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Geo-environmental and socio-economic impacts of artisanal and small-scale mining in Ethiopia: challenges, opportunities, and sustainable solutions

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Artisanal and Small-scale Mining (ASM) in Ethiopia plays a vital role in the national economy, contributing significantly to foreign exchange earnings and employment, particularly in rural regions such as Oromia and Benishangul-Gumuz. It provides livelihoods for millions, with many households experiencing enhanced income levels compared to those reliant solely on agriculture. However, ASM is accompanied by substantial geo-environmental and socio-economic challenges that pose risks to both the environment and local communities. These challenges include widespread environmental degradation, pollution, health hazards, and social issues such as child labor and poor working conditions. This review aims to systematically evaluate the key impacts of ASM in Ethiopia, focusing on both its socio-economic benefits and the environmental consequences. A comprehensive literature search was conducted across academic databases including Google Scholar, Scopus, Web of Science, PubMed and Science direct, utilizing keywords like "artisanal mining," "small-scale mining," "geo-environmental impacts," "socio-economic challenges," "sustainable practices," and "Ethiopia." Studies published between 2015 and 2024 were selected based on relevance and rigor, and findings were synthesized into themes covering environmental impacts, health risks, socio-economic benefits, and barriers to sustainable practices. The review reveals that while ASM contributes positively to the economy, particularly in rural areas, it also leads to severe geo-environmental consequences such as soil erosion, mercury contamination, water pollution, deforestation, and biodiversity loss. Additionally, health risks, including respiratory issues and HIV prevalence, and socio-economic challenges, including child labor and high school dropout rates, are prevalent in mining regions. Despite existing regulatory efforts, inconsistent enforcement, limited capacity, and lack of resources hinder the effectiveness of policies. The findings emphasize the need for balanced, sustainable solutions that address the economic benefits of ASM while mitigating its environmental and socio-economic costs. Strengthening regulations, adopting cleaner technologies,

improving health and safety standards, and enhancing community engagement are critical to ensuring the long-term sustainability of ASM in Ethiopia.

KEYWORDS

artisanal mining, Ethiopia, geo-environmental impacts, socio-economic challenges, sustainable practices

1 Introduction

Artisanal and Small-scale Mining (ASM) is a key economic activity that plays a pivotal role in providing livelihoods to millions globally, especially in developing countries. The International Labour Organization (ILO) estimates that over 40 million people are directly involved in ASM, with an additional 150 million depending on mining-related industries (ILO, 2021). Despite its economic importance, ASM is often characterized by informal practices, employing low-tech and labor-intensive methods that contrast sharply with large-scale industrial mining operations. While ASM significantly contributes to local economies, particularly in regions where formal employment is scarce, it also presents a range of environmental and social challenges (Alemu, 2018; Abebil et al., 2023).

Globally, ASM's impact is multifaceted. It is associated with considerable geo-environmental degradation, including deforestation, land erosion, water contamination, and habitat destruction (Fritz et al., 2022). For example, ASM activities in the Amazon Basin have been linked to deforestation rates as high as 4% annually, significantly affecting biodiversity and ecosystem services (Álvarez-Berríos et al., 2021). Furthermore, mercury contamination resulting from gold extraction has become an alarming global concern, with an estimated 1,000 tons of mercury released annually into the environment due to ASM operations (UNEP, 2022). The socio-economic impact of ASM is equally complex; while it provides crucial income and employment in rural areas, it is also associated with poor working conditions, health risks, and social challenges, including high rates of occupational injuries, fatalities, and the spread of diseases such as HIV/AIDS in regions like Ghana (Hilson et al., 2021). Moreover, the informal nature of ASM often leads to inadequate regulatory frameworks, further exacerbating the environmental and health concerns (Nursamsi et al., 2024).

In Africa, ASM is a significant economic activity, particularly in rural areas where formal employment opportunities are scarce (Mimba et al., 2023). The environmental consequences of ASM in these regions are severe, with the sector contributing to widespread deforestation, land degradation, and water pollution (Moyo et al., 2022). For instance, in the Democratic Republic of the Congo, gold mining has been linked to extensive environmental degradation, impacting biodiversity (Otamonga and Poté, 2020). In Ethiopia, ASM has a long-standing history, particularly in gold mining, and continues to be a crucial sector for the country's economy, employing over a million individuals, primarily in rural areas with limited alternative income sources (Hailemariam, 2024). Ethiopia's ASM sector is a significant contributor to the country's gold exports, underscoring its economic importance (Keili et al., 2021). However, the informal nature of ASM and the absence of adequate regulatory oversight have resulted in substantial environmental challenges, such as deforestation, soil erosion, and water pollution (Yihdego et al., 2018).

Ethiopia's rich mineral resources, coupled with its growing reliance on ASM, make the sector's geo-environmental impacts particularly pronounced (Mudau, 2019). The country is home to diverse and fragile ecosystems that are highly susceptible to land degradation and climate change (Teku and Eshetu, 2024). Given the centrality of agriculture and natural resources to Ethiopia's economy and food security, the degradation of land and water resources by ASM presents a critical challenge to the nation's sustainable development goals (Chaka and Rupprecht, 2024). In this context, it is essential to explore the socio-economic dynamics influencing ASM activities, the challenges associated with environmental degradation, and the opportunities for implementing sustainable practices within the sector (Etefa, 2019). This review aims to critically assess the geo-environmental and socio-economic impacts of ASM in Ethiopia. By examining the environmental degradation caused by ASM, the review underscores the urgent need for sustainable solutions that balance the economic benefits of the sector with the imperative of environmental protection. Furthermore, this study seeks to explore the socio-economic drivers behind ASM activities in Ethiopia and to identify potential pathways for enhancing environmental stewardship in the sector. In light of Ethiopia's socio-economic context, marked by poverty and limited access to formal employment, this review is both timely and relevant, addressing a crucial issue that lies at the intersection of economic development and environmental sustainability in the Ethiopian ASM sector.

2 Overview of artisanal and small-scale mining (ASM) in Ethiopia

2.1 Definition and characteristics

ASM in Ethiopia is an informal, labor-intensive sector where individuals or small groups mine using rudimentary tools and techniques (Nyssen and Kiros, 2022. This contrasts sharply with large-scale industrial mining operations that rely on advanced technologies. The focus of ASM in Ethiopia is on precious minerals such as gold, tantalum, and gemstones, with gold being the most significant (Hailemariam, 2023). Other minerals include opals, sapphires, and industrial minerals like salt and gypsum (Kyngdon-McKay et al., 2016). Most ASM operations are informal, lacking formal recognition or government licensing, which restricts miners' access to legal markets and technical support, and makes them vulnerable to exploitation by middlemen (Hailemariam, 2024). The miners, many of whom are from marginalized communities such as women and youth, are typically unskilled, with many

operations being family-based (Kebeta Djigsa, 2021). The methods used, like panning, sluicing, and hand-dug pits, are low-cost but environmentally unsustainable, often leading to significant land degradation, low productivity, and high labor intensity (Yihdego et al., 2018).

2.2 Regulatory framework and policy landscape

In response to the growing significance of ASM in Ethiopia, the government has sought to regulate the sector through policies and legislative frameworks, such as the Mining Operations Proclamation (2010, 2013). These frameworks aim to address key issues like environmental degradation, miners' safety, and the legal rights of ASM workers. The National ASM Policy (2018) also highlights the importance of integrating ASM into the formal economy by providing technical support, facilitating credit access, and promoting equitable benefits for mining communities. Despite these advancements, challenges persist in implementation, such as poor enforcement of regulations and structural issues within policy design that hinder the sector's potential (Hailemariam, 2024).

2.3 Socio-economic contributions of ASM

ASM is a critical contributor to Ethiopia's economy, accounting for approximately 65% of the nation's foreign exchange earnings and directly employing around 1.3 million people (Alemu, 2018). Moreover, it provides a livelihood for an estimated 7.5 million individuals, with households engaged in ASM in regions such as Oromia and Benishangul-Gumuz experiencing a 30%–40% increase in income compared to those reliant solely on agriculture (Tessema et al., 2024). For marginalized groups, especially women, ASM provides an essential source of income (Getaneh and Shikur, 2022). The sector contributes significantly to the national economy, especially through gold exports, which form a major part of Ethiopia's foreign exchange earnings. However, the benefits of ASM are tempered by fluctuating commodity prices, exploitative middlemen, and limited access to financial services due to the sector's informal nature (Hagos et al., 2016). Despite these hurdles, the sector has lifted many households out of poverty, with some regions seeing a significant increase in income compared to agricultural-only households (Hassen, 2022, February).

2.4 Interplay between ASM and ecosystem dynamics

ASM in Ethiopia has profound effects on ecosystems, particularly in sensitive areas like forests, riverbanks, and highlands (Weleabzgi et al., 2021). Common environmental impacts include deforestation, soil erosion, and water pollution, often exacerbated by unregulated mining practices (Lemessa et al., 2022). The clearing of land for mining disrupts habitats, threatens biodiversity, and undermines ecosystem services. Additionally, toxic chemicals such as mercury used in gold extraction contaminate water sources, affecting aquatic life and the health of local communities (Abate and Sisay, 2024). However, the relationship between ASM and ecosystems is not entirely negative. By adopting environmentally friendly mining practices, such as alternative processing methods and land rehabilitation, the sector can reduce its ecological footprint and contribute positively to local development (Lemessa et al., 2022). Formalizing ASM through better policies and regulations can also encourage sustainable practices, providing miners with the necessary support to protect the environment while continuing to benefit economically (Abate and Sisay, 2024). The key to achieving this balance lays in integrating conservation efforts with sustainable mining, ensuring both environmental protection and economic growth.

3 Geology and geographical distribution ASM in Ethiopia

Ethiopia's breathtaking and varied landscapes, from towering plateaus to rugged mountain ranges and deep valleys are crucial to the development and distribution of ASM across the country Yihdego et al., 2018). The country's topography, shaped by the majestic Ethiopian Highlands and the Great Rift Valley, has created ideal conditions for mineral-rich deposits that attract miners (Wolearegay et al., 2025). The highlands often referred to as the "Roof of Africa," rise over 4,000 m, while the Rift Valley divides Ethiopia into western and eastern plateaus, creating distinct geological environments (Mudau, 2019). Ethiopia's geology is largely defined by the ancient Arabian-Nubian Shield, a region rich in Precambrian rocks that are home to valuable minerals like gold and base metals (Mulaba-Bafubiandi et al., 2023). The western and northern parts of the country, in particular, are abundant in gold, making them central to artisanal mining activities (Mudau, 2019). On the other hand, the volcanic and sedimentary rocks of the Rift Valley host gemstones like opal, adding a sparkle to the ASM industry (Mulaba-Bafubiandi et al., 2023). These geological features ranging from volcanic belts to sedimentary basins give Ethiopia a diverse mix of mineral resources that support the livelihoods of many artisanal miners (Denkayhu and Gondar, 2017).

However, Ethiopia's rugged topography presents both opportunities and challenges. While mineral deposits are often accessible on the surface and near the ground, the steep and often unstable landscapes pose difficulties for miners (Fenta, 2017). Mining in remote areas makes transportation difficult, and implementing sustainable mining practices is a challenge. In fact, steep terrains are prone to rock collapses, landslides, and subsidence, leading to dangerous conditions for miners (Etefa, 2019). Tragically, in 2021 and 2022, several fatal accidents occurred in mining areas like the Wadla Delanta opal mining site, highlighting the hazards of ASM in these regions (Getaneh and Shikur, 2022). Despite these risks, Ethiopia's unique geological setting continues to draw artisanal miners eager to access valuable surface and near-surface deposits (Chaka and Rupprecht, 2024). The widespread geographic distribution of ASM across Ethiopia can be seen, especially in regions with rich mineral deposits, like the greenstone belts, which are known for gold and other metals (Alemu, 2018). Understanding Ethiopia's

TABLE 1 Analyzed breakdown of key minerals mined in the districts across Ethiopia.

Region	Districts	Key minerals mined	Source
Amhara	Kobo, Gubalafto, Woreillu, Legambo, Bure	Gold, construction minerals	Ethiopian Geological Survey, (2021)
	Wadla Dilanta, Wegel Tena, Tsehay Mewcha	Opal, gemstones, construction minerals	Getaneh and Shikur (2022)
Oromia	Dendi, Ambo	Tantalum, Gold, construction minerals	Ethiopian Ministry of Mines and Petroleum. (2021)
	Adama, Boset	Construction minerals (Sand, Stone)	Etefa, (2019)
	Adola, Shakiso	Gold, Emerald, construction minerals	Jima, (2020)
	Yabelo, Moyale	Opal, gemstones, construction minerals	Mencho, (2022)
SNNPR	Mizan Aman, Guraferda	Gold, Tantalum, construction minerals	Keili et al. (2021)
	Chena, Decha	Gold, construction minerals	Techane et al. (2023)
Tigray	Shire, Asgede Tsimbla	Gold	Weldegiorgis et al. (2017)
	Atsbi Wenberta, Hawzen	Gemstones (Opal)	Redehey, (2017)
Benishangul-Gumuz	Dangur, Guba, Asosa, Kurmuk	Gold, construction minerals	Haile et al. (2024)
Gambella	Abobo, Gog, Jikawo, Itang	Gold, construction minerals	Ethiopian Geological Survey, (2021)
Afar	Gewane, Teru, Berhale, Dalol	Potash, Salt, construction minerals	Hagos et al. (2016)
Somali	Jijiga, Kebri Beyah	Salt, Gypsum, construction minerals	Ethiopian Geological Survey (2021)
	Dolo Ado, Moyale	Gold, construction minerals	Desta, (2016)

geological and topographical complexities is vital for creating policies that can support and sustain ASM, ensuring miners' safety while enhancing the sector's productivity. Table 1 provides summarized breakdown of key minerals mined in different districts across Ethiopia. This distribution reflects the wide-ranging potential of ASM and its importance to local economies.

4 Methodology

This review was conducted using a systematic and integrative approach to evaluate the geo-environmental impacts, socio-economic challenges, and sustainable solutions associated with ASM in Ethiopia. The methodology was designed to ensure a comprehensive understanding of the current state of ASM, its impacts, and potential pathways for sustainable development. The process involved several key steps.

4.1 Literature search and selection

A thorough literature search was conducted across multiple academic databases, including Google Scholar, Scopus, Web of Science, PubMed and Science direct, to identify relevant peer-reviewed articles, books, reports, and policy documents published between 2015 and 2025 (Figure 1). The search focused on keywords such as "artisanal mining," "small-scale mining," "geo-environmental impacts," "socio-economic challenges," "sustainable practices," and "Ethiopia." Grey literature, including government reports, NGO publications, and conference proceedings, was also reviewed to ensure comprehensive coverage of the topic.

4.2 Inclusion and exclusion criteria

The selection of sources was guided by specific inclusion and exclusion criteria. Studies were included if they: (i) provided empirical or theoretical insights into the environmental, socio-economic, or health impacts of ASM in Ethiopia; (ii) offered analyses of policy frameworks or sustainable practices in ASM; or (iii) discussed opportunities and challenges related to ASM. Studies focusing solely on large-scale mining or those outside the specified timeframe were excluded to maintain relevance.

4.2.1 Data extraction and synthesis

Relevant data were systematically extracted from the selected sources, focusing on the environmental impacts (soil degradation, water pollution, biodiversity loss, etc.), socio-economic implications (livelihoods, income, health risks, etc.), and regulatory challenges associated with ASM in Ethiopia. The extracted information was then synthesized to identify key themes, patterns, and gaps in the existing literature. A thematic analysis was employed to categorize the findings into challenges, opportunities, and sustainable solutions, ensuring a coherent narrative throughout the review.

4.2.2 Comparative approach

A comparative approach was adopted, drawing on case studies from other countries with similar ASM dynamics to contextualize Ethiopia's situation. This approach helped to identify best practices, technological innovations, and policy frameworks that could be adapted to the Ethiopian context.

4.2.3 Validation through expert consultation

To validate the findings, informal consultations with experts in the fields of environmental science, mining, and Ethiopian socio-economic development were conducted. These consultations

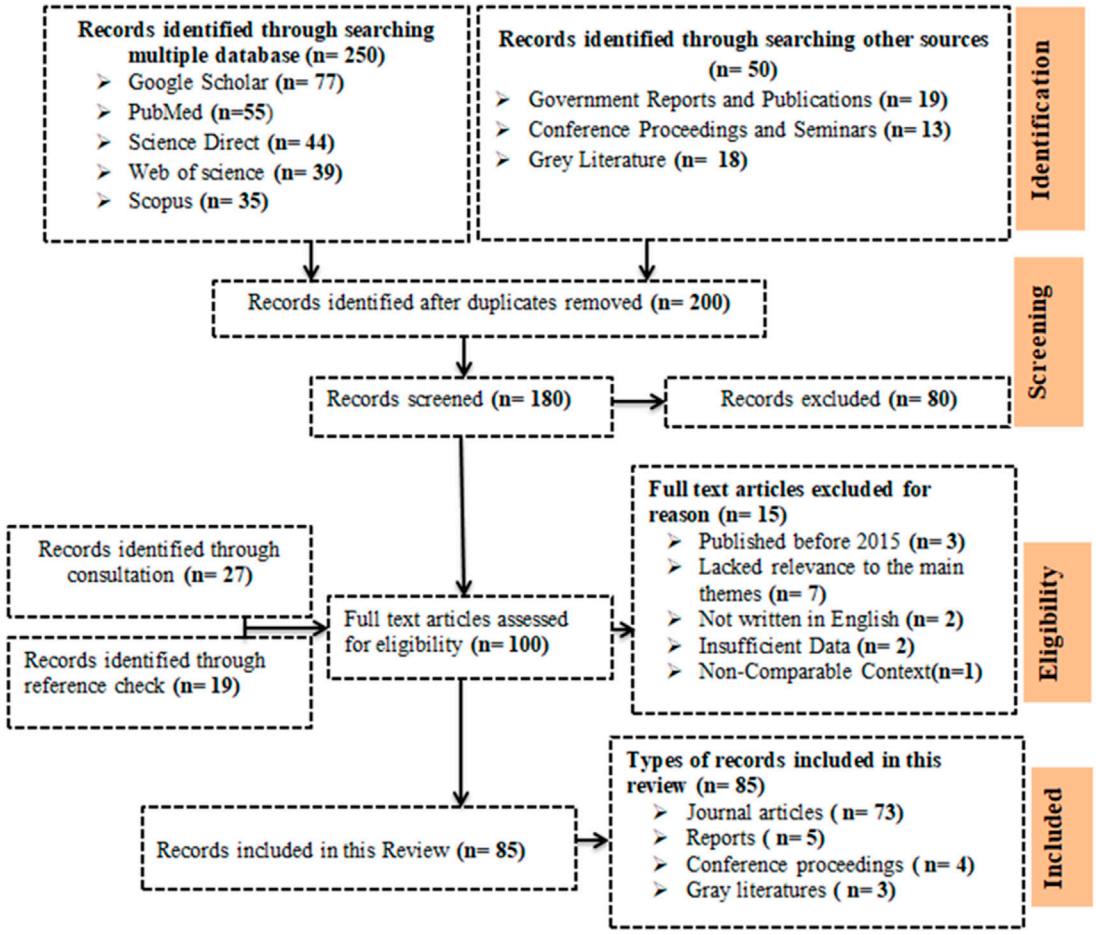

FIGURE 1
PRISMA flow diagram of the review.

provided additional perspectives on the challenges and opportunities within the ASM sector in Ethiopia and helped refine the recommendations for sustainable solutions.

4.3 Reporting and recommendations

The findings of this review were systematically documented, focusing on the most pressing geo-environmental impacts and socio-economic challenges of ASM in Ethiopia. The review concludes with actionable recommendations aimed at policymakers, industry stakeholders, and local communities, emphasizing the need for integrated sustainable practices, improved regulatory frameworks, and technological innovations to mitigate the adverse impacts of ASM while harnessing its potential for socio-economic development.

5 Results and discussion

5.1 Search results and inclusion process

The literature search was conducted using multiple databases and other relevant sources to ensure a comprehensive review. A total of 250 records were identified through database searches, including Google Scholar (n = 77), PubMed (n = 55), Science Direct (n = 44), Web of Science (n = 39), and Scopus (n = 35). Additionally, 50 records were retrieved from other sources such as government reports and publications (n = 19), conference proceedings and seminars (n = 13), and grey literature (n = 18). After removing duplicates, 200 records remained for screening. An initial screening of titles and abstracts led to the exclusion of 80 records, primarily due to lack of relevance to the study objectives. The remaining 100 full-text articles were assessed for eligibility. During this stage, 15 records were excluded based on various criteria: Published before 2015 (n = 3), Lacked relevance to the main themes (n = 7), Not written in English (n = 2), Insufficient data (n = 2), Non-comparable context (n = 1). Further, 46 additional records were identified through consultation (n = 27) and reference checks (n = 19), bringing the total number of records included in the final review to 85. The final selection comprised 73 (86%) journal articles, 5 (6%) reports, 4 (5%) conference proceedings, and 3 (3%) grey literature sources (Figure 2). This rigorous screening and selection process ensured that the included studies were relevant, methodologically sound, and aligned with the objectives of this review.

The 85 included studies provided a rich and diverse set of data, offering insights into the environmental, socio-economic, and policy

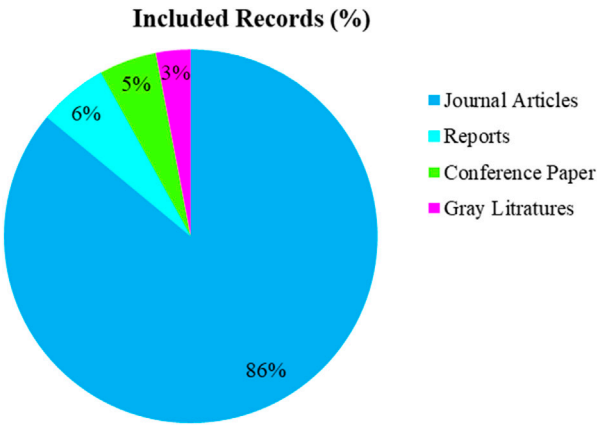

FIGURE 2
Proportion of included records in Percent.

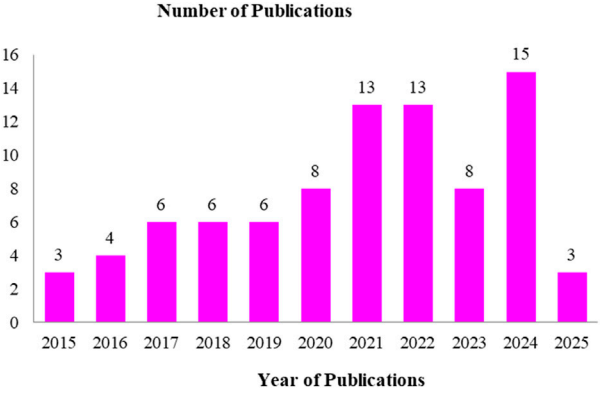

FIGURE 3
Number of included records by Year of publications.

dimensions of area exclosures in Ethiopia. These studies spanned a wide time frame, with the majority published between 2018 and 2024, reflecting a growing interest ASM in the country. The temporal distribution of included records shows a fluctuating yet generally increasing trend in research output. From 2015 to 2019, publications rose gradually from 3 to 6 per year, indicating steady academic engagement. A notable increase occurred in 2020 with eight publications, followed by peak years in 2021 and 2022, each with 13 records, reflecting heightened research interest. Although 2023 saw a decline to eight publications, 2024 reached the highest count of 15, demonstrating renewed focus. The sharp drop to three publications in 2025 is due to the early stage of the year. Overall, the data highlights periods of growing interest, with peak productivity between 2020 and 2024 (Figure 3).

5.2 Geo-environmental impacts of artisanal and small-scale mining (ASM) in Ethiopia

ASM in Ethiopia, while providing economic opportunities, has detrimental geo-environmental consequences that affect both the environment and local communities. This review delves into the most pressing impacts soil degradation, water pollution, biodiversity loss, and air quality deterioration drawing comparisons with similar regions to underscore their severity.

5.2.1 Soil degradation and erosion

ASM significantly contributes to soil degradation and erosion in Ethiopia, posing severe environmental and socio-economic consequences (Alemu, 2018). The mining process disrupts natural soil structures through vegetation clearance, open-pit excavation, and improper disposal of mine tailings, exposing the land surface to accelerated erosion by wind and water (Lemessa et al., 2022). Studies indicate that soil loss in Ethiopia's ASM hotspots is alarmingly high. For instance, in the Wadla Delanta opal mining area, soil erosion rates reach 13.2 tons per hectare annually, surpassing global averages and demonstrating the acute impact of mining-related disturbances (Getaneh and Shikur, 2022). This excessive soil loss depletes the organic-rich topsoil necessary for agriculture, leading to reduced soil fertility, lower crop productivity, and heightened food insecurity among local communities (Teku et al., 2024a).

Comparative studies in Oromia and Tigray regions reveal similar patterns of degradation. In these areas, mining activities have stripped protective vegetation, causing severe gully erosion and land degradation (Lemessa et al., 2022). Furthermore, studies from ASM-intensive regions of Sub-Saharan Africa, such as Ghana and Nigeria, corroborate Ethiopia's experience, illustrating how uncontrolled mining accelerates land degradation and exacerbates desertification trends (Hilson & Maconachie, (2020). The cumulative effects of such soil degradation extend beyond immediate mining zones, impacting downstream agricultural lands and water bodies through sedimentation, further reducing land productivity and disrupting ecosystems (Moyo et al., 2022). The economic ramifications of ASM-induced soil erosion are substantial. Declining agricultural yields increase dependency on imported food, burdening local economies. Additionally, land rehabilitation efforts require significant financial investments, which are often beyond the reach of smallholder farmers and local governments (Hilson, 2016). Without strategic interventions, the progressive loss of soil resources in Ethiopia's mining regions could have long-term consequences for national food security and rural livelihoods (Teklemariam, 2015).

Addressing these challenges necessitates the adoption of sustainable mining practices. Implementing land reclamation strategies, such as reforestation, terracing, and controlled mining techniques, can mitigate soil erosion (Desta, 2016). Regulatory frameworks that enforce proper tailings management and rehabilitation obligations for miners are also critical (Hailemariam, 2024). Learning from successful soil conservation measures in other mining-affected regions, such as those implemented in Tanzania and Rwanda, could provide viable policy insights for Ethiopia's ASM sector (Abate et al., 2024). In conclusion, soil degradation and erosion resulting from ASM present a critical environmental challenge in Ethiopia. The loss of productive soil not only disrupts local agriculture but also has far-reaching socio-economic implications. Addressing these impacts requires a combination of policy enforcement, sustainable mining practices, and community-based land restoration initiatives to

ensure the long-term viability of both mining and agriculture in the affected regions.

5.2.2 Water pollution and resource depletion

Water pollution from ASM is a critical concern. The use of hazardous chemicals such as mercury and cyanide in gold extraction has contaminated rivers and groundwater (Lemessa et al., 2022). In areas like Benishangul-Gumuz, elevated mercury levels in water sources have posed significant health risks to humans and wildlife alike (Haile et al., 2024). The presence of heavy metals in water bodies can lead to bioaccumulation in aquatic ecosystems, causing long-term ecological and health hazards for communities relying on these water sources (Chimdi and Degefu, 2019). Moreover, mining operations require large quantities of water, leading to the depletion of local resources. In Ethiopia's arid regions, where water scarcity is already a pressing issue, the overuse of water for mining exacerbates the problem, affecting agricultural and domestic water supply (Abate and Sisay, 2024). Studies in the Afar and Somali regions have highlighted cases where excessive water withdrawal by mining activities has led to declining groundwater levels, threatening both livestock and crop production (Hagos et al., 2016). Similar trends have been observed in other mining-intensive regions globally. In Latin American countries such as Peru and Bolivia, unregulated ASM activities have strained water resources, causing conflicts between miners, farmers, and local communities over water allocation (Espin, 2020). The Ethiopian case mirrors these international experiences, underscoring the urgent need for regulatory measures to monitor and control ASM's water consumption and pollution impacts.

Addressing water pollution and resource depletion requires a multi-faceted approach. Implementing mercury-free extraction technologies, such as gravity concentration and cyanide leaching in controlled environments, could significantly reduce water contamination (Desta, 2016). Additionally, integrating water management policies that regulate ASM water use and promote sustainable mining practices can help conserve critical water resources (Lemessa et al., 2023). Community-driven initiatives, such as water monitoring programs and restoration projects, could further mitigate the environmental damage caused by ASM activities (Jima, 2020). In conclusion, the impact of ASM on water pollution and resource depletion poses severe environmental and socio-economic challenges in Ethiopia. Without effective intervention, mining-related water contamination and excessive usage will continue to threaten public health, agricultural productivity, and ecosystem integrity. Implementing sustainable mining practices, strengthening regulatory frameworks, and promoting alternative extraction methods are essential steps toward mitigating ASM's adverse effects on Ethiopia's water resources.

5.2.3 Biodiversity loss and habitat destruction

The impact of ASM on biodiversity is profound, particularly in forested areas (Abebil et al., 2023). As miners clear land for extraction, habitats for both flora and fauna are destroyed, leading to biodiversity loss (Quarm et al., 2022). In Ethiopia's Oromia region, for example, gold mining has led to the deforestation of approximately 40% of the forest area surrounding Shakiso and Adola over the past 2 decades (Mencho, 2022). Habitat destruction disrupts vital ecological functions, including nutrient cycling and water regulation, and contributes to human-wildlife conflicts as animals encroach on agricultural areas (Etse et al., 2023; Teku et al., 2024b) The deforestation caused by ASM also diminishes the availability of forest products crucial resources for local communities. Many indigenous and rural populations rely on forests for fuelwood, medicinal plants, and other ecosystem services (Meaza et al., 2015). The depletion of these resources exacerbates economic vulnerabilities, particularly for those dependent on non-timber forest products (Ofosu et al., 2020).

The loss of biodiversity in Ethiopia parallels what is seen in other African countries, where ASM often leads to severe ecological disruption and loss of natural resources vital to local economies and cultures (Asamoah et al., 2018; 6; Yego et al., 2018; Nursamsi et al., 2024). For instance, in Ghana and the Democratic Republic of Congo, mining-related deforestation has significantly reduced wildlife populations, leading to ecosystem imbalances and threatening conservation efforts (Gaisie, 2024; Otamonga and Poté, 2020). Mitigating biodiversity loss from ASM requires the enforcement of environmental regulations that limit deforestation and promote ecosystem restoration. Reforestation initiatives, community-led conservation programs, and sustainable land-use planning are crucial strategies for preserving biodiversity in ASM-affected areas (Franks et al., 2020). Additionally, integrating biodiversity considerations into mining policies can help balance economic benefits with environmental sustainability (Ofosu et al., 2020). In general, biodiversity loss and habitat destruction due to ASM in Ethiopia pose severe ecological and socio-economic challenges. Sustainable mining practices, stricter regulatory enforcement, and conservation initiatives are essential to mitigating the negative impacts of ASM on biodiversity and ensuring the long-term health of Ethiopia's ecosystems.

5.2.4 Air quality deterioration

Air quality deterioration, often overlooked, is a significant health risk linked to ASM. The burning of mercury during gold extraction releases toxic fumes, contributing to air pollution. In regions like Amhara and Oromia, miners and local communities report higher rates of respiratory diseases, including asthma and bronchitis (Denkayhu and Gondar, 2017). The long-term exposure to mercury vapor and other toxic emissions can cause severe neurological damage, such as tremors and memory loss, reducing life expectancy among miners and their families (Abate and Sisay, 2024). This issue mirrors the health crises seen in other mining communities worldwide, where poor air quality and exposure to harmful substances lead to widespread respiratory and neurological disorders.

While Ethiopia's ASM-related geo-environmental impacts are alarming, they are not unique. Other regions, particularly in sub-Saharan Africa, face similar challenges (Hilson et al., 2021). However, the scale of degradation in Ethiopia's semi-arid and arid regions presents a heightened risk of desertification, exacerbated by factors like soil erosion and water scarcity (Meaza et al., 2015; 103; Teku and Derbib, 2025; Teku and Workie, 2025). Ethiopia's reliance on agriculture as the primary livelihood further magnifies the socio-economic consequences of these environmental issues (Mencho, 2022). Similar mining regions globally face the need

for sustainable practices, but Ethiopia's specific challenges, including rapid population growth and dependence on land-based economies, require tailored solutions that integrate environmental preservation with economic development (Hagos et al., 2016). This review underscores the urgent need for better regulation and intervention to mitigate the geo-environmental impacts of ASM in Ethiopia. Comparative global insights suggest that sustainable mining practices, along with strengthened environmental policies, are essential to curbing these detrimental effects and ensuring the long-term wellbeing of both the environment and local communities.

5.3 Health problems derived from artisanal and small-scale mining (ASM) in Ethiopia

While ASM in Ethiopia serves as a crucial livelihood for many, it brings with it serious health risks that affect workers and surrounding communities (Alkadir et al., 2020). The challenges range from immediate injuries to long-term diseases, some even leading to fatalities (Liyew et al., 2021). These health issues are exacerbated by unsafe working conditions, exposure to hazardous substances, and the lack of adequate healthcare services in mining regions (Hagos et al., 2016). Below is a synthesis of the key health problems associated with ASM in Ethiopia, with a focus on the geographic variability of these issues across different regions.

5.3.1 Injuries and fatalities

Mining accidents are tragically common in Ethiopia's ASM sector, and the absence of safety measures further exacerbates these risks. In the Shakiso area of Oromia, for example, between 2015 and 2020, there were at least 50 fatalities attributed to mine collapses and accidents involving poorly implemented safety protocols (Mencho, 2022). Furthermore, the Ethiopian Ministry of Mines and Petroleum reported a sharp 15% rise in mining-related injuries and fatalities between 2019 and 2020 (Ethiopian Ministry of Mines and Petroleum, 2021). In some mining sites, such as Delanta, up to 86.3% of deaths result from rock collapses and land subsidence (Alemu, 2018). These hazards highlight the dangerous working conditions prevalent in many ASM operations across Ethiopia. Comparatively, similar patterns of mining-related injuries and fatalities are observed in other ASM-dominant regions, such as Ghana and the Democratic Republic of the Congo (Ajith et al., 2021). In Ghana's ASM sector, illegal and unregulated mining has resulted in an average of 200 fatalities annually, primarily due to mine collapses and unsafe working conditions (Usman Kaku et al., 2021; Otamonga and Poté, 2020). Likewise, in the Democratic Republic of the Congo, a lack of enforcement of safety regulations contributes to frequent fatal accidents, exacerbated by child labor and poor structural integrity of mines (Otamonga and Poté, 2020). These parallels underscore the urgent need for improved safety regulations and enforcement mechanisms to mitigate mining-related casualties in Ethiopia and beyond.

5.3.2 Respiratory diseases

Dust and particulate matter are prevalent on most ASM sites, creating a severe risk to miners' respiratory health. In the Guji Zone, 25% of miners suffer from respiratory issues, including chronic bronchitis and silicosis, which are caused by prolonged exposure to silica dust (Mencho, 2022). The Adola and Shakiso districts, known for their significant ASM activity, have seen a surge in such respiratory ailments, mirroring the pattern observed in other global ASM hotspots, like parts of South America and Southeast Asia, where mining operations expose workers to hazardous airborne pollutants (Owusu-Nimo et al., 2018). Comparative studies highlight similar health risks in ASM regions worldwide. In Peru, miners working in informal gold extraction sites frequently develop silicosis and pneumoconiosis due to inadequate protective measures (Duff and Downs, 2019). Likewise, in Indonesia, ASM activities have been linked to high levels of respiratory diseases among workers and nearby communities, emphasizing the widespread impact of unregulated mining practices (Moyo et al., 2022). These findings suggest that Ethiopia must implement occupational health standards, including dust control measures and protective gear, to mitigate respiratory risks in ASM operations.

5.3.3 Mercury poisoning

Mercury use in gold extraction processes poses another grave health concern. In regions like Benishangul-Gumuz, high levels of mercury exposure have led to alarming health risks, including neurological damage and kidney failure. A study by Abebil et al. (2023) found that nearly 40% of ASM workers tested had dangerously elevated mercury levels, with symptoms such as tremors and memory loss reported among affected populations. The widespread practice of using mercury without adequate safety measures mirrors similar concerns in other ASM-rich regions, such as parts of Africa and Asia, where the use of mercury has led to significant public health crises (Hilson, 2016). In Ghana and Nigeria, mercury contamination has been linked to severe cases of mercury poisoning among miners and their families, with long-term effects on cognitive development in children (Mufandaedza, 2021). Similarly, in Indonesia's artisanal gold mining sector, mercury pollution has severely contaminated local waterways, impacting aquatic life and posing risks to downstream communities (Mulaba-Bafubiandi et al., 2023). These parallels highlight the urgent need for stricter regulations on mercury use in Ethiopia's ASM sector, as well as the promotion of alternative gold extraction techniques, such as gravity concentration and cyanidation, to mitigate health risks.

5.3.4 Vector-borne diseases

ASM significantly contributes to the spread of vector-borne diseases, primarily due to the creation of stagnant water pools in and around mining sites. These water bodies provide ideal breeding grounds for mosquitoes, which are the primary vectors of diseases such as malaria and dengue fever (Abate and Sisay, 2024). In Ethiopia, ASM activities in regions like Gambella have been directly linked to a rise in malaria cases. According to the Gambella Regional Health Bureau (2022), malaria incidence in ASM-affected areas has surged by 30% over the past 3 years. The presence of abandoned mining pits that accumulate rainwater, coupled with poor drainage systems, exacerbates the situation by increasing mosquito populations (Hagos et al., 2016). The health implications of this trend extend beyond malaria. Other mosquito-borne diseases, such as dengue fever, are also becoming more prevalent, especially as climate change creates favorable

conditions for vector proliferation. Reports indicate that in ASM-intensive zones, the lack of proper sanitation and waste disposal further contributes to disease transmission, as poor hygiene facilitates the spread of additional vector-borne infections, including leishmaniasis (Weldegiorgis et al., 2017).

The Ethiopian case aligns with findings from other mining-intensive regions in Africa, such as Ghana and the Democratic Republic of Congo (DRC), where ASM has been linked to heightened malaria prevalence (Hilson et al., 2017; Otamonga and Poté, 2020). In Ghana's Obuasi mining region, malaria cases among miners and surrounding communities increased by 25% between 2018 and 2021 due to the formation of water-filled mining pits (Sey and Belford, 2019). Similarly, in the DRC, ASM operations in the Ituri province have exacerbated malaria transmission, particularly among vulnerable populations like children and pregnant women (Rutherford and Buss, 2022). A broader comparison with mining regions in Southeast Asia, particularly in Indonesia and the Philippines, reveals a parallel public health crisis (Chimdi and Degefu, 2019). In Indonesia's Kalimantan region, unregulated ASM has resulted in widespread stagnant water accumulation, leading to a surge in dengue fever cases (Fritz et al., 2022). Similarly, in the Philippines' Compostela Valley, an area with significant ASM activity, local health authorities reported a doubling of malaria cases over 5 years due to increased mosquito breeding sites (Ofosu et al., 2020).

Despite the well-documented correlation between ASM and vector-borne diseases, mitigation strategies remain inadequate in many ASM-dependent communities (Keili et al., 2021). In Ethiopia, interventions such as insecticide-treated mosquito nets (ITNs) and indoor residual spraying (IRS) have been deployed, but these measures often fail to address the root cause the persistent presence of stagnant water in mining areas (Granitzio et al., 2017). Other regions, such as Ghana and Indonesia, have introduced integrated vector management strategies; including filling abandoned mining pits with soil or promoting alternative water drainage methods, with some degree of success (Obiri et al., 2016). In conclusion, the link between ASM and vector-borne disease proliferation is evident both in Ethiopia and globally. The creation of stagnant water bodies due to mining activities serves as a primary driver of increased malaria and dengue fever cases. Lessons from other regions suggest that addressing this issue requires a combination of targeted health interventions and environmental management strategies to minimize water stagnation in ASM-affected areas. Without such integrated approaches, ASM communities will continue to face severe public health challenges, exacerbating existing socio-economic vulnerabilities.

5.3.5 HIV exposure

The high-risk environment surrounding ASM also makes miners more vulnerable to HIV, due to the transient lifestyle, poor access to healthcare, and high-risk behaviors such as unprotected sex and substance abuse (Alemu, 2018). In the Shakiso district of Oromia, HIV prevalence among ASM workers stands at a troubling 12%, which is much higher than the national average of 1.1% (Weldegiorgis et al., 2017). The social dynamics of the ASM workforce, including the influx of young workers, often exacerbate the spread of HIV. In Delanta, where a significant portion of miners are young, HIV/AIDS cases have risen by 24% since the onset of mining activities, with young boys and girls being at the heart of the problem (Alemu, 2018). The health burden from HIV is compounded by co-morbidities such as tuberculosis (TB), which is frequently seen in HIV-positive miners. In the Adola district, around 20% of HIV-positive miners also suffer from TB; illustrating the compounded health risks these workers face (Getaneh and Shikur, 2022). Despite the high prevalence of HIV and other health concerns, efforts to address these issues remain insufficient. Awareness campaigns, condom distribution, and access to antiretroviral therapy (ART) are often lacking or poorly implemented in mining areas, leaving workers vulnerable to both the immediate and long-term effects of these diseases (Alkadir et al., 2020). The Ethiopian Ministry of Health has acknowledged these gaps in healthcare provision for miners, further emphasizing the need for stronger health interventions (Ethiopian Ministry of Health, 2022).

5.4 Socio-economic challenges linked to artisanal and small-scale mining (ASM) in Ethiopia

ASM in Ethiopia, though vital to the livelihoods of many, comes with a complex array of socio-economic challenges that hinder the wellbeing of local communities and undermine sustainable development (Abebil et al., 2023). From informality in the sector to labor exploitation and child labor, these issues demand urgent attention. Below, the author examines these critical challenges and their impact on both local communities and the broader mining sector in Ethiopia, with comparisons to similar regions worldwide.

5.4.1 The informality and lack of regulation

At the heart of Ethiopia's ASM sector lays its informal nature, which complicates both regulation and development (Abebil et al., 2023). The absence of formal recognition for miners means that they operate without licenses or legal status. This informality stems from weak regulatory frameworks and insufficient enforcement, especially in remote areas like Oromia and Benishangul-Gumuz (Alemu, 2018). This lack of regulation not only prevents miners from accessing vital resources such as financial services, technical support, and markets, but it also deprives the government of potential tax revenue that could be reinvested into local communities or the mining sector itself (Yihdego et al., 2018). Additionally, the informal status of the industry makes it difficult to address significant problems such as environmental degradation, hazardous working conditions, and illegal mining activities, which flourish outside the oversight of regulatory authorities (Ministry of Mines and Petroleum, 2022). In regions like Shakiso and Adola, where informal mining dominates, miners often lack safety equipment and work in unsafe, unstable environments (Mencho, 2022). Compared to regions with more formalized sectors, like South Africa's regulated gold mining industry, Ethiopian ASM sites exhibit a much higher rate of accidents and fatalities (Mufandaedza, 2021). These regions struggle with the balancing act of promoting economic growth while trying to formalize a scattered and transient industry that locals fear could threaten their livelihoods.

5.4.2 Labor conditions and the unseen cost of child labor

Within Ethiopia's ASM communities, labor conditions are harsh, with miners working in precarious environments that pose significant health and safety risks. The lack of proper equipment, exposure to toxic chemicals like mercury, and poor health standards make these communities vulnerable to injuries and chronic diseases. Furthermore, without labor rights or formal contracts, workers often face exploitation, with many earning below-subsistence wages. The situation is particularly dire for children. Due to economic hardships and limited access to education, many young people are drawn into mining activities, exacerbating the socio-economic challenges faced by their families. In places like Wadla Dilanta and Tsehay Mewcha, a disturbing number of children and adolescents work in the mines, some as young as 10 years old. The introduction of opal mining has led to a 7% increase in school dropouts in the region (Getaneh and Shikur, 2022). These children are at high risk of injuries, respiratory diseases, and long-term developmental problems, thus perpetuating the cycle of poverty (Elias and Alemu, 2022). In comparison, in many parts of Latin America, where child labor laws are better enforced, similar mining practices are less likely to include children (Rutherford and Buss, 2022). The stark difference illustrates the importance of education and policy intervention to break this cycle.

5.4.3 Gender inequality

Gender plays a central role in the socio-economic challenges faced by ASM communities in Ethiopia (Chaka and Rupprecht, 2024). Women, who are crucial to the mining process, often perform the most physically demanding tasks, such as hauling materials, processing ores, and gold panning. Despite their significant contributions, they receive little recognition, face discrimination, and have limited access to resources and advancement opportunities (Abate and Sisay, 2024). Gender-based violence and exploitation are also pervasive, further marginalizing women and girls in these communities (Alemu, 2018). A study conducted in the Adola district found that women were not only more likely to suffer from workplace accidents but also faced additional barriers due to cultural and social norms. In contrast, countries like Ghana, which has seen successful initiatives to support women in mining through better safety standards and gender-focused policies, offer an alternative path forward (Asamoah et al., 2018). Such strategies could help Ethiopian women achieve more equitable access to resources and improved working conditions (Weldegiorgis, et al., 2017). Addressing these gender inequalities will require targeted interventions that empower women, provide education, and ensure their rights are respected in the mining sector.

5.4.4 Conflict and land rights

ASM in Ethiopia often sparks intense conflict over land use and ownership, particularly in regions where land rights are unclear or contested (Hassen, 2022, February). This issue is most prominent in areas where mining activities occur on communal land, agricultural fields, or forested areas (Ofosu et al., 2020). As mining intensifies especially in gold-rich zones like Gambella and Oromia the influx of miners creates significant tension with local and indigenous communities (Keili et al., 2021). These groups may find themselves displaced or face environmental degradation as a result of mining operations, which directly impacts their access to land and resources (Eneyew et al., 2024). The core of these conflicts lays in weak governance and a lack of clear land tenure systems, which leaves communities vulnerable to exploitation (Yihdego et al., 2018). In many cases, miners encroach on land that is vital for agriculture or is designated as a protected area (Warkisa et al., 2021). Local farmers, who depend on the land for their survival, are often forced to abandon their crops and livelihoods due to the environmental damage caused by mining (Chaka and Rupprecht, 2024). The loss of water resources and soil degradation further complicates their ability to maintain sustainable livelihoods. Moreover, when authorities or mining companies relocate communities, they do so without providing adequate compensation or resources to help these families rebuild their lives (Hailemariam, 2024).

This displacement not only disrupts local economies but also leads to the erosion of traditional ways of life, cultural identity, and social cohesion (Weleabzgi et al., 2021). The tension over land use also ignites broader conflicts, especially in areas marked by ethnic diversity or where the state presence is weak (Hagos et al., 2016). In regions like Oromia and Benishangul-Gumuz, clashes between artisanal miners and local communities often escalate into violent disputes, sometimes involving ethnic groups with competing interests (Lemessa et al., 2023). The lack of resolution to these land disputes fosters an unstable environment that hampers long-term development (Zerga and Tsegaye, 2020). As these conflicts continue to undermine community ties, they also inhibit economic progress and create an environment of insecurity that prevents the mining sector from evolving in a sustainable manner (Hailemariam, 2024). Resolving land tenure issues and fostering dialogue between all stakeholders is critical to ensuring that ASM activities can coexist with the local populations and contribute positively to the economy (Hilson et al., 2021).

6 Opportunities for sustainable artisanal and small-scale mining (ASM) practices in Ethiopia: A path towards balance

Ethiopia's ASM sector offers considerable opportunities for sustainable development, balancing economic growth with environmental conservation and social wellbeing (Alemu, 2018). Despite the sector's notable challenges ranging from environmental degradation to socio-economic inequalities there are growing prospects for positive change (Abate and Sisay, 2024). This review highlights how technological innovation, community engagement, formalization, and market incentives can transform the sector into a more sustainable and equitable industry.

6.1 Technological innovations

The environmental impacts of traditional ASM methods in Ethiopia, including land degradation, water pollution, and biodiversity loss, are significant Fagariba et al., 2024). However, emerging technologies provide a promising way forward. For instance, gravity separation technologies are being introduced to replace harmful chemicals like mercury in gold extraction, a major

pollutant in mining communities (Hilson and Maconachie, 2020). These eco-friendly methods allow for cleaner extraction, reducing both health risks and water contamination (Kolie et al., 2019). Additionally, mobile processing units are revolutionizing the industry by enabling on-site mineral processing and waste management, minimizing transportation costs and environmental damage (Kamga et al., 2018). Technologies that manage waste, like tailings management systems, are also gaining traction in Ethiopia. These systems reduce harmful runoff into nearby water bodies and can be paired with reforestation efforts to restore degraded landscapes (Hagos et al., 2016). While some pilot projects have shown positive results in Ethiopia's mining communities, scaling these technologies across the nation requires sustained governmental and international support. When compared with similar regions, like Peru and Ghana, where similar eco-friendly technologies have been successfully implemented (Obiri et al., 2016; Purevjav, 2024), Ethiopia stands to benefit from adopting and expanding these innovations.

6.2 Community engagement and capacity building

Sustainability in ASM requires the active participation of local communities (Yego et al., 2018). In Ethiopia, community engagement is essential for aligning mining practices with local priorities and ensuring long-term environmental stewardship (Teklemariam, 2015). Educating miners and local communities about sustainable techniques fosters a culture of responsibility and environmental awareness (Meaza et al., 2015). Programs that provide alternative livelihoods, such as agriculture or eco-tourism, not only reduce dependence on mining but also alleviate pressures on natural resources (Jima, 2020). By building capacity within local communities, Ethiopia has begun to implement community-based monitoring systems, where residents are trained to assess environmental conditions and report violations (Meaza et al., 2015). These initiatives have shown success in regions like Oromia, where local involvement has led to better regulatory compliance and stronger conflict resolution mechanisms (Meaza et al., 2015). In many ways, the Ethiopian model mirrors successful community-driven programs in countries such as Indonesia and Tanzania, where local monitoring significantly improved environmental outcomes and reduced illegal mining activities (Mimba et al., 2023). Moreover, prioritizing the involvement of women and marginalized groups in these efforts has proven critical in fostering inclusive development (Rutherford and Buss, 2022). By ensuring that everyone, especially those historically excluded, has a voice, Ethiopia can ensure that its ASM sector becomes not only sustainable but also equitable.

6.3 Formalization and legal reforms

One of the key challenges facing ASM in Ethiopia is its informality. Many miners work without legal recognition or protection, leading to unsafe working conditions, environmental destruction, and limited economic benefits (Hailemariam, 2024). Formalizing ASM operations is a crucial step toward improving environmental outcomes and securing better livelihoods for miners (Regassa, 2022). Through formalization, miners can gain legal recognition, access financial services, and benefit from technical support, all of which contribute to sustainable development (Alemu, 2018). Legal reforms are necessary to facilitate the process of formalization. Simplifying licensing procedures and ensuring that regulations are enforceable and transparent can help integrate ASM into the formal economy (Keili et al., 2021). Ethiopia has already seen some success in regions like Oromia and Tigray, where pilot projects have led to improved environmental compliance and better income for miners (Etefa, 2019). Compared to similar regions like Mali and Guinea, where formalization efforts have led to higher productivity and safety standards (Álvarez-Berríos et al., 2021), Ethiopia is on the right path but requires more widespread implementation.

6.4 Eco-friendly certification and market incentives

Introducing eco-friendly certifications is another strategy to encourage sustainable ASM practices in Ethiopia (Hailemariam, 2024). Programs like Fairmined or Fairtrade Gold incentivize miners to adopt responsible practices by offering market access to consumers who are willing to pay premium prices for sustainably sourced products (Hilson and Maconachie, 2020). These certification programs can significantly improve the financial viability of small-scale mining, as evidenced by pilot projects in Ethiopia's Southern Nations, Nationalities, and Peoples' Region (SNNPR). Certified miners in this region have reported higher incomes and better working conditions, along with a reduced environmental footprint (Zerga and Tsegaye, 2020). Additionally, Payment for Ecosystem Services (PES) programs, which compensate miners for protecting ecosystems such as through reforestation or water conservation have gained attention as a promising incentive model (Lemessa et al., 2023). Similar programs in regions like Colombia and Kenya have demonstrated that linking financial rewards to sustainable practices can drive significant environmental and economic benefits (Yego et al., 2018). The Ethiopian government, in partnership with NGOs and the private sector, must now focus on scaling these initiatives. Clear standards, technical support, and market connections are key to maximizing the potential of eco-friendly certifications and market incentives (Abate and Sisay, 2024). In doing so, Ethiopia can follow the successful examples set by other nations that have used such market-driven solutions to enhance both the economy and the environment.

7 Case studies and best practices in artisanal and small-scale mining (ASM) in Ethiopia

The ASM sector is a vital source of livelihood in Ethiopia but also a significant contributor to environmental degradation

TABLE 2 Successful interventions in reducing the geo-environmental impacts of ASM activities in Ethiopia.

Intervention	Description
Tulu Kapi Gold Project, Oromia	The project introduced mercury-free gold processing and provided training in sustainable mining and alternative livelihoods like agriculture. It reduced mercury contamination and improved soil through better tailings management. Challenges included scaling up due to limited resources and the need for ongoing technical support (Chimdi and Degefu, 2019; Granitzio et al., 2017; Warkisa et al., 2021)
Keffa Forest Coffee Certification, SNNPR	This initiative integrated artisanal mining with forest conservation by promoting agroforestry and organic certification. It helped balance mining with forest preservation, leading to increased income. Challenges included limited market access for certified products and weak local governance for enforcing environmental regulations (Zerga and Tsegaye, 2020)
Wollega University Capacity Building	A partnership with the Ministry of Mines and Petroleum trained miners in waste management, soil conservation, and water protection. This improved environmental management and soil stabilization. However, high training costs and maintaining long-term miner engagement were challenges (Etefa, 2019)

TABLE 3 Effective strategies for reducing the environmental impacts of ASM from other countries with similar ASM challenges.

Intervention	Description
Formalization and Legal Reforms in Ghana	Ghana formalized its ASM sector with a licensing system, mandatory EIAs, and a mercury-free gold certification. This reduced illegal mining, improved compliance, and increased government revenue. Challenges include corruption and miner resistance to formalization. Ethiopia could adopt similar strategies for its ASM sector (Hilson and Maconachie, 2020)
Community-based Environmental Monitoring in Peru	In Peru, local communities in Madre de Dios monitor ASM's environmental impacts, guiding policy and enforcement. This community-driven approach fosters environmental stewardship and accountability, offering valuable lessons for Ethiopia's ASM sector (Álvarez-Berríos et al., 2021)
Technological Innovation and Miner Cooperatives in Mongolia	Mongolia promoted low-cost, mercury-free extraction technologies and miner cooperatives, improving environmental management and incomes. This cooperative model could be adapted in Ethiopia to facilitate cleaner technologies and resource sharing, though initial support is crucial (Li et al., 2024)

(Jima, 2020). However, there have been notable efforts both within Ethiopia and internationally to mitigate the adverse impacts of ASM through successful interventions and the adoption of best practices (Meaza et al., 2015). This section provides an in-depth examination of case studies from Ethiopia, as well as international best practices, focusing on their implementation, challenges, and lessons learned.

7.1 Successful interventions in Ethiopia

Several interventions in Ethiopia have demonstrated success in reducing the geo-environmental impacts of ASM (Chimdi and Degefu, 2019; Etefa, 2019; Granitzio et al., 2017; Warkisa et al., 2021; Zerga and Tsegaye, 2020). These initiatives often involve multi-stakeholder collaboration, integrating technological innovations, community engagement, and regulatory reforms. Table 2 below provides example for successful interventions in reducing the geo-environmental impacts of ASM activities in Ethiopia.

7.2 International best practices

Several countries with similar ASM challenges have developed best practices that offer valuable lessons for Ethiopia. These international examples (Table 3), provide insights into effective strategies for reducing the environmental impacts of ASM while enhancing the livelihoods of miners.

8 Policy recommendations for sustainable artisanal and small-scale mining (ASM) in Ethiopia

Addressing the geo-environmental and socio-economic challenges posed by Artisanal and Small-scale Mining ASM in Ethiopia requires a comprehensive and multi-faceted policy approach. Effective policy interventions must strengthen environmental regulations, incentivize sustainable mining practices, and establish robust institutional frameworks that facilitate collaboration among all stakeholders. Table 4 outlines detailed policy recommendations to achieve these goals, drawing on successful case studies, international best practices, and the unique socio-economic context of Ethiopia.

9 Future research directions for artisanal and small-scale mining (ASM) in Ethiopia

Addressing the complex challenges associated with ASM in Ethiopia requires ongoing research to fill knowledge gaps and explore innovative solutions. Future research should focus on understanding the long-term impacts of ASM on ecosystems and socio-economic dynamics, as well as developing and implementing cutting-edge technologies and practices that can mitigate the environmental footprint of ASM. This section outlines key research directions that are critical for advancing sustainable ASM practices in Ethiopia.

TABLE 4 Policy recommendations for Sustainable ASM in Ethiopia.

Policy approach	Recommendations
Enhancing Regulatory Frameworks	Develop ASM-specific environmental guidelines aligned with international standards but adapted to Ethiopia's context
	Introduce mandatory EIAs for all ASM operations, with compliance monitored through regular audits
	Strengthen regulatory bodies (MoMP, EPA) with better training, site visits, and penalties for non-compliance
	Use modern technologies (GIS, drones) to monitor ASM activities and environmental impacts in real-time
Incentivizing sustainable practices	Provide financial incentives (subsidies, loans) for adopting cleaner extraction technologies and water management
	Invest in training programs in local languages to teach sustainable mining and waste management techniques
	Establish eco-certification schemes to reward miners meeting environmental and social standards, boosting market value
	Promote alternative livelihoods (agriculture, handicrafts, ecotourism) to reduce dependence on mining
Strengthening Governance and Collaboration	Develop an integrated ASM management framework for inter-agency collaboration and policy coherence
	Create multi-stakeholder platforms at national and regional levels for dialogue, conflict resolution, and coordination
	Empower local governments and community organizations for better ASM regulation and environmental management
	Encourage Public-Private Partnerships (PPPs) for technology transfer, funding, and market access for certified ASM products
	Implement a robust M&E system to track environmental, social, and economic impacts, ensuring regular assessments

9.1 Knowledge gaps

9.1.1 Long-term impacts on specific ecosystems

While considerable research has been conducted on the immediate environmental impacts of ASM, there remains a need for comprehensive studies on the long-term effects on specific ecosystems. Understanding these impacts is crucial for developing effective management and restoration strategies.

9.1.1.1 Recommendations for research

- ➢ Longitudinal Studies on Ecosystem Health: Conduct longitudinal studies to assess the long-term impacts of ASM on soil quality, water resources, and biodiversity in key mining regions. These studies should track changes over extended periods to determine the cumulative effects of mining activities and the effectiveness of restoration efforts.
- ➢ Impact Assessment on Sensitive Ecosystems: Focus research on the impacts of ASM in sensitive ecosystems, such as wetlands, river basins, and protected areas. Understanding how mining activities affect these critical areas can inform targeted conservation strategies and help protect valuable ecological resources.
- ➢ Socio-economic Dynamics of ASM Communities: Investigate the socio-economic dynamics of ASM communities to better understand how mining activities influence local economies, health, and social structures over time. Research should explore issues such as income distribution, community cohesion, and the long-term health impacts of mining-related pollutants.

9.1.2 Socio-economic impact assessments

ASM's socio-economic impacts are multifaceted and require deeper analysis to address challenges and harness opportunities effectively.

9.1.2.1 Recommendations for research

- ➢ Long-term Economic Impacts: Examine the long-term economic impacts of ASM on local and national economies, including its contributions to employment, income stability, and poverty alleviation. Research should assess how changes in ASM practices affect economic outcomes and identify strategies to maximize benefits.
- ➢ Health and Safety Research: Study the long-term health impacts of ASM on miners and surrounding communities, particularly concerning exposure to hazardous substances such as mercury and cyanide. Research should aim to quantify health risks and develop strategies to mitigate them.
- ➢ Gender Dynamics in ASM: Explore the gender dynamics within ASM communities to understand how mining activities affect men and women differently. Research should address issues such as access to resources, decision-making power, and the socio-economic roles of women in ASM.

9.2 Innovation in sustainable practices

9.2.1 Development of cleaner technologies

Research into innovative technologies is essential for reducing the environmental footprint of ASM and improving the sustainability of mining practices.

9.2.1.1 Recommendations for research

- ➢ Emerging Extraction Technologies: Investigate new extraction technologies that minimize environmental impacts, such as advanced gravity separation methods, bioleaching, and alternative processing techniques that reduce the use of harmful chemicals.
- ➢ Waste Management Innovations: Explore innovative waste management practices to address the challenges of tailings and waste disposal in ASM. Research should focus on

developing methods for recycling and repurposing mining waste, as well as techniques for reducing waste generation.

- ➢ Water Management Solutions: Study advanced water management technologies that can reduce water consumption and pollution in ASM operations. This includes research on water recycling systems, low-impact water treatment methods, and strategies for minimizing water use in mining processes.

9.2.2 Sustainable mining practices and community engagement

Encouraging research into sustainable mining practices and effective community engagement is critical for promoting long-term sustainability in ASM.

9.2.2.1 Recommendations for research

- ➢ Community-Based Management Models: Research community-based management models that integrate local knowledge and participation into ASM governance. Studies should explore how these models can improve environmental stewardship and enhance the socio-economic benefits of mining.
- ➢ Impact of Certification Schemes: Investigate the effectiveness of eco-friendly certification schemes in promoting sustainable ASM practices. Research should assess the impact of certification on environmental performance, market access, and economic benefits for miners.
- ➢ Policy and Practice Integration: Explore ways to integrate research findings into policy and practice to drive effective ASM management. This includes examining the role of policy frameworks in supporting innovation, facilitating technology transfer, and promoting sustainable practices.

10 Conclusion

Artisanal and Small-scale Mining (ASM) in Ethiopia embodies both significant economic potential and severe geo-environmental and socio-economic challenges. As a critical livelihood source for millions, ASM contributes to foreign exchange earnings and provides income to communities facing agricultural dependency. However, these benefits are overshadowed by environmental degradation, including soil erosion, water contamination, biodiversity loss, and deteriorating air quality. The adverse health effects on miners and surrounding communities—exacerbated by inadequate safety measures and exposure to hazardous substances—further underscore the urgent need for intervention. Moreover, ASM-related socio-economic tensions, including labor exploitation and gender disparities, demand comprehensive policy responses.

Despite these challenges, Ethiopia has the opportunity to transform ASM into a more sustainable and inclusive industry. Comparative experiences from Ghana, South Africa, Indonesia, and Colombia illustrate the effectiveness of integrating technological advancements, strengthening regulatory frameworks, and fostering community engagement in mitigating ASM's negative impacts. Formalizing the sector, improving labor conditions, and addressing health risks through targeted interventions are essential steps toward ensuring that ASM contributes positively to both economic growth and environmental stewardship.

Moving forward, Ethiopia must prioritize a multi-stakeholder approach that balances economic development with sustainability. Implementing cleaner technologies, enhancing environmental policies, and offering market-based incentives can help align ASM practices with long-term national development goals. By learning from global best practices and tailoring them to its unique socio-environmental context, Ethiopia can harness ASM's economic potential while safeguarding its natural resources and the wellbeing of its people.

Author contributions

DT: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abate, T. W., and Sisay, A. Z. (2024). Traditional opal mining practice in Ethiopia, challenges and its economic impact on rural households: the case of wollo opal mining. *F1000Research* 13, 1388. doi:10.12688/f1000research.156436.1

Abebil, F., Tefera, Y., Tefera, W., Kumie, A., Mulugeta, H., and Kassie, G. (2023). Nonfatal occupational injuries among artisanal and small-scale gold mining workers in Ethiopia. *Environ. health insights* 17, 11786302231171809. doi:10.1177/11786302231171809

Ajith, M. M., Ghosh, A. K., and Jansz, J. (2021). A mixed-method investigations of work, government and social factors associated with severe injuries in artisanal and small-scale mining (ASM) operations. *Saf. Sci.* 138, 105244. doi:10.1016/j.ssci.2021.105244

Alemu, M. G. (2018). Artisanal small-scale opal mining (ASOM) insecurity in the Delanta wereda, Ethiopia: the shifting landscape of multidimensional insecurity in the face of emergent ASOM wealth. *Afr. Secur. Rev.* 27 (1), 61–87. doi:10.1080/10246029.2017.1294094

Alkadir, S., Gelana, T., and Gebresilassie, A. (2020). A five year trend analysis of malaria prevalence in Guba district, Benishangul-Gumuz regional state, western Ethiopia: a retrospective study. *Trop. Dis. Travel Med. Vaccines* 6, 18. doi:10.1186/s40794-020-00112-4

Álvarez-Berríos, N., L'Roe, J., and Naughton-Treves, L. (2021). Does formalizing artisanal gold mining mitigate environmental impacts? Deforestation evidence from the Peruvian Amazon. *Environ. Res. Lett.* 16 (6), 064052. doi:10.1088/1748-9326/abede9

Asamoah, E. O., Xu, W., Huang, W., and Yang, W. (2018). Environmental impacts of artisanal gold mining: a case study of Nkaseim Community–Ghana. *J. Environ. Earth Sci.* 8 (12), 116–130.

Chaka, K. J., and Rupprecht, S. (2024). Assessment of project risk management in selected mining companies in Ethiopia. *Int. J. Innovation Manag. Econ. Soc. Sci.* 4 (1), 47–63. doi:10.59615/ijimes.4.1.47

Chimdi, A., and Degefu, G. (2019). Assessment of the effect of tulu kapi gold mining project related wastes on the status of physico-chemical parameters of gomo and guracho streams water. *Glob. J. Environ. Res.* 13 (3), 40–50. doi:10.5829/idosi.gjer.2019.40.50

Denkayhu, B. T., and Gondar, E. (2017). Spectroscopic studies of natural gem-agate in sedimentary and volcanic host rocks from (bellesa, addis zemen and bure). *Amhara Natl. Reg. State (Ethiopia)*.

Desta, G. (2016). Ethiopia: transformation of "rain-fed lootable mining" economy in dead end? *Res. Humanit. Soc. Sci.* 6 (1), 22–30.

Duff, P. M., and Downs, T. J. (2019). Frontline narratives on sustainable development challenges/opportunities in the 'illegal'gold mining region of Madre de Dios, Peru: Informing an integrative collaborative response. *Extr. Industries Soc.* 6 (2), 552–561. doi:10.1016/j.exis.2019.01.005

Elias, H., and Alemu, A. (2022). Final report ETH-21156 july 2022.

Eneyew, D. M., Adamu, A. Y., Abebe, S. Z., Dubiniewicz, A. K., and Nigussie, A. B. (2024). Economic potentials, challenges and opportunities for sustainable mining in Wollo opal mining, Ethiopia. *Mineral. Econ.*, 1–14. doi:10.1007/s13563-024-00480-9

Espin, J. (2020). The prevention of green crimes in artisanal and small-scale gold mining in Peru: translating laws into practice. *Illegal Min. Organ. Crime, Corruption, Ecocide a Resource-Scarce World*, 469–496. doi:10.1007/978-3-030-46327-4_17

Etefa, D. F. (2019). The role of multi-purpose cooperatives in the economic development in Ethiopia, the case of lalo-assabi district (west wollega zone, oromia regional state).

Ethiopian Geological Survey (2021). Mineral resources of Somali region. Available online at: https://www.ethiomining.gov.et.

Ethiopian Ministry of Health (2022). *National HIV/AIDS strategy and progress report*. Addis Ababa: MoH.

Ethiopian Ministry of Mines and Petroleum (2021). *Annual report on artisanal and small-scale mining in Ethiopia*. Addis Ababa: MoMP.

Etse, D., McMurray, A., and Muenjohn, N. (2023). Sustainable procurement practice: the effect of procurement officers' perceptions. *J. Bus. ethics* 184 (2), 525–548. doi:10.1007/s10551-022-05150-w

Fagariba, C. J., Sumani, J. B. B., and Mohammed, A. S. (2024). Artisanal and small-scale gold mining impact on soil and agriculture: evidence from upper denkyira east municipality, Ghana. *Eur. J. Environ. Earth Sci.* 5 (3), 12–20. doi:10.24018/ejgeo.2024.5.3.443

Fenta, Y. A. (2017). *Identification and spectroscopic characterization of natural gem Agate from West Belessa*. North Gondar, Ethiopia (Doctoral dissertation: University of Gondar.

Franks, D. M., Ngonze, C., Pakoun, L., and Hailu, D. (2020). Voices of artisanal and small-scale mining, visions of the future: report from the international conference on artisanal and small-scale mining and quarrying. *Extr. industries Soc.* 7 (2), 505–511. doi:10.1016/j.exis.2020.01.011

Fritz, M., McQuilken, J., Collins, N., and Weldegiorgis, F. (2022). *Global trends in artisanal and small-scale mining (ASM): a review of key numbers and issues*. Winnipeg, MB, Canada. International Institute for Sustainable Development. (IISD).

Gaisie, O. (2024). Intersection between ecological destruction and human rights: study of illegal mining activities in Ghana.

Getaneh, W., and Shikur, M. (2022). Artisanal opal mining and associated environmental and socio-economic issues in opal mine sites of Wollo province, Ethiopia. *GeoJournal* 87 (4), 3323–3339. doi:10.1007/s10708-021-10440-3

Granitzio, F., Rayner, J., and Aregay, T. (2017). Tulu kapi gold project: a history of "repeated" discoveries in western Ethiopia. *Kefi Min. Plc*.

Hagos, G., Sisay, W., Alem, Z., Niguse, G., and Mekonen, A. (2016). Participation on traditional gold mining and its impact on natural resources, the case of Asgede Tsimbla, Tigray, Northern Ethiopia. *J. Earth Sci. Geotechnical Eng.* 6 (1), 89–97.

Haile, N. Z., Huluka, A. T., and Beyene, A. B. (2024). Analysis of the factors influencing local employment in the mining sector in the Benishangul-Gumuz Regional state of Ethiopia. *Sci. Afr.* 26, e02364. doi:10.1016/j.sciaf.2024.e02364

Hailemariam, Y. (2023). A critical appraisal of the legislative power over mineral resources in the ethiopian federation. *Rev. Drept Constituțional* (02), 65–90. doi:10.47743/rdc-2023-2-0004

Hailemariam, Y. (2024). A critical appraisal of the legal and policy framework for sustainable mining in Ethiopia. *J. Sustain. Dev. Law Policy* 15 (1), 106–143. doi:10.4314/jsdlp.v15i1.4

Hassen, A. E. (2022). Competency oriented management for sustainable artisanal and small-scale mining sector development in Ethiopia. *Nat. Resour. Forum*. 46 (1), 116–135. doi:10.1111/1477-8947.12246

Hilson, G. (2016). Farming, small-scale mining and rural livelihoods in Sub-Saharan Africa: a critical overview. *Extr. Industries Soc.* 3 (2), 547–563. doi:10.1016/j.exis.2016.02.003

Hilson, G., Hilson, A., Maconachie, R., McQuilken, J., and Goumandakoye, H. (2017). Artisanal and small-scale mining (ASM) in sub-Saharan Africa: re-conceptualizing formalization and 'illegal'activity. *Geoforum* 83, 80–90. doi:10.1016/j.geoforum.2017.05.004

Hilson, G., and Maconachie, R. (2020). Artisanal and small-scale mining and the sustainable development goals: opportunities and new directions for sub-Saharan Africa. *Geoforum* 111, 125–141. doi:10.1016/j.geoforum.2019.09.006

Hilson, G., Van Bockstael, S., Sauerwein, T., Hilson, A., and McQuilken, J. (2021). Artisanal and small-scale mining, and COVID-19 in sub-Saharan Africa: a preliminary analysis. *World Dev.* 139, 105315. doi:10.1016/j.worlddev.2020.105315

International Labour Organization (ILO) (2021). *Global estimates of artisanal and small-scale mining*. Geneva: ILO.

Jima, A. O. (2020). The socioeconomic effects of large scale gold mining on local community in Ethiopia: empirical evidence from lega dambi gold mining company. *J. Indig. Knowl. Dev. Stud.* 1 (2).

Kamga, M. A., Olatubara, C. O., Atteh, M. M., Nzali, S., Adenikinju, A., Mbiatso, T. Y., et al. (2018). Perception of the environmental degradation of gold mining on socio-economic variables in Eastern Cameroon, Cameroon. *Eur. J. Sustain. Dev. Res.* 2 (2), 23. doi:10.20897/ejosdr/85117

Kebeta Djigsa, W. (2021). Towards socially responsible mining investment in Ethiopia: imagining a new moral economy. *Rev. Pub Adm. Manag.* 9, 291.

Keili, A., Elias, H., and Bekele, K. (2021). *Artisanal and small-scale mining in Ethiopia Scoping study for a comprehensive survey*. London, United Kingdom. International Growth Centre Policy Brief ETH2104.

Kolie, B., Yao, J., Sunahara, G., and Duonamou, L. (2019). Environmental impact of Lefa gold mining on its local population, Republic of Guinea. *Nat. Resour.* 10 (08), 305–323. doi:10.4236/nr.2019.108020

Kyngdon-McKay, Y., Jorns, A., Wheat, B., Cushman, T., and Nemomissa, S. (2016). An analysis of the commercial potential of Ethiopia's coloured gemstone industry.

Lemessa, F., Simane, B., Seyoum, A., and Gebresenbet, G. (2022). Analysis of the concentration of heavy metals in soil, vegetables and water around the bole Lemi industry park, Ethiopia. *Heliyon* 8 (12), e12429. doi:10.1016/j.heliyon.2022.e12429

Lemessa, F., Simane, B., Seyoum, A., and Gebresenbet, G. (2023). Assessment of the impact of industrial wastewater on the water quality of rivers around the bole lemi industrial park (BLIP), Ethiopia. *Sustainability* 15 (5), 4290. doi:10.3390/su15054290

Li, X., Wei, Y., Cao, D., Xu, L., Zhang, Y., Wei, J., et al. (2024). Cooperative exploration model of coal–Ge deposit: a case study of the Wulantuga coal–Ge deposit in Shengli coalfield, Inner Mongolia, China. *Energy Explor. Exploitation*, 01445987241239351. doi:10.1177/01445987241239351

Liyew, A. M., Kassie, A., Teshale, A. B., Alem, A. Z., Yeshaw, Y., and Tesema, G. A. (2021). Exploring spatiotemporal distribution of under-five mortality in Ethiopia: further analysis of Ethiopian Demographic and Health Surveys 2000, 2005, 2011 and 2016. *BMJ Paediatr. open* 5 (1), e001047. doi:10.1136/bmjpo-2021-001047

Meaza, H., Ali, M., Hishe, S., and Tesfamariam, Z. (2015). Small scale gold mining effects on the miners and local communities in semi-arid region of Ethiopia. *J. Geogr. za Geografiju* 10 (1), 25–40. doi:10.18690/rg.10.1.3935

Mencho, B. B. (2022). Assessing the effects of gold mining on environment: a case study of Shekiso district, Guji zone, Ethiopia. *Heliyon* 8 (12), e11882. doi:10.1016/j.heliyon.2022.e11882

Mimba, M. E., Mbafor, P. U. T., Fils, S. C. N., and Nforba, M. T. (2023). Environmental impact of artisanal and small-scale gold mining in east Cameroon, sub-saharan Africa: an overview. *Ore Energy Resour. Geol.* 15, 100031. doi:10.1016/j.oreoa.2023.100031

Ministry of Mines and Petroleum (2022). *State of Artisanal and Small-Scale Mining in Ethiopia*. Addis Ababa, Ethiopia: Ministry of Mines and Petroleum. Accessed May 12, 2022

Moyo, T., Chitaka, T. Y., Lotter, A., Schenck, C. J., and Petersen, J. (2022). Urban mining versus Artisanal and Small-Scale Mining (ASM): an interrogation of their contribution to sustainable livelihoods in sub-Saharan Africa. *Extr. Industries Soc.* 12, 101173. doi:10.1016/j.exis.2022.101173

Mudau, D. G. (2019). Opportunities and challenges faced by foreign mining investors in Ethiopia.

Mufandaedza, S. M. (2021). *The impact of trade liberalisation on mining sector total factor productivity change of selected countries from SADC*. South Africa: Doctoral dissertation, North-West University.

Mulaba-Bafubiandi, A. F., Ukponu, M. U., Odo, A. U., Singh, N., and Chauke, B. B. (2023). "Contemporary issues in the governance and regulation of artisanal and small-scale mining (ASM) in Africa," in *Mining law and governance in Africa* (Routledge), 98–129.

Nursamsi, I., Phinn, S. R., Levin, N., Luskin, M. S., and Sonter, L. J. (2024). Remote sensing of artisanal and small-scale mining: a review of scalable mapping approaches. *Sci. Total Environ.* 951, 175761. doi:10.1016/j.scitotenv.2024.175761

Nyssen, J., and Kiros, H. (2022). Map of Tigray's mineral resources (north Ethiopia)-Canadian and other international mining licenses.

Obiri, S., Mattah, P. A., Mattah, M. M., Armah, F. A., Osae, S., Adu-Kumi, S., et al. (2016). Assessing the environmental and socio-economic impacts of artisanal gold mining on the livelihoods of communities in the Tarkwa Nsuaem municipality in Ghana. *Int. J. Environ. Res. Public Health* 13 (2), 160. doi:10.3390/ijerph13020160

Ofosu, G., Dittmann, A., Sarpong, D., and Botchie, D. (2020). Socio-economic and environmental implications of artisanal and small-scale Mining (ASM) on agriculture and livelihoods. *Environ. Sci. Policy* 106, 210–220. doi:10.1016/j.envsci.2020.02.005

Otamonga, J. P., and Poté, J. W. (2020). Abandoned mines and artisanal and small-scale mining in Democratic Republic of the Congo (DRC): survey and agenda for future research. *J. Geochem. Explor.* 208, 106394. doi:10.1016/j.gexplo.2019.106394

Owusu-Nimo, F., Mantey, J., Nyarko, K. B., Appiah-Effah, E., and Aubynn, A. (2018). Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: a focus on the Western Region. *Heliyon* 4 (2), e00534. doi:10.1016/j.heliyon.2018.e00534

Purevjav, B. (2024). *Improving water management in mining regions through understanding stakeholders' views and perspectives on integrated water resources management*. Doctoral dissertation, Vancouver, BC, Canada. University of British Columbia.

Quarm, J. A., Anning, A. K., Fei-Baffoe, B., Siaw, V. F., and Amuah, E. E. Y. (2022). Perception of the environmental, socio-economic and health impacts of artisanal gold mining in the Amansie West District, Ghana. *Environ. Challenges* 9, 100653. doi:10.1016/j.envc.2022.100653

Redehey, B. G. (2017). Youth in artisanal gold mining: risks and opportunities; the case of Asgede Tsimbla Woreda, Northwestern Tigray national regional state, Ethiopia. *Int. J. Capacity Build. Educ. Manag.* 3 (2), 1–8.

Regassa, A. (2022). Frontiers of extraction and contestation: dispossession, exclusion and local resistance against MIDROC Laga-Dambi gold mine, southern Ethiopia. *Extr. industries Soc.* 11, 100980. doi:10.1016/j.exis.2021.100980

Rutherford, B., and Buss, D. (2022). "The (in) visibility of women and mining: the gendering of artisanal and small-scale mining," Abingdon, Oxfordshire, United Kingdom. Sub-Saharan Africa: Taylor and Francis.

Sey, E., and Belford, E. J. (2019). Levels of heavy metals and contamination status of a decommissioned tailings dam in Ghana. *EQA-International J. Environ. Qual.* 35, 33–50. doi:10.6092/issn.2281-4485/9060

Techane, G., Sahilu, G., Alakangas, L., Mulat, W., and Kloos, H. (2023). Assessment of heavy metal pollution associated with tailing dam in gold mining area, southern Ethiopia. *Geosystem Eng.* 26 (1), 1–11. doi:10.1080/12269328.2022.2160833

Teklemariam, S. (2015). Artisanal/small scale gold mining activity and its role in sustainable lvelihood of the rural community: a case of hademdemi village. *Gash Barka Reg. Eritrea*.

Teku, D., Abebe, A., and Fetene, M. (2024b). Ethiopian orthodox tewahedo church sacred forests as sanctuaries for endangered species: key roles, challenges and prospects. *Sustain. Environ.* 10 (1), 2391614. doi:10.1080/27658511.2024.2391614

Teku, D., and Derbib, T. (2025). Uncovering the drivers, impacts, and urgent solutions to soil erosion in the Ethiopian Highlands: a global perspective on local challenges. *Front. Environ. Sci.* 12, 1521611. doi:10.3389/fenvs.2024.1521611

Teku, D., and Eshetu, S. (2024). Impact of climatic variabilities and extreme incidences on the physical environment, public health, and people's livelihoods in Ethiopia. *Front. Clim.* 6, 1435138. doi:10.3389/fclim.2024.1435138

Teku, D., Kesete, N., and Abebe, A. (2024a). GIS based annual soil loss estimation with revised universal soil loss equation (RUSLE) in the upper Meki sub-catchment, rift valley sub-basin, Ethiopia. *Cogent Food and Agric.* 10 (1), 2311802. doi:10.1080/23311932.2024.2311802

Teku, D., and Workie, M. D. (2025). Longitudinal analysis of soil erosion dynamics using the RUSLE model in Ethiopia's Lake Ziway watershed: implications for agricultural sustainability and food security. *Front. Environ. Sci.* 12, 1506001. doi:10.3389/fenvs.2024.1506001

Tessema, Z. K., Zelalem, Y., and Moges, A. (2024). An Ethnobotanical study of medicinal plants used by the local people of Assosa District, Benishangul Gumuz Regional State, Ethiopia. *Ethnobot. Res. Appl.* 29, 1–29. doi:10.32859/era.29.66.1-29

The National ASM Policy (2018). Ministry of Mines and Petroleum. (2018). *The National Artisanal and Small-Scale Mining Policy of Ethiopia*. Addis Ababa, Ethiopia: Ministry of Mines and Petroleum. Accessed March 26, 2022.

United Nations Environment Programme (UNEP) (2022). *Global mercury assessment 2022*. Nairobi: UNEP.

Usman Kaku, D., Cao, Y., Al-Masnay, Y. A., and Nizeyimana, J. C. (2021). An integrated approach to assess the environmental impacts of large-scale gold mining: the nzema-gold mines in the ellembelle district of Ghana as a case study. *Int. J. Environ. Res. Public Health* 18 (13), 7044. doi:10.3390/ijerph18137044

Warkisa, G., Asrat, A., Omitogun, A. A., and Oljira, T. (2021). Petrogenesis of gold-hosting Neoproterozoic syenite from the Tulu Kapi area, western Ethiopia. *J. Afr. Earth Sci.* 176, 104145. doi:10.1016/j.jafrearsci.2021.104145

Weldegiorgis, F. S., Mesfin, B., and Sturman, K. (2017). Looking for oil, gas and mineral development in Ethiopia: prospects and risks for the political settlement. *Extr. Industries Soc.* 4 (1), 151–162. doi:10.1016/j.exis.2016.12.003

Weleabzgi, B., Alemayehu, T., and Estifanos, S. (2021). Assessing the environmental impact of artisanal gold mining activities on the waters and sediments around meli, northwestern Tigray, Ethiopia. *Momona Ethiop. J. Sci.* 13 (2), 281–299. doi:10.4314/mejs.v13i2.6

Wolearegay, A. H., Amare, Y. B., Hagos, A. A., Mesfin, K. A., Abraha, H., Cheepurupalli, N. R., et al. (2025). Evaluation of open pit mine design with a focus on the Dichinama marble resource in Western Tigray, Ethiopia. *Arabian J. Geosciences* 18 (3), 56–14. doi:10.1007/s12517-025-12200-w

Yego, E. K., Kebenei, S., Cheserek, G., and Sitienei, A. (2018). Nexus between artisanal gold mining and community livelihood in nandi and west pokot mining regions, Kenya. *Kabarak J. Res. and Innovation* 6 (1), 68–78. doi:10.58216/kjri.v6i1.126

Yihdego, Y., Salem, H. S., Ayongaba, B., and Veljkovic, Z. (2018). Mining sector challenges in developing countries, Tigray, Ethiopia and inspirational success stories from Australia. *Int. J. Min. Mineral Eng.* 9 (4), 321–367. doi:10.1504/ijmme.2018.097440

Zerga, K., and Tsegaye, B. (2020). Coffee diversity and conservation in Ethiopia. *Sustain. Agric. Rev.* 39, 35–55. doi:10.1007/978-3-030-38881-2_2