacking in Nigeria. International partnerships and technology transfer initiatives could help bridge this gap and enable Nigerian mining companies to adopt CCS technologies in the future.

### **Circular Economy in Mining**

The circular economy offers another opportunity for reducing carbon emissions and minimizing environmental impacts. By reusing and recycling materials, mining companies can reduce waste, lower energy consumption, and enhance resource efficiency. Countries like Chile and Australia have embraced circular economy principles in mining by reprocessing mine tailings and recycling water used in mineral processing [43]. Nigeria can integrate circular economy practices into its mining sector by promoting the recycling of mine waste and encouraging companies to adopt water-efficient technologies. This will require the development of policies that incentivize waste recycling and the establishment of infrastructure to support circular mining practices. Global experiences in climate-smart mining offer valuable lessons for Nigeria as it seeks to transition to more sustainable mining practices. The integration of renewable energy into mining operations, the adoption of energy-efficient technologies, and the reduction of carbon emissions through CCS and circular economy practices are critical pathways for Nigeria. While challenges such as high capital costs and regulatory gaps exist, the potential for renewable energy use in Nigerian mines and the opportunities for reducing emissions make climate-smart mining feasible. By learning from global leaders in the mining sector and creating a supportive policy environment, Nigeria can take significant strides towards achieving a more sustainable and climate-resilient mining sector.

### **Challenges and Opportunities for Transition to Climate-Smart Mining in Nigeria**

The transition from traditional mining practices to climate-smart mining (CSM) presents both challenges and opportunities for Nigeria. This review focuses on the economic and infrastructural constraints faced by Nigeria in its mining sector, the financial investments needed to support climate-smart mining, and the challenges in upgrading infrastructure and energy supply. By examining these factors, this section provides insights into the

feasibility of transitioning to CSM and identifies areas where Nigeria can leverage global best practices to overcome these challenges.

### **Economic and Infrastructural Constraints**

One of the major obstacles to transitioning to climate-smart mining in Nigeria is the economic and infrastructural constraints that the country's mining sector faces. Unlike countries with more developed mining industries, Nigeria's mining sector has historically been underfunded and underdeveloped, relying primarily on artisanal and small-scale mining (ASM). These conditions have created significant barriers to the adoption of sustainable and climate-friendly mining practices.

### **Underdeveloped Infrastructure**

Nigeria's mining infrastructure is underdeveloped, making it difficult to implement the advanced technologies and practices necessary for climate-smart mining. Most mining operations, especially ASM, still rely on outdated equipment and manual labor, which are inefficient and environmentally harmful [53]. Additionally, the lack of adequate transportation and logistics infrastructure hampers the movement of minerals, equipment, and energy resources, further increasing operational costs [48]. In countries such as Chile and Australia, the availability of modern infrastructure - such as power grids, efficient transportation networks, and communication systems - has facilitated the adoption of renewable energy and other CSM practices [37]. Nigeria will need to make significant investments in upgrading its mining infrastructure to create a conducive environment for climate-smart mining.

### **Energy Supply Issues**

Energy supply is a critical component of mining operations, and Nigeria's unreliable energy infrastructure poses a significant challenge. Mining operations in Nigeria are heavily dependent on diesel-powered generators, which are costly and environmentally damaging due to high carbon emissions [50]. The lack of access to reliable grid electricity in many mining regions has limited the potential for renewable energy integration, such as solar and wind power, which could help reduce the sector's carbon footprint. The global trend toward renewable energy in mining has been driven by countries with robust energy infrastructure. For example, Australia's DeGrussa Copper-Gold Mine relies on a combination of solar power and battery storage systems to reduce its reliance on diesel fuel [56]. For Nigeria, overcoming energy supply issues will require significant investments in expanding grid connectivity and developing renewable energy infrastructure in mining regions.

### **Financial Investments Needed for Climate-Smart Mining**

Transitioning to climate-smart mining will require substantial financial investments. These investments are necessary to modernize equipment, upgrade infrastructure, develop renewable energy sources, and implement advanced technologies that can reduce carbon emissions and enhance energy efficiency.

### **Costs of upgrading mining technologies**

Implementing climate-smart mining practices involves upgrading existing technologies to more energy-efficient and environmentally friendly alternatives. For instance, replacing diesel-powered equipment with electric vehicles (EVs) or hybrid systems, as seen in Canada and Australia, can significantly reduce greenhouse gas (GHG) emissions and improve air quality in underground mines [35]. However, the high upfront costs of acquiring new technologies, as well as the additional costs associated with training personnel and maintaining equipment, present a financial challenge for Nigerian mining companies. Most Nigerian mining companies, particularly those in the artisanal and small-scale mining sector, lack access to the necessary capital to invest in climate-smart technologies (Garba, 2018). The government will need to provide financial incentives, such as grants, low-interest loans, or tax credits, to encourage mining companies to invest in sustainable technologies. Additionally, international development agencies and private investors could play a crucial role in financing the transition by providing funding and technical support for green mining projects.

### **Investment in renewable energy infrastructure**

Renewable energy is a key component of climate-smart mining, but developing renewable energy infrastructure requires significant financial investment. In countries like Chile, mining companies have invested in large-scale solar farms to power their operations, reducing reliance on fossil fuels and lowering emissions [37]. The cost of developing similar renewable energy projects in Nigeria could be prohibitively high, especially for smaller mining companies. To make renewable energy more accessible, Nigeria will need to develop public-private partnerships that can finance the construction of solar and wind energy facilities near mining sites. International organizations, such as the World Bank and the International Renewable Energy Agency (IRENA), have supported renewable energy initiatives in developing countries and could help Nigeria finance its transition to climate-smart mining [10].

### **Challenges in securing investment**

Nigeria's mining sector has historically struggled to attract large-scale investments, due to a combination of regulatory uncertainty,

political instability, and poor infrastructure [47]. Without substantial investment, the transition to climate-smart mining will be difficult to achieve. The Nigerian government will need to create an enabling environment for investors by ensuring regulatory stability, reducing bureaucratic hurdles, and offering attractive financial incentives. In addition, Nigeria can look to global examples of successful investment models. For instance, South Africa's Mining and Renewable Energy Program has attracted private investment through government-backed initiatives that provide financial guarantees and technical support to renewable energy projects in the mining sector (Chamber of Mines of South Africa). Nigeria could adopt similar strategies to attract both local and international investors to support its climate-smart mining transition.

### **Challenges in Upgrading Infrastructure and Energy Supply**

As previously noted, the infrastructure challenges in Nigeria's mining sector are significant barriers to climate-smart mining. The key areas where Nigeria must focus its efforts include modernizing transportation and energy infrastructure and ensuring that mining companies have access to reliable and sustainable energy sources.

#### **Upgrading Transportation Infrastructure**

Efficient transportation infrastructure is essential for the mining industry, as it facilitates the movement of minerals, machinery, and other resources. However, many of Nigeria's mining regions, particularly in the northern and central parts of the country, lack adequate roads, railways, and ports. This makes it difficult to transport heavy machinery and materials to mining sites and increases the costs of mining operations [50]. Global mining leaders, such as Canada and Australia, have developed well-established transportation networks that support their mining industries, enabling the efficient movement of goods and resources while minimizing operational costs [35]. Nigeria will need to make substantial investments in transportation infrastructure, including the development of new roads, railways, and ports, to support its mining sector's transition to climate-smart practices.

#### **Energy Infrastructure Challenges**

Nigeria's energy infrastructure, particularly its power generation and distribution systems, is another critical challenge. Many of Nigeria's mining operations rely on off-grid diesel generators due to the lack of reliable access to electricity. This reliance on diesel power is both costly and environmentally unsustainable. To facilitate the transition to climate-smart mining, Nigeria must focus on improving access to grid electricity and expanding renewable energy infrastructure. The development of decentralized renewable

energy systems, such as solar mini-grids and wind farms, could provide reliable and sustainable energy sources for mining operations in remote areas [57]. Moreover, the government can introduce policies that incentivize the integration of renewable energy into mining operations, such as feed-in tariffs and subsidies for renewable energy projects.

### **Opportunities for Transition to Climate-Smart Mining**

Despite the challenges, Nigeria has significant opportunities to transition to climate-smart mining. The country's rich solar resources, the growing global demand for green minerals, and the potential for international collaboration create opportunities for Nigeria to adopt climate-smart practices.

#### **Harnessing Solar Energy for Mining Operations**

Nigeria has abundant solar resources, particularly in its northern region, where most mining activities are concentrated. By investing in solar power infrastructure, Nigeria can significantly reduce its reliance on diesel-powered generators and lower carbon emissions. Countries like Chile have successfully integrated solar power into their mining operations, with large-scale solar farms providing a stable and cost-effective energy supply (IRENA, 2020). Nigeria can follow this model by encouraging private investment in solar energy and creating a regulatory environment that supports renewable energy integration in the mining sector.

#### **Tapping into Global Demand for Green Minerals**

The global shift towards renewable energy and electric vehicles has increased the demand for green minerals, such as lithium, cobalt, and rare earth elements. Nigeria, with its vast mineral resources, is well-positioned to supply these critical minerals. By adopting climate-smart mining practices, Nigeria can enhance its competitiveness in the global market for green minerals and attract investment from multinational companies looking for sustainable mineral sources [10].

#### **International Collaboration and Knowledge Transfer**

International collaboration presents a valuable opportunity for Nigeria to transition to climate-smart mining. Countries like Canada and South Africa have implemented successful climate-smart mining initiatives, and Nigeria can benefit from knowledge transfer and technology sharing through partnerships with these countries. Additionally, international organizations such as the World Bank, the African Development Bank, and IRENA can provide financial and technical support for Nigeria's climate-smart mining projects. The transition to climate-smart mining in Nigeria

presents both significant challenges and exciting opportunities. Economic and infrastructural constraints, such as underdeveloped mining infrastructure and unreliable energy supply, are major barriers to the adoption of sustainable practices. However, the growing global demand for green minerals, Nigeria's abundant solar resources, and the potential for international collaboration create opportunities for Nigeria to successfully transition to climate-smart mining. To overcome the challenges, Nigeria will need to make substantial financial investments in modernizing its mining sector, upgrading infrastructure, and expanding renewable energy capacity. By learning from global best practices and creating a supportive policy environment, Nigeria can position itself as a leader in sustainable and climate-smart mining in Africa.

## Conclusion

The transition from sustainable mining to climate-smart mining is critical for Nigeria as it seeks to balance economic growth with environmental stewardship. Climate-smart mining offers a path to reduce the mining sector's environmental footprint while improving resilience to climate change. By adopting energy-efficient technologies, reducing greenhouse gas emissions, and integrating sustainable practices such as ecosystem restoration, Nigeria can position its mining industry to contribute meaningfully to a low-carbon economy. The findings of the study revealed that realizing this transition will require significant policy reforms, investment in modern technologies, and a commitment to stronger regulatory oversight. Collaboration between government, industry, and local communities is essential to ensure that climate-smart mining practices are effectively implemented and beneficial to all stakeholders. Lessons from other countries show that this shift is achievable with the right mix of innovation, regulatory frameworks, and public-private partnerships. In conclusion, adopting climate-smart mining in Nigeria presents an opportunity to transform the sector into a driver of sustainable development. Through proactive measures and strategic planning, the country can not only reduce its environmental impact but also position itself as a leader in environmentally conscious resource extraction [58-60].

## Recommendations

**Based on the findings of the study, the following recommendations were made**

1. There is need for the government to strengthen existing environmental regulations and amend the Minerals and Mining Act 2007 to require the adoption of renewable energy, carbon capture technologies, and energy-efficient practices in mining operations. The amendment should include provisions for climate change mitigation, set

emissions reduction targets, and promote circular economy practices.

2. Enhanced Monitoring and Enforcement: Establish an independent Environmental Mining Compliance Agency (EMCA) with the authority to enforce compliance, conduct regular audits, and impose penalties for non-compliance.
3. Revise Environmental Impact Assessments (EIAs): Update the Environmental Impact Assessment Act to include climate impact assessments and mandatory climate mitigation plans for new mining projects.
4. Introduce New Laws such as Climate-Smart Mining and Renewable Energy Integration Act: Create legislation mandating the use of renewable energy sources in mining operations and provide tax incentives, grants, and subsidies for green technology investments.
5. Carbon Pricing and Emission Reduction in Mining Act: Implement a carbon tax or cap-and-trade system for mining companies to incentivize reductions in greenhouse gas emissions, with revenue reinvested in renewable energy and community development.
6. ASM Climate-Smart Development Act: Enact a law to formalize artisanal and small-scale mining (ASM), offering support for sustainable practices, mercury-free technologies, and renewable energy use.
7. National Energy Policy: Update to incorporate renewable energy integration for mining operations, set energy efficiency targets, and provide incentives for renewable energy projects in mining regions.
8. Financial Incentives for Climate-Smart Investments: Establish a Climate-Smart Mining Fund to offer low-interest loans, grants, and tax breaks for investments in green technologies and renewable energy by mining companies.

Capacity Building for Regulatory Agencies: Develop training programs for regulatory agencies on climate-smart practices, enforcement tools, and collaboration with international organizations to enhance regulatory effectiveness.

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