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Modernizing Artisanal and Small-Scale Mining

Harnessing new technologies for sustainable development

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Modernizing Artisanal and Small-Scale Mining:
Harnessing new technologies for sustainable development

May 2024

Written by Nellie Mutemeri and Nydia Ponnan

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Acronyms

3Ts	tin, tantalum, and tungsten
ASM	artisanal and small-scale mining
ASGM	artisanal and small-scale gold mining
DMCS	digital mining cadastre system
DRC	Democratic Republic of the Congo
GPS	geographic positioning system
ICT	information and communication technology
LIDAR	light detection and ranging
LSM	large-scale mining
NGO	non-governmental organization
OHS	occupational health and safety
RFID	radio frequency identification
PPE	personal protective equipment
UAV	unmanned aerial vehicle
UNDP	United Nations Development Programme
XRF	X-ray fluorescence spectrometer

1.0 Background

1.1 Introduction

Technology drives change in every part of our lives, in every country around the world. Technology impacts society in many ways: it can boost productivity and efficiency, enhance communication, democratize access to information, and increase the interconnectedness of people around the globe. Disruptive technologies are already having a transformative impact on the large-scale mining sector. Big data, advanced analytics, and machine learning are boosting recovery and output. Automation and robotics are reducing operation costs and risks. Digitization is improving workers' health and safety, and early detection software and sensors are reducing downtime. The use of operational enhancing technologies is helping mining companies counter the industry-wide productivity downswing it has experienced since the mid-2000s (Lala et al., 2016; Ramdoo, 2019; Ramdoo et al., 2021).

BOX 1. DEFINITION OF TERMS

Technology: For the purpose of this report, technology is the systematic application of scientific knowledge, tools, and techniques to create, enhance, and streamline processes, replacing manual and traditional methods. It signifies a dynamic progression, empowering societies with unprecedented efficiency, innovation, and the ability to overcome challenges.

Artisanal and small-scale mining (ASM): Artisanal mining refers to individuals, small groups, or families extracting minerals with minimal or no mechanization, often informally. Artisanal miners often operate on a small scale, focusing on local deposits. Small-scale mining, on the other hand, encompasses a broader scope, including operations that may use more advanced equipment and involve larger groups or formalized enterprises. It is important to note that ASM occurs on a spectrum, with artisanal mining representing the more grassroots and manual end and small-scale mining extending along the spectrum to incorporate a wider range of technologies and organizational structures. While both share characteristics of simplicity and limited resources, this spectrum highlights the varying degrees of formality, scale, and technological advancement within ASM.

Similarly, the deployment and dissemination of new technologies in the ASM sector hold promise to enhance the productivity and incomes of ASM operators. Although ASM is understood to employ rudimentary, non-mechanized methods, this is not entirely accurate. Many ASM operators have already mechanized their operations to increase productivity: ASM miners are often found using sluices, dredges, generators, small water pumps, crushers, grinders, ball mills, and balances. The introduction of new, accessible technologies in ASM could improve worker safety, reduce mercury use in gold processing, increase traceability, and create more robust mineral value chains. Technology could impact the lives of ASM stakeholders far beyond increased yields; having access to information, finance, and markets could address many of the negative conditions associated with ASM. ASM directly employs approximately 45 million people across 80 countries; using a multiplier, it is estimated that three times as many people work in supporting industries (World Bank, 2020). Therefore, leveraging technology to produce better socio-economic outcomes would benefit hundreds of millions of people across the world.

While technology has the potential to generate positive outcomes, the introduction of new technologies can also bring forth a myriad of negative impacts. Job losses, in particular, emerge as a notably concerning potential consequence. Various studies[1] underscore the displacement of labour caused by automation across different sectors. In the context of ASM, this trend could have devastating effects on the livelihoods of ASM stakeholders and associated service providers. It is essential to highlight that women are disproportionately at risk of job loss due to automation (Brussevich et al., 2018). Women constitute a third of the global ASM workforce, with even higher percentages in certain countries and regions—for instance, women account for 50% of Africa's ASM workforce (Ramdoo et al., 2023; Weldegiorgis, 2018). Women in ASM often occupy peripheral, lower-earning roles, and the increased mechanization of the sector will likely result in heightened levels of job insecurity, impacting women first.

The implementation of productivity-enhancing technologies poses environmental challenges, as evidenced in agriculture, where technology use has been linked to reduced biodiversity, increased soil degradation, water quality issues, and grassland encroachment (Killebrew et al., 2010). In the context of ASM, activities already contribute to environmental degradation, and an escalation of mining at an unsustainable rate could lead to irreparable harm. Recognizing the dual potential for positive and negative impacts, this report aims to scrutinize how emerging technologies will affect the ASM sector. Additionally, the potential consequences of job redundancies in large-scale mining (LSM) due to technological advancements raise particular concerns, especially in remote areas with limited alternative livelihood options. All of these factors accentuate the necessity for a nuanced exploration of the socio-economic dynamics at play.

1.2 Research Objectives

This research centres on exploring the impacts of emerging technologies in the ASM sector. The primary goal is a comprehensive analysis of ASM's current state, including tools, techniques, and technologies across the mining life cycle, along with addressing cross-cutting issues like monitoring and enforcement, occupational health and safety (OHS),

[1] Studies conducted by researchers such as Acemoglu and Restrepo (2017, 2019), Brynjolfsson and McAfee (2014), Chiacchio et al. (2018), and Piva and Vivarelli (2017).

access to finance, and access to information. Distinguishing between artisanal and small-scale mining, the study also examines newly developed, phase-specific technologies. The overarching objective is to assess the benefits, opportunities, and policy options linked to emerging technologies in ASM, offer insights into worker safety, reduce mercury use, improve traceability, and establish robust mineral value chains. Additionally, the research includes a gap analysis of new technologies that identifies crucial areas for advancement to drive sustainable development within the industry. Additional information regarding the research approach and methodology is available in Appendix A.

2.0 The Technological Landscape in ASM: Current state and emerging trends

This section critically examines the present state of ASM, distinguishing between artisanal mining and small-scale mining, by analyzing the tools, techniques, and technologies utilized across the mining life cycle, as illustrated in Figure 1. The detailed breakdown in the accompanying box initiates our exploration, offering a comprehensive description of the ASM spectrum, including operational modes, motivations, and the types of activities associated with this sector. Furthermore, insights are provided into newly developed tools, techniques, and technologies tailored for each phase of the ASM life cycle. This section also traces the progression in technologies used, emphasizing the evolving landscape and innovative advancements in ASM practices.

BOX 2. UNDERSTANDING THE ASM SPECTRUM

ASM unfolds as a multifaceted sector, where a diverse array of actors, methodologies, and motivations converge. Understanding this intricate tapestry is pivotal for grasping the nuanced dynamics that define ASM.

A pivotal distinction emerges between artisanal mining and small-scale mining, encapsulating a spectrum of operational scales, methodologies, and overarching objectives.

1. Artisanal mining

Artisanal mining, the foundational element of ASM, is often characterized by a hands-on, labour-intensive approach that echoes time-honoured, culturally embedded practices. In this milieu, manual techniques predominate, representing an intimate connection to traditional methods passed down through generations. Artisanal miners, driven by a blend of cultural heritage and subsistence needs, engage in smaller-scale operations that embody a profound connection to the land and its resources.

2. Small-scale mining

In contrast, small-scale mining introduces a layer of complexity, as it melds traditional practices with more advanced technologies and larger operational scales. While still retaining elements of artisanal roots, small-scale mining ventures beyond manual techniques. Advanced equipment comes into play, signalling a departure from purely traditional methods and often ushering in a realm where the boundaries between artisanal and industrial mining practices become blurred.

3. Stakeholder motivations in ASM

The realm of ASM is enriched by stakeholders driven by diverse motivations. Economic survival and subsistence propel a significant segment, turning to mining as a lifeline for financial stability in regions with limited alternative opportunities. Simultaneously, a subset values cultural heritage, viewing mining as a means to preserve and perpetuate ancestral practices amid the currents of modernization.

Understanding the motivations within ASM is integral for crafting policies that resonate with the specific needs and aspirations of different groups, fostering a sustainable and inclusive sector.

The distinction between metallic and non-metallic mining lies in the types of minerals or materials extracted from the Earth's crust.

A. Metallic mining

- Minerals extracted: Metallic mining involves the extraction of metals from the earth. Common examples include gold, silver, copper, iron, zinc, and nickel.
- Methods: In metallic ASM, various methods may be employed, including simple hand tools, manual digging, panning, and basic processing techniques. Small-scale machinery may also be used, but the scale and technology involved are far less advanced compared to large-scale mining operations.

B. Non-metallic mining

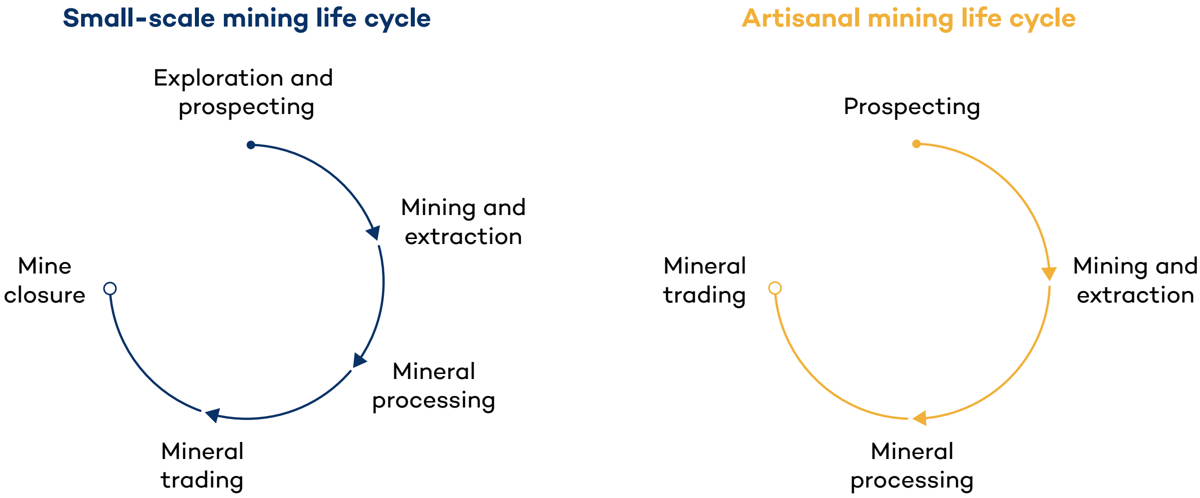
- Minerals extracted: Non-metallic mining involves the extraction of non-metallic resources or minerals. This category includes materials like sand, gravel, limestone, clay, gemstones, and other industrial minerals.
- Methods: Similar to metallic ASM, non-metallic ASM typically relies on basic tools and manual labour. Excavation, sorting, and basic processing methods are commonly used. In some cases, non-metallic mining may involve the use of small-scale machinery for extraction and processing.

Engagement in metallic and non-metallic ASM is shaped by diverse factors, encompassing economic, social, and environmental dimensions. In metallic ASM, individuals or communities are often drawn by limited economic opportunities, finding allure in the potential income from extracting valuable metals such as gold, silver, or copper. In regions with scarce formal employment, metallic ASM becomes a vital livelihood option. Motivation stems from economic gain and the accessibility of metallic resources in the local environment, prompting participation. On the other hand, for some non-metallic minerals ASM is influenced by construction and infrastructure needs, with materials like sand, gravel, and limestone being essential. Local demand for non-metallic minerals in construction, road maintenance, and agriculture drives engagement, addressing both economic and local development considerations. While economic motivations are less pronounced than in metallic ASM, non-metallic ASM still serves as a source of income for individuals and communities through the sale of materials.

2.1 The ASM Life Cycle

Figure 1 illustrates the mining life cycle for artisanal and small-scale operations. It initiates with prospecting and exploration, involving the search for minerals, identification of ore deposits, and the technical and economic assessment of the mineral deposit to determine resources and reserves in small-scale mining scenarios. The following stages encompass mine development and production, with the latter divided into ore extraction (mining) and mineral processing to prepare the ore for the market. Depending on its mineral and operational nature, ore may undergo processing at a secondary location or be transported post-processing for sale. The life cycle progresses next to the mineral sale stage.

FIGURE 1. Small-scale and artisanal mining life cycle



Source: Authors.

The final phase, mine closure, involves tailings management, site restoration, and remediation, typically undertaken by formalized small-scale operations. Ideally, closure should include monitoring and evaluation before land relinquishment to the government; however, this crucial step is often neglected in ASM.

2.2 Exploration and Prospecting

While both artisanal and small-scale operators undertake prospecting and exploration activities, these aspects are of lesser concern for this report. More detailed information about this step in the value chain can be found in Appendix B.

2.3 Mining and Ore Extraction

Mining is the act of "digging" or extracting ore. This process can range from rudimentary to mechanized in ASM, depending on the mineral, the level of formality, technical capacity, and capitalization. At the rudimentary end, alluvial and hard rock miners use picks, axes, hoes, chisels, shovels, and hammers for extraction. The ore extraction methods are also dependent on the type of deposit, as detailed below.

2.3.1 Alluvial and Eluvial

Next to rivers, dams, and streams, ASM miners can be seen panning (see Figure 2) for minerals (typically gold or diamonds), and they also use elementary (homemade) sluice boxes to concentrate ore from sediments in waterbodies. More equipped operations will use excavators to extract large amounts of mineral-bearing sediments. Some miners use dredges with high-suction pumps to extract ore from riverbed deposits. Without access to dredges, miners in the Democratic Republic of the Congo (DRC) and Sierra Leone, for example, build dikes with sandbags in the middle of the river to divert the water and extract ore from the drier isolated side. This method is dangerous, as dam breaks have caused miners to drown (Priester et al., 2010). ASM miners also dive into waterbodies to extract gravel using buckets and bags, though often without the necessary diving equipment. The extracted minerals are hauled onto a canoe-like structure that floats on the surface. This method is risky because the miner can drown or sustain injuries due to improper protection equipment. A technique called "hydraulicking," which uses a high-pressure pump to dislodge ore from highly weathered slopes of eluvial and alluvial deposits, is commonly used by miners in Guyana and the DRC (Hustrulid, 1998).

FIGURE 2. Metal pan and calabash in Mali

Credit: Nellie Mutemeri, 2014.

FIGURE 3. Open-pit ASM in Guinea

Credit: Nellie Mutemeri, 2021.

FIGURE 4. An excavator used in ASM in Guinea

Credit: Nellie Mutemeri, 2021.

2.3.2 Open Pit

At the most basic level, miners use picks and spades to dig open pits (see Figure 3) that are usually wider than they are deep. The ore is transported to processing areas, and the mode of transport is dependent on the level of capitalization. Small pumps are used to evacuate the water. Mechanized operations sometimes use tractor loader backhoes or excavators (see Figure 4) to dig, and where practised, proper mine planning involves benching and monitoring slope stability. Open-pit mining is considered to be the least dangerous and most efficient form of mining; however, miners can still be injured due to improper equipment use and rock falls (Priester et al., 2010). There are interventions by development practitioners trying to improve safety by teaching safer ways of open-pit mining (Ministry of Mines, n.d.).

2.3.3 Underground Mining

Underground ASM ore extraction predominantly occurs in two forms: (i) in relatively shallow shafts and adits that are developed by the miners and (ii) by accessing old, abandoned, often derelict (sometimes operational) LSM mines. Underground mining is the most challenging form of mining; on virgin ground, miners must construct deep (could be as deep as 35 m) mineshafts, excavate in poorly constructed tunnels with little ventilation and then bring the ore up to the surface for processing (Schwartz et al., 2021). Underground miners use the same rudimentary tools as the other miners—pickaxes, shovels, hammers, etc. Depending on the hardness of the rock, some ASM miners use automated tools such as pneumatic drills and jackhammers, and yet others use explosives to blast the rock. The ore is loaded into bags or buckets and then pulled up to the surface using a pulley, winch, or windlass. Underground mining is considered the most dangerous form of mining because miners risk rockfalls and mine collapse, which can result in death. Due to poor ventilation in the tunnels, miners are exposed to dust and air pollution. More informed and better-capitalized miners may use rudimentary air blowers or include ventilation shafts in the mine design to improve ventilation.

Table 1 presents a compilation of mining and ore extraction tools, techniques, and technologies actively utilized in ASM. The table delineates the distinctions between tools employed by mechanized, better-capitalized small-scale operations and those commonly adopted by artisanal miners.

TABLE 1. Current trends in mining and ore extraction

<table>
<tr><th colspan="4">Types of technology used in mining and ore extraction</th></tr>
<tr><th rowspan="2"></th><th colspan="2">Relevance for artisanal mining</th><th rowspan="2">Relevance for capitalized small-scale mining</th></tr>
<tr><th>Informal mining</th><th>Formal mining</th></tr>
<tr><td>Digital infrastructure</td><td>n/a</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Tools</td><td>• Picks
• Axes
• Hoes
• Chisels
• Shovels
• Hammers
• Pans
• Manual dredges
• Dikes with sandbags
• Pulleys
• Manual winches
• Windlasses</td><td>• Picks
• Axes
• Hoes
• Chisels
• Shovels
• Hammers
• Pans
• Manual dredges
• Dikes with sandbags
• Pulleys
• Manual winches
• Windlasses</td><td>• High-pressure pumps
• Dredges with high-suction pumps
• Pneumatic drills
• Jackhammer
• Explosives
• Compressors
• Excavators
• Higher-capacity water pumps
• Tractor loader backhoes
• Air blowers
• Ventilation shafts
• Mechanized winches</td></tr>
<tr><td>Techniques</td><td>• Dimension stone extraction using in-situ rock cutting and "plug and feathering"[2] underground support (using timber and sandbags)</td><td>• Dimension stone extraction using in-situ rock cutting and "plug and feathering" underground support (using timber and sandbags)</td><td></td></tr>
</table>

Source: Authors.

2.3.4 New Technologies for Mining and Extraction

In this section, it becomes evident that the capitalization of ASM operations correlates with advancements in the tools used, resulting in improved output and efficiency, as illustrated in Table 2. This progression may open up avenues for technology transfer, particularly from mechanized or better-capitalized small-scale miners to artisanal miners through the sale of cost-effective second-hand tools.

2 For a description of the plug-and-feather method, see https://www.mindat.org/glossary/plug-and-feather_method.

TABLE 2. The progression of tools used in mining

Manual tools	Semi-mechanized tools
Picks, axes, hoes, chisels, shovels, hammers	Jackhammer
Picks, axes, hoes, chisels, shovels, hammers	Explosives
Pulleys, manual winches, windlass	Mechanized winches
Picks, axes, hoes, chisels, shovels, hammers	Tractor loader backhoes/excavator
Dikes with sandbags	Dredges with high-suction pumps

Source: Authors.

Mining and extraction activities conducted by ASM operators are characterized by their physically demanding, labour-intensive, and repetitive nature. The reliance on less efficient methods, techniques, and technologies often leads to sub-optimal mining practices, fostering hazardous working conditions that pose risks of injuries or fatalities (World Bank, 2020). Despite these challenges, it is crucial to acknowledge the potential disparities in technology accessibility and adoption. More organized and capitalized ASM operations are likely to have greater opportunities to incorporate innovations, thereby enhancing safety and productivity in their activities. Regrettably, at the time of writing, there are no imminent technologies in development to address these concerns, which emphasizes the pressing need to explore innovative solutions[3] within the ASM sector.

2.3.5 Technological Landscape Evaluation: A gap analysis of mining and extraction

The predominant use of rudimentary tools, such as picks, axes, and shovels, poses significant safety concerns, leading to a high risk of injuries and fatalities. Moreover, limited access to advanced technologies, including digital infrastructure, hinders the efficiency and safety of ASM operations, particularly in informal settings. Environmental impact is also a concern, with certain practices like the use of water diversion techniques potentially causing harm. Underground mining, the most challenging form of ASM, faces issues of poor ventilation, dust exposure, and air pollution, emphasizing the need for improved safety measures. Inadequate training and education contribute to unsafe practices among ASM miners. Technology transfer challenges further exacerbate disparities, hindering the adoption of advanced tools by artisanal miners. The reliance on labour-intensive methods and the absence of imminent technological developments underscore the necessity for innovative solutions within the ASM sector.

[3] To illustrate, precision farming technologies involve leveraging data and technology to optimize diverse agricultural practices, such as precision planting and harvesting. Similarly, precision mining technologies, exemplified by accurate mapping and real-time monitoring, hold the promise of enhancing the efficiency of ore extraction in ASM.

Policy recommendations to bridge the gaps in mining and extraction:

1. **Safety standards and training implementation**: Develop and implement robust training programs aimed at educating ASM miners on safer mining practices; prioritize the establishment and enforcement of comprehensive safety standards for ASM operations; and collaborate with relevant stakeholders, including industry experts and local communities, to ensure that safety standards and training programs are tailored to the unique challenges and needs of ASM operations.
2. **Technology access**: Establish support mechanisms, including subsidies or incentives, to promote the adoption of technologies by ASM operators, facilitating a gradual transition from rudimentary tools to more efficient and safer alternatives. Encourage the implementation of mentorship programs where experienced industrial and/or small-scale miners assist artisanal miners in integrating modern technologies into their operations.
3. **Environmental regulations and sustainable practices**: Implement comprehensive environmental protection policies that encourage the adoption of sustainable mining practices and technologies, minimize ecological damage, and ensure rigorous monitoring and enforcement mechanisms to guarantee compliance.

2.4 Transportation

Transport is required at various stages of the ASM value chain. After excavation, the ore is often transported to a processing centre or a second location where it is packaged for sale. Once processed, the mineral can be transported to a refiner, an individual buyer, or a buying centre. In addition, mine waste and effluent water often need to be transported to disposal sites such as tailing ponds or dumps.

Depending on the capitalization of the operation, the miners could use animals such as donkeys or horses to carry mining materials or pull carts. People, often women and children, can be found carrying buckets or sacks or using wheelbarrows to transport the minerals to the second location or to be sold; some miners use motorcycles (two- and three-wheelers) (see Figure 5). Better-capitalized operations will use lorries and trucks to move the minerals along the different stages of the value chain.

Table 3 delineates the modes of transportation employed in ASM, distinguishing those utilized by mechanized, better-capitalized small-scale operations from those generally used by artisanal operators.

TABLE 3. Current trends in ASM-related transportation

Types of technology used for transportation in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure	Mobile phones	Mobile phones	Mobile phones
Tools	• Animals (beasts of burden, e.g., donkeys) • Animal-drawn carts • People • Wheelbarrows • Motorcycles (two- and three-wheelers, usually hired)	• Animals (beasts of burden, e.g., donkeys) • Animal-drawn carts • People • Wheelbarrows • Motorcycles (two- and three-wheelers, usually hired)	• Three-wheelers (owned) • Lorries • Trucks • Conveyor belts
Techniques	n/a	n/a	n/a

Source: Authors.

FIGURE 5. A three-wheeler carrying ore in Mali

Credit: Nellie Mutemeri, 2014.

2.4.1 New Technologies for Transportation

The primary factor influencing the choice of transportation among ASM operators is the extent of financial resources available to invest in the operation. When capital is limited, ASM operators resort to manual hauling techniques involving animals or human labour. In contrast, operators with adequate funding typically opt for mechanized transportation methods. Currently, there is a lack of specialized technologies designed to streamline the transportation of minerals or waste produced by ASM. The only notable exception is the use of mobile devices by miners to coordinate transportation logistics. Although it may seem like there is limited room for innovative solutions to improve the transportation of ASM-produced materials, lessons from other sectors highlight the potential application of technology in this space. In the smallholder agriculture sector—for example, where they face analogous capital constraints—Hello Tractor[4] in Kenya and Nigeria and Trotro Tractor[5] in Ghana connect tractor owners to smallholder farmers through a digital tractor-sharing application, giving smallholder farmers without capital, access to tractors to improve their productivity.

2.4.2 Technological Landscape Evaluation: A gap analysis of transportation

The transportation landscape reveals significant gaps characterized by limited technological advancements, underutilized digital infrastructure, and a dependency on capitalization for modern transportation methods. Predominantly, artisanal operators resort to traditional modes of transportation, such as animals, human labour, and manual tools like wheelbarrows, and mechanized transportation is seen in capitalized small-scale mining operations. While mobile phones are somewhat employed, the overall integration of digital infrastructure for optimizing transportation logistics is lacking. The ASM sector, as a whole, faces a dearth of specialized technologies designed to streamline the transportation of minerals and waste.

Policy recommendations to bridge the gaps in transportation:

1. **Research and development funding**: Allocate funding for research and development specifically focused on creating innovative technologies for ASM transportation and support partnerships between research institutions, technology developers, and the ASM sector to identify and implement tailored solutions.
2. **Collaboration with other sectors**: Establish collaborations with other sectors, particularly the smallholder agriculture sector, to leverage insights from their successful approaches to addressing similar challenges, with the aim to inspire and adapt technologies for enhancing transportation in ASM.

2.5 Mineral Processing

Mineral processing increases the value of the ore material and involves a wide range of activities, depending on the mineral of economic interest. For most ores, including precious metals, gemstones, and base metals, this involves a process of comminution, mineral separation, and further upgrading or refining. The next section demonstrates these processes further using gold as an example that is commonly exploited in the ASM sector. For a more comprehensive examination of mineral processing, please refer to Annex 4.

[4] For more information on Hello Tractor, see https://hellotractor.com.

[5] For more information on Trotro Tractor, see https://www.trotrotractor.com.

Gold Recovery Technologies:

The gold recovery process encompasses three main stages: comminution, mineral separation, and refining, each employing various technologies.

FIGURE 6. An ASM miner crushing using a rock in Tanzania

Credit: Nellie Mutemeri, 2013.

1. Comminution:

- **Crushing, milling, and pulverization**: Mechanized methods involve the use of jaw crushers, stamp mills, and ball mills, while rudimentary practices include manual grinding using mortars, pestles, or large stones. The efficiency of these methods varies, impacting gold recovery rates.

2. Separation:

- **Gravity-concentration technologies**: Technologies range from traditional panning to more advanced methods like sluices, shaking tables, and centrifugal concentrators. These technologies preconcentrate gold by exploiting gravity differentials, improving efficiency compared to manual practices.
- **Mercury amalgamation technologies**: Despite being considered a "bad practice," some ASM miners still employ mercury amalgamation. Whole-ore amalgamation and concentrate amalgamation are used with varying levels of mercury containment and recovery.
- **Cyanidation technologies**: Advanced operations utilize cyanide leaching systems. Technologies involve batch leaching in tanks or vats, heap leaching, and subsequent gold removal using activated carbon and zinc. However, the use of cyanide poses environmental and health risks.

FIGURE 7. A miner using an amalgamation barrel in Colombia

Credit: Nellie Mutemeri, 2015.

3. Smelting:

- Smelting technologies: In cases where high-grade concentrate or gold sponge recovery is required, smelting techniques come into play. Tools for smelting include chemical fluxes like borax to enhance the process of producing a cleaner doré.

Table 4 outlines mineral processing tools, techniques, and technologies, highlighting distinctions between those employed by mechanized, better-capitalized small-scale operations and those used by artisanal operators.

TABLE 4. Current trends in mineral processing

<table>
<tr><th colspan="4">Types of technology used for mineral processing in ASM</th></tr>
<tr><th rowspan="2"></th><th colspan="2">Relevance for artisanal mining</th><th rowspan="2">Relevance for capitalized small-scale mining</th></tr>
<tr><th>Informal mining</th><th>Formal mining</th></tr>
<tr><td>Digital infrastructure</td><td>n/a</td><td>n/a</td><td>Automated machinery controls</td></tr>
<tr><td>Tools</td><td>• Grinders
• Pestles and mortars
• Hand-held hammers
• Self-fabricated ball mills
• Magnets separation with recycled magnets
• Panning dishes
• Ground sluices
• Sluice boxes
• Manual jigs
• Copper plates
• Charcoal burners
• Blow torches</td><td>• Grinders
• Pestles and mortars
• Hand-held hammers
• Self-fabricated ball mills
• Magnets separation with recycled magnets
• Panning dishes
• Ground sluices
• Sluice boxes
• Manual jigs
• Copper plates
• Charcoal burners
• Blow torches</td><td>• Sluice boxes
• Copper plates
• Amalgamation barrels
• Rock crushers (e.g., jaw, cone, etc.)
• Screens (trommel, shaker, vibrating, grizzly, etc.)
• Wet pan mills
• Ball and rod mills
• Concentrators
• Mercury retorts
• Fume hoods
• Furnaces
• Mechanized jigs
• Advanced mechanized sluices
• Shaking tables
• Cyclones
• Spirals
• Ore feed hoppers</td></tr>
<tr><td>Techniques</td><td>• Manual crushing and milling
• Wet gravity concentration
• Magnetic separation
• Hand sorting
• Dry winnowing
• Settling ponds
• Mercury amalgamation
• Smelting
• Roasting</td><td>• Manual crushing and milling
• Wet gravity concentration
• Magnetic separation
• Dry winnowing
• Settling ponds
• Mercury amalgamation
• Smelting
• Roasting</td><td>• Mechanized crushing and milling
• Wet gravity concentration
• Magnetic separation
• Mercury amalgamation
• Froth flotation
• Cyanidation (including vat leaching, heap leaching, and agitated tank leaching)</td></tr>
</table>

Types of technology used for mineral processing in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
			• Borax application in smelting • Aqua regia (hydrochloric acid and sulphuric acid) dissolution

Source: Authors.

2.5.1 New Technologies for Mineral Processing

The adoption of novel technologies in the current phase of gold production has been motivated by the search for viable alternatives to the employment of hazardous chemicals, notably mercury and cyanide. Specific emphasis has been placed on methods for extracting gold without the use of mercury, as exemplified in Table 5. This emphasis is driven by a compelling need to adhere to the Minamata Convention on mercury pollution[6]. Mercury-free technologies in mineral processing refer to approaches that either eliminate or minimize the reliance on mercury, particularly in gold extraction. These technologies mitigate the environmental and human health repercussions associated with artisanal and small-scale gold mining (ASGM) while simultaneously enhancing recovery rates. Despite the benefits, challenges such as cost and capacity barriers, along with limited incentives for ASGM operators, have impeded the widespread adoption of these technologies.

[6] https://minamataconvention.org/en

TABLE 5. Mineral processing technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Chemical leaching	A cyanide-processing technique using an innovative source of cyanide reagent (e.g., locally sourced cassava waste).	**Gold Eco-Leaching**, National University of Engineering in Peru, Peru[7]	It is appropriate for different ore types; it is a non-proprietary method.	The solution has a 50%–60% recovery rate lower than some comparable methods and requires some knowledge of metallurgy, which artisanal miners may not have. The cyanide reagent may pose a threat to ASM miners due to the health risks associated with cyanide and a threat to the environment if applied to reprocessing mercury-laden tailings.
Hydromet-allurgical	Porous polymer network sorbent and membrane materials that replace mercury in the gold mining process. These can serve as a precision-level purification platform to remove toxic or precious metals from water.	**Porous Polymer Sorbents**, Chemfinity, US[8]	An environmentally friendly, non-toxic gold recovery method with precise removal of metals and toxins from wastewater that eliminates the need for heavy machinery and provides opportunities for ASM by replacing mercury use and purifying water for reuse.	Financial obstacles for ASM operators and limitations in operational capacity pose significant challenges for adoption in the sector.

[7] https://www.artisanalminingchallenge.com/innovation/gold-eco-leaching

[8] https://www.engineeringforchange.org/news/chemfinitys-membrane-prototypes-replace-mercury-gold-mining/

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Hydromet-allurgical	This method applies to the cyanide-free dissolution of gold with hydrochloride acid, perchloric acid, and precipitation of the gold in the filtrate with sodium metabisulphite.	**iGoli Mercury-free Gold Extraction**, Mintek, South Africa[9]	This mercury-free, cyanide-free method uses easily available reagents.	The solution's weaknesses include the need for a power supply, reliance on chemicals and technical expertise for process control, and the cost, making it unaffordable for individual artisanal miners.
Physical separation (gravity and magnetic)	A sluice box with magnetic plates that captures fine gold and may also be used at former mining sites to remove mercury from the environment.	**Cleangold**, Cleangold LLC, United States[10]	This affordable (USD 40–200), non-technical, non-motorized sluice box equipped with magnetic plates to capture fine gold as small as 5 microns can be seamlessly integrated into or entirely replace a miner's current setup. This solution has the potential to increase a miner's yield by up to 50% without relying on mercury. It offers the opportunity to process gold and rework tailings responsibly.	ASM miners might hesitate to adopt a new, unfamiliar technology.

[9] https://www.altamet.com.au/wp-content/uploads/2023/02/ALTA-2023-GPM-Abstract-Mintek.pdf
[10] https://www.cleangold.com

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Physical separation (gravity)	This gold concentrator is suitable for coarse and fine metals, hard rock, and eluvial and alluvial deposits.	**Gold Kacha**, APT, South Africa[11]	It is adaptable to both coarse and fine precious metals, suitable for diverse deposits (hard rock, eluvial, and alluvia), scalable through nesting multiple units for larger tonnage, and affordable for artisanal miners. It offers opportunities for deployment in various mining contexts with water and electricity and can serve as a centralized processing centre for multiple ASM operators in an area.	It requires a power supply and water, and the estimated recoveries, ranging from 70%–75%, may not be compelling enough to incentivize miners accustomed to using mercury.
Physical separation (gravity)	The shaking table is a simple solution for physical separation using movement and water.	**Gemini shaking table**, JXSC Mine Machinery Factory (and several others), China[12]	It is effective for hard rock and eluvial deposits, achieves a remarkable 99% recovery rate, and is based on well-understood physical separation principles.	The solution demands a power supply and a reliable water supply and is limited to processing small batches of ore at a time.

Source: Authors.

11 https://www.aptprocessing.com/modular-mining-equipment/gravity-concentration/gold-concentrator-goldkacha
12 https://www.jxscmachine.com/gravity-separator/gemini-shaking-table/

2.5.2 Technological Landscape Evaluation: A gap analysis of mineral processing

Gaps in the technology landscape for mineral processing include a reliance on hazardous chemicals like mercury and cyanide, leading to significant environmental and health risks. While ASM operators currently employ traditional and rudimentary methods, such as manual grinding and gravity concentration, there is a pressing need for safer and more sustainable technologies. The lack of readily accessible alternatives to hazardous chemicals poses a challenge, contributing to the sector's status as the largest source of mercury pollution globally. The emergence of new technologies, such as mercury-free methods, holds promise for reducing the industry's environmental impact and improving recovery rates. However, barriers such as cost, technical capacity limitations, and the need for reliable water and power supplies hinder the widespread adoption of these alternatives in the ASM sector.

Policy recommendations to bridge the gaps in mineral processing:

1. **Research and development funding for safer technologies**: Allocate significant funding for targeted research and development to create and enhance safer mineral processing technologies for ASM while concurrently supporting collaborative initiatives among research institutions, technology developers, and ASM operators to identify, test, and validate alternative technologies aiming to eliminate or reduce the use of hazardous chemicals.
2. **Financial incentives for adoption of safer practices**: Introduce financial incentives, subsidies, or grants for ASM operators to adopt and integrate safer mineral processing technologies, implementing a tiered incentive structure that accommodates the scale of operations to ensure accessible financial support for both informal and formal mining entities transitioning to environmentally friendly and health-conscious practices.
3. **Capacity building**: Developing comprehensive capacity-building programs aims to train ASM operators in utilizing new, safer mineral processing technologies, addressing potential hesitancy or a lack of technical expertise while concurrently facilitating technology transfer through mentorship programs, workshops, and knowledge-sharing initiatives from better-capitalized industrial and/or small-scale mining operations and research institutions, fostering a seamless transition to safer practices.

2.6 Beneficiation

Mineral value addition and beneficiation are often delinked from ASM activities; however, many ASM operators do participate in this step of the value chain. In Ghana, Mali, and Burkina Faso, the artisanal miners have a long history of producing gold jewellery (McQuilken and Hilson, 2016; AMDC, 2017). In Chad, artisans use steel to make knives and other agricultural tools. In Uganda and Zambia, ASM miners, predominantly women, participate in the cutting and polishing of gemstones (IGF, 2018). In South Africa, many of the sand and aggregate mining operators also produce cement bricks. Unlike brickmaking, which requires relatively simple and accessible equipment, the beneficiation of some minerals can require expensive equipment like high-precision diamond cutters or gold refineries, which, in many countries, are only accessible if provided by governments, development agencies, or LSM companies. The Gemmology Centre in Madagascar provides such a service and has been instrumental in setting up similar facilities in other African countries, including Tanzania, Zambia, and Kenya.

The beneficiation of clay to produce pottery is common in many rural communities around the world, as is the production of stone sculptures and ornaments using simple carving and polishing methods. In South Africa and Lesotho, ASM operators add value to quarried sandstone using simple stone masonry techniques to produce ornaments and stone cladding to supply the construction sector.

TABLE 6. Current trends in beneficiation

Types of technology used for beneficiation in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure	n/a	n/a	Automated machinery controls
Tools	• Hammers, chisels • Shovels • Handmade brick moulds • Charcoal furnaces	• Hammers, chisels • Shovels • Handmade brick moulds • Charcoal furnaces • Blow torches	• Faceting machines (gemstones) • Tumblers (gemstones) • Lapidary saws (gemstones) • Grinders (gemstones) • Slip-casting moulds (pottery) • Pottery wheels • Electric and gas kilns (pottery and brickmaking) • Advanced mechanized moulding and forming equipment (brickmaking) • Bridge saws (stonework) • Edge polishers (stonework) • Grinding machines (stonework) • Polishing machines (stonework) • Splitting machines (stonework) • Cutting machines (stonework) • Stone drilling machines (stonework)

Types of technology used for beneficiation in ASM			
	Relevance for artisanal mining		Relevance for capitalized small-scale mining
	Informal mining	Formal mining	
Techniques	• Smelting to upgrade doré (gold) • Brick moulding • Pottery hand forming (clay) • Handmade stone sculpture (stone) • Firing bricks in a kiln clamps • Open firing of pottery • Gold and silversmithing • Iron forging	• Smelting to upgrade doré (gold) • Brick making (development minerals) • Pottery making (clay) • Handmade stone sculpture (stone) • Stone masonry (dressing) • Gold and silversmithing	• Smelting to upgrade doré (gold) • Brick moulding • Pottery forming • Sculpting Stone (stone) • Firing of pottery and bricks in kiln clamps • Gold and silversmithing

Source: Authors.

Table 6 delineates the beneficiation tools, techniques, and technologies employed in ASM, distinguishing between those utilized by mechanized, better-capitalized small-scale operations and those generally used in ASM.

2.6.1 New Technologies for Beneficiation

Enhancing the value of mineral products through mineral value addition significantly boosts economic returns for ASM operators. It is noteworthy that while beneficiation typically leads to increased value, in some cases, it is more closely associated with the manufacturing sector rather than ASM operations. Despite this, the study revealed a dearth of technological advancements tailored specifically to improve the beneficiation of ASM-produced materials. Instead, what prevails is the adoption of existing industrial-scale methods in sectors such as brickmaking and pottery production within ASM contexts. This absence of ASM-specific technological innovations underscores a critical gap in the value chain where the integration of suitable technologies could yield substantial positive impacts.

2.6.2 Technological Landscape Evaluation: A gap analysis of beneficiation

The lack of specific technological advances in mineral value addition and beneficiation tailored for ASM hinders the sector's overall progress. Existing beneficiation tools, techniques, and technologies employed in ASM often involve pre-existing industrial-scale methods rather than innovations tailored to the unique needs and constraints of ASM operators.

Policy recommendations to bridge the gaps in beneficiation:

1. **Establish research and development initiatives**: Allocate funding for dedicated research and development initiatives focused on creating innovative and cost-effective ASM-specific mineral value addition and beneficiation technologies.

2.7 Mineral Trading

ASM-mined minerals and metals are sold in a variety of ways. In a number of countries, governments have set up buying centres where they evaluate mineral products and buy from registered miners. For example, the Entreprise Générale du Cobalt in the DRC was established to buy cobalt from ASM operators, and the state mining company in Chile, Empresa Nacional de Minería (ENAMI), buys ores or concentrate from small-scale copper miners. In Ghana, the state-owned Precious Minerals Marketing Company buys gold and diamonds from artisanal miners. In Zimbabwe, Fidelity Printers and Refiners, wholly owned by the Reserve Bank of Zimbabwe, buys gold produced by artisanal miners, and the Minerals Marketing Corporation of Zimbabwe facilitates access to the market for other minerals produced by artisanal miners, such as chromite, tin, tantalite, and tungsten. Government buying centres employ diverse analytical techniques, including microscopes, atomic absorption spectrometers, fire assay facilities, and X-ray fluorescent spectrometers (XRF), to assess material grade,[13] determine prices, and enhance traceability[14] within the supply chain.

FIGURE 8. Digital scale in Guyana

Credit: Nellie Mutemeri, 2019.

Simultaneously, private mineral traders, who are licensed by the government in certain countries, also purchase ASM products. These traders have access to equipment (see Figure 8) for evaluating mineral products and determining buying prices. Moreover, private mineral buyers may operate facilities to upgrade mineral products before selling locally or exporting them to international markets.

[13] Grade assessment—involving the categorization of minerals based on quality and determining fair compensation for miners— is pivotal for pricing negotiations.

[14] Traceability ensures transparency by tracking the origin and movement of minerals throughout the supply chain, contributing to ethical and sustainable practices.

In addition to regulated mineral trading, it is crucial to acknowledge the existence of unregulated predatory buying arrangements in the ASM sector. These unscrupulous practices can exploit the vulnerabilities of artisanal miners, leading to unfair compensation, unethical practices, and a lack of traceability within the supply chain. Unlike government-regulated processes, private mineral traders operating without sufficient oversight may engage in exploitative pricing and contribute to adverse socio-economic impacts on artisanal miners.

TABLE 7. Current trends in mineral trading

Types of technology used for beneficiation in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure	Mobile phones	• Mobile phones • Digital scales	• Mobile phones • Automated controls for hand-held X-ray fluorescent spectrometer (XRF) • Atomic absorption spectrometers
Tools	• Homemade balances • Manual balances • Measuring cylinder • Electronic scales	• Homemade balances • Manual balances • Measuring cylinder • Electronic balances	• Electronic scales • Microscopes • Fire assay facilities • Hand-held X-ray fluorescent spectrometer (XRF) • Atomic absorption spectrometers
Techniques	• Visual inspection of mineral product • Density determination	• Visual inspection of mineral product • Density determination	• Visual inspection of mineral product • Density determination

Source: Authors.

As such, throughout the trading process, both miners and traders utilize distinct equipment and techniques to safeguard their interests. Miners employ various tools, including scales and visual inspection, during mineral assessment, while both parties may use different analytical techniques, such as microscopes and advanced spectrometers, during negotiation and pricing. Traders often possess facilities for upgrading mineral products, utilizing advanced equipment to enhance mineral quality. While the equipment used by miners and traders may vary based on resource availability and technological access, both contribute to the intricate process of ASM mineral trading, navigating complexities in negotiations, striving for fair compensation, and ensuring traceability within the supply chain.

Table 7 outlines mineral trading methods, techniques, and technologies, distinguishing between those utilized by mechanized, better-capitalized small-scale operations and those generally employed in ASM.

2.7.1 New Technologies for Mineral Trading

There has been a focus on improving the traceability of ASM minerals to ensure that the mining activities related to these minerals have not caused any harm to people and the environment, including land degradation, deforestation, loss of biodiversity, farm invasions, water pollution, mercury releases, crime, child labour, narco-trafficking, and the spread of diseases. These traceability activities are typically linked to access to market initiatives because ASM occurs in isolated areas, generally away from central buying centres, and many ASM operators do not have the networks or marketing knowledge to sell their minerals to well-paying international buyers. As a result, ASM-mined minerals are often sold at below market value to unregistered buyers, which greatly disadvantages ASM operators as they are unable to earn enough money to graduate from subsistence mining. Table 8 showcases mineral trading technologies that can improve the earning potential of ASM operators by linking them to formal fair markets.

TABLE 8. Mineral trading technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Track and trace	Track and trace technologies in ASM utilize digital systems like blockchain, geographic positioning system (GPS), and unique identifiers (QR codes or radio frequency identification [RFID] tags) to monitor and document the mineral supply chain, enhancing transparency and accountability from extraction to market and promoting responsible sourcing.	• ASM Progress App, Alliance for Responsible Mining, Colombia[15] • Moyo Gems, Moyo Gems, Tanzania[16] • The Analytical Fingerprint, BGR, Great Lakes Region[17]	This approach ensures the traceability and the provenance of ASM-produced minerals from mine to market, thereby reducing the risk of the mineral being associated with negative, irresponsible practices and improving the market value.	It requires significant groundwork and may push ineligible ASM miners to access black markets or other informal structures.

15 https://www.responsiblemines.org/en/
16 https://moyogems.com
17 https://www.bgr.bund.de/EN/Themen/Min_rohstoffe/CTC/Analytical-Fingerprint/analytical_fingerprint_node_en.html

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Digital marketplace	Digital marketplace technologies in ASM use online platforms to connect miners with buyers, streamlining transactions, improving market access, and enhancing transparency in the mineral supply chain for fair and sustainable sourcing.	• Virtu Gem, Virtu Gem, Malawi, Kenya, and Zambia[18] • Sissai, United Nations Development Programme (UNDP)/Sissai, Peru[19]	This technology provides improved access to markets through online retailing for ASM-produced goods.	There is potential for resistance from ASM operators, and data, internet access and literacy are required.

Source: Authors.

[18] https://virtugem.com
[19] https://pe.sissai.com

2.7.2 Technological Landscape Evaluation: A gap analysis of beneficiation

The technological landscape in mineral trading for ASM reveals significant gaps, notably the absence of tailored technological innovations designed to meet the unique challenges faced by ASM operators. This deficiency extends to traceability and accountability measures within the supply chain, with unregulated predatory buying arrangements exploiting vulnerabilities and hindering ethical practices. Moreover, the prevalent sale of ASM-mined minerals below market value to unregistered buyers underscores challenges in accessing fair markets, impeding the economic advancement of ASM operators. While emerging technologies like track and trace systems and digital marketplaces offer potential solutions, their adoption faces resistance, compounded by issues such as limited data access, internet connectivity, and digital literacy.

Policy recommendations to bridge the gaps in mineral trading:

1. **Incentivize the adoption of track and trace technologies**: Allocate financial resources and implement incentives to encourage the adoption of track and trace technologies, such as blockchain, GPS, and unique identifiers (QR codes or RFID tags), in ASM mineral trading. These technologies can enhance transparency and accountability, ensuring the traceability of minerals from extraction to market. The incentives should be structured to support ASM operators in implementing these systems, mitigating the potential challenges associated with groundwork and facilitating their integration into formal markets.
2. **Promote digital literacy and market access initiatives**: Develop comprehensive programs aimed to enhance digital literacy among ASM operators, facilitating their participation in digital marketplaces. These programs include training on the use of online platforms for trading minerals, connecting ASM miners with buyers, and streamlining transactions. Additionally, create initiatives that improve internet access in remote ASM areas and address any resistance from operators, ensuring they benefit from fair market prices. This holistic approach should empower ASM communities to leverage digital tools for improved market access and sustainable sourcing.
3. **Develop information and communication technology (ICT) infrastructure for remote connectivity**: Allocate resources for the establishment and improvement of ICT infrastructure in remote areas where ASM operators are prevalent. This initiative aims to ensure that even in remote locations, ASM operators have access to reliable and high-speed internet connectivity, fostering their integration into digital platforms for mineral trading.

2.8 Mine Closure: Waste management, remediation, and restoration

Notably, ASM operators grapple with substantial challenges in waste management, a struggle exacerbated by limited capital and capacity. Vital tasks, including soil replacement, shaping and amelioration, revegetation, and biodiversity reestablishment, crucial for effective mine closure, are frequently impeded.

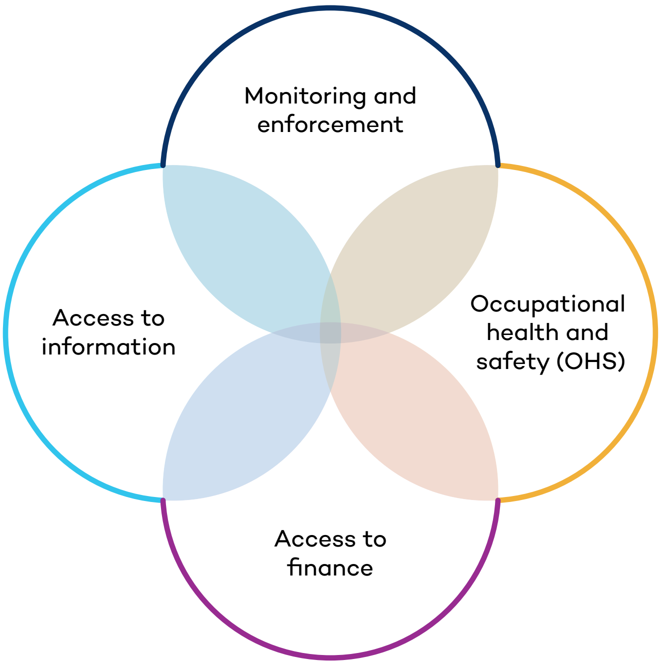
The nomadic tendencies of many ASM miners, driven by a pursuit of opportunities, contribute to the abandonment of open pits, uncovered and uncontained tailings ponds, and dumps at previous sites. The disposal of ASM tailings often involves releasing them into waterbodies or depositing them openly on the mine site. In rare instances, miners may resort to constructing concrete settling ponds, periodically emptying tailings onto a dump.

It is important to recognize that this phase of the value chain—encompassing waste management, remediation, restoration activities, and mine closure efforts—lies beyond the scope of this report. Comprehensive details and additional information on this aspect can be found in Annex 3.

2.9 Cross-Cutting Issues in ASM

In addition to the ASM life cycle, as described above, a number of cross-cutting issues in ASM present challenges to the sector that could be improved through technological advancements. This section provides insight into selected transversal issues (see Figure 2) and the development of technologies that would contribute to a more productive ASM sector.

FIGURE 9. Cross-cutting issues in ASM



Source: Authors.

2.9.1 Monitoring and Enforcement

Effective natural resource governance hinges on the establishment and upkeep of suitable institutional and administrative frameworks to support and regulate mining activities. An integral aspect of monitoring and enforcement involves the implementation of mineral governance systems to empower authorities to issue permits and manage information related to ASM operations.

Countries with active mining sectors, such as Botswana[20], Namibia[21], and Zambia[22], have taken strides by developing publicly accessible mining cadastres. These cadastres serve as comprehensive platforms for tracking mining activities, promoting transparency, and facilitating public oversight. Ghana, for instance, has adopted an internet-based system that has streamlined the application and issuance of small-scale mining permits (Hilson, Bartels and Hu, 2022).

A mining cadastre essentially acts as a publicly accessible geo-portal displaying a country's mining titles, detailing the various phases of mine or land development and the corresponding ownership. Stakeholders in the mining sector can leverage the cadastre to submit applications and documentation for government review. Beyond regulatory functions, mining cadastres play a crucial role in record-keeping, exploration, prospecting, and overall natural resource management.

The integration of mining cadastres with geological information management systems enhances their utility by capturing geological data generated through exploration permits and mining rights. This information becomes invaluable for future applications, including supporting the development of ASM. Trimble[23], a leading developer of mining cadastres, has demonstrated success in crafting tailored systems designed to capture and manage mineral traceability records, promoting responsible mineral due diligence. Rwanda has notably implemented such a system.

However, challenges persist in some countries where tracking mining operations is hindered by limited state capacity and the persistence of outdated analogue systems. Addressing these challenges is crucial for achieving effective governance and the sustainable management of natural resources in the mining sector. Table 9 provides an overview of the methods employed for monitoring and enforcement in the ASM sector.

TABLE 9. Current trends in monitoring and enforcement

Types of technology used for beneficiation in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure		• Digital mining cadastre • Tablet • Mobile phone	• Digital mining cadastre • Hand-held smart devices (including mobile phones)
Tools	n/a	n/a	n/a
Techniques	Mineral governance systems	Mineral governance systems	Mineral governance systems

Source: Authors.

20 https://portal.miningcadastre.gov.bw/page/landing
21 https://maps.landfolio.com/Namibia/
22 https://portals.landfolio.com/zambia/
23 https://www.trimble.com/en

2.9.1.2 New Technologies for Monitoring and Enforcement

Inefficient systems make operations monitoring and the collection of taxes and royalties more difficult for governments. ASM regulators must have the capacity and tools to monitor and enforce compliance with the law in order to limit conflict over land and resources, stop environmental destruction, and ensure proper working conditions, among others. As ASM activities typically happen in remote areas, far from governmental offices, many regulators struggle to properly monitor ASM activities due to limited manpower or insufficient resources (vehicles, petrol, airplanes, and helicopters) to travel to ASM sites. The adoption of new technologies or innovations could reduce the costs and time associated with monitoring and enforcement and improve the capacity of institutional actors to ensure compliance. See Table 10 for potential technological solutions.

TABLE 10. Monitoring and enforcement technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
ASM monitoring	Monitoring technologies in ASM employ satellite imagery and advanced analytics to track mining activities, environmental changes, and land-use patterns. Utilizing geospatial analysis and artificial intelligence, these technologies contribute to effective monitoring, management, and the promotion of responsible practices within the ASM sector.	• **Unmanned aerial vehicles (UAVs)/drones** • **Project Inambari**, Skytruth, United States • **ASMSpotter**, dida/Levin Sources, Germany, United Kingdom	Detection and monitoring of ASM activities can be used by governments to stop environmental damage caused by ASM operators and to support formalization initiatives.	Technical capacity and training are needed to operate the technology. Licensing the technology may be too expensive for governments to afford, and private companies could use it to thwart ASM operations and the livelihoods of ASM miners.
Governance	Governance technologies in ASM aim to enhance regulatory frameworks, formalization processes, and the overall management of ASM. These technologies often involve online platforms and impact assessment tools and contribute to improved governance, legal compliance, and informed decision making within the ASM sector.	• **Registro Especial de Comercializadores Y Procesadores de Oro (RECPO) Online**, Ministry of Energy and Mines of Peru/UNDP, Peru • **Mining Impact Calculator,** Conservation Strategy Fund, United States	Improved governance of the ASM sector can be achieved through data collection and data production.	It may exclude or threaten the livelihoods of ASM miners who are unable to formalize.

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Reporting tools	Reporting technologies in ASM involve digital platforms and tools for efficient data collection, analysis, and sharing, enhancing transparency, accountability, and sustainability in ASM.	• **Remote Environmental Monitoring**, Timby, Canada	Communities can monitor and anonymously and safely report illegal ASM and any negative impacts. It can enhance governmental capacity and response time and can assist non-governmental organizations (NGOs) or conservation organizations in responding to community grievances.	Surveillance can threaten the livelihoods of ASM miners.

Source: Authors.

2.9.1.3 Technological Landscape Evaluation: A gap analysis of monitoring and enforcement

The technological landscape for monitoring and enforcing ASM activities reveals significant gaps and challenges. Many countries face limitations in state capacity and rely on outdated analogue systems, hindering the effective tracking of mining operations. Remote ASM sites, coupled with insufficient resources, pose challenges for regulators to monitor activities. The adoption of new technologies, such as UAVs, online platforms, and reporting tools, offers potential solutions. However, technical capacity, high licensing costs, and the potential misuse of technology by private entities raise concerns. Additionally, there is a risk that governance technologies may exclude ASM miners who are unable to formalize, and reporting tools could inadvertently threaten their livelihoods.

Policy recommendations to bridge the gaps in monitoring and enforcement:

1. **Enhance technological infrastructure and training**: Governments should prioritize investments in upgrading technological infrastructure to monitor and enforce ASM activities. This strategy includes the development of digital mining cadastres, satellite monitoring systems, and online governance platforms. Simultaneously, robust training programs should be implemented to enhance the technical capacity of regulators, ensuring the effective utilization of these technologies. By providing adequate resources and training, authorities can overcome the limitations associated with outdated analogue systems and build the expertise necessary for the successful implementation of advanced monitoring tools. Collaboration with technology providers and international organizations can facilitate the transfer of knowledge and resources to strengthen the technological foundation for ASM governance.

2.9.2 Occupational Health and Safety

ASM is dangerous work, which often involves strenuous, repetitive manual tasks with limited automation or equipment (World Bank, 2023). Due to the working conditions, miners are frequently exposed to toxins, dust and noise pollution, infectious diseases and physical hazards. However, as a consequence of limited government oversight and the lack of finances to purchase the necessary OHS gear, ASM is often carried out with little concern for the health and safety of the miners and surrounding communities (World Bank, 2023). In underground shafts, ASM miners use candles or handheld torches (see Figure 10) for light, the former being a hazard because of the occurrence of hydrocarbon emissions underground.

When ASM operators do consider mine safety management, the miners have been seen using personal protective equipment (PPE), specifically hard hats, work boots, high-visibility jackets, and masks.

FIGURE 10. Torches used in ASM in Mali

Credit: Nellie Mutemeri, 2014.

TABLE 11. Current trends in OHS

Types of technology used for OHS in ASM			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure	• Two-way radios • Mobile phones	• Two-way radios • Mobile phones	• Two-way radios • Mobile phones
Tools	• PPE • Hand-held torches • Candles • Hand-held blowers	• PPE • Hand-held torches • Candles • Hoses • Hand-held blowers	• PPE • Hand-held torches • Petrol and diesel pumps for dewatering • Mining ventilation fans • Electric lighting • Miners' cap lamps
Techniques	• Ventilation shafts	• Ventilation shafts	• Ventilation shafts

Source: Authors.

To communicate with workers aboveground, some miners use two-way radios or mobile phones. Miners with technical knowledge may create tunnels or ventilation shafts to increase air circulation underground. Well-capitalized operations may purchase ventilation fans to aid with ventilation in the mine shaft, and petrol and diesel pumps are used for dewatering underground workings and open pits.

Table 11 presents a list of some OHS tools, techniques, and technologies utilized in the ASM sector. The table distinguishes between those employed by mechanized, better-capitalized small-scale operations and those generally used in ASM.

2.9.2.1 New Technologies for OHS

The adoption of technology to improve health and safety in ASM could meaningfully enhance the working conditions for ASM operators and reduce their level of exposure to hazards. At the time of writing, only one technology that had been created with OHS in ASM in mind was identified (as highlighted in Table 12).

TABLE 12. OHS technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Digital PPE	Digital, wearable PPE integrates sensors into safety gear like smart helmets or vests, monitoring conditions and vital signs. Enabling real-time data transmission enhances safety practices, aids early hazard detection, and improves the well-being of ASM operators in challenging environments.	• **Picoyune,** United States[24]	Wearable, real-time mercury level detection limits hazardous mercury exposure.	Challenges include cost barriers and a lack of incentive for ASM operators to purchase PPE.

Source: Authors.

2.9.2.2 Technological Landscape Evaluation: A gap analysis of OHS

The technological landscape exposes notable deficiencies in OHS practices, thereby endangering miners as a result of demanding manual tasks and a lack of adequate automation. A lack of government oversight and financial constraints often result in inadequate safety measures. Miners primarily rely on PPE such as hard hats, boots, jackets,

[24] https://www.picoyune.com

and masks, with some using hand-held torches and candles for lighting in underground shafts. Communication tools like two-way radios and mobile phones are employed, and better-capitalized operations may invest in ventilation fans and pumps for dewatering. However, the gap persists, especially for informal and less-funded operations.

Policy recommendations to bridge the gaps in OHS:

1. **Financial incentives for technology adoption**: Governments and international organizations should explore financial incentives and support mechanisms to encourage the adoption of advanced OHS technologies in ASM. This could involve subsidies, grants, or partnerships with technology providers to make digital PPE more accessible to ASM operators. Creating awareness about the long-term benefits of technology adoption for health and safety may also incentivize miners to invest in these tools.
2. **Establish a regulatory framework for OHS standards**: Policy-makers should establish and enforce clear OHS standards for ASM operations. This includes incorporating guidelines for the use of advanced safety technologies. Governments should collaborate with industry experts, technology developers, and ASM communities to create a regulatory framework that promotes the adoption of innovative safety solutions. Establishing a certification system for OHS technologies could ensure compliance and raise the overall safety standards within the ASM sector.

2.9.3 Access to Finance

ASM operators are often unable to access formal financial institutions due to the informal manner in which most ASM operates, the lack of acceptable collateral, low levels of financial literacy, and the inaccessibility of financial institutions to remote ASM miners (Witni et al., 2020). Consequently, they are relegated to informal lending structures that offer unfavourable, sometimes predatory, lending terms, such as exorbitant interest rates or impossible payback periods.

TABLE 13. Current trends in access to finance products for ASM

Types of technology used for financing in ASM			
	Relevance for artisanal mining		Relevance for capitalized small-scale mining
	Informal mining	Formal mining	
Digital infrastructure	n/a	n/a	n/a
Tools	n/a	n/a	n/a
Techniques	• Informal lending structures	• Informal lending structures • Personal loans from financial institutions	• Informal lending structures • Personal loans from financial institutions • Commercial loans from financial institutions

Source: Authors.

Table 13 lists trends in access to finance products available to ASM operators, differentiating some of those used by mechanized, better-capitalized small-scale operations from those used generally in ASM.

2.9.3.1 New Technologies for Access to Finance

Access to credit and capital for ASM miners to advance their operations through investments in equipment and technology could result in greater productivity and higher volumes and revenue. Greater economic yields can aid ASM miners in overcoming many of the challenges associated with ASM. Innovations like mobile money, microfinance, and cryptocurrencies (as detailed in Table 14), which have been designed to disrupt and democratize financial service provision, can offer solutions to the current challenges facing ASM operators' access to finance.

TABLE 14. Access to finance technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Mobile money	This digital financial technology allows users to conduct financial transactions, including payments, transfers, and withdrawals, using a mobile device. It provides a convenient and secure alternative to traditional banking, enabling users to manage their finances, make purchases, and access various financial services through mobile applications or SMS-based platforms.	• **M-Pesa,** Safaricom, Kenya[25] • **GCash,** Mynt the Philippines[26] • **Tigo Pesa,** Tigo, Tanzania[27]	It can increase financial inclusion and be used to save and invest.	It requires telecoms infrastructure, and because women are more likely to have a lower level of literacy and less likely to have a mobile phone, and/or data, this technology could result in gendered access.

[25] https://www.safaricom.co.ke/personal/m-pesa
[26] https://asianbankingandfinance.net/financial-technology/news/gcash-operator-mynt-buys-payment-platform-globe-41m
[27] https://www.tigo.co.tz/tigo-pesa/

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Microfinance	This financial service model offers small-scale loans, savings, and insurance to empower individuals and businesses, especially those excluded from traditional banking, fostering financial inclusion and economic development.	• **BRAC**, globally[28] • **FINCA International**, globally[29] • **Grameen Bank**, Bangladesh[30]	Microfinance was designed for marginalized groups to enhance financial inclusion and provide unbanked populations with access to capital and credit.	Applying for financing requires the ASM operator to visit a branch, which is generally located in an urban centre and hard for ASM operators who operate in remote areas to access. Microfinance institutions offer loans at a higher interest rate than commercial banks.
Cryptocurrency	Cryptocurrency is a decentralized digital currency using blockchain technology for secure, transparent transactions. It operates without central authorities, employs cryptography for security, and offers global accessibility.	• **GoldFinX** – GoldFinX, Spain[31]	It can increase access to financial resources for ASM and could potentially improve productivity, efficiency, and responsible mining.	High dividends may put a financial strain on the ASM operation, resulting in an unsustainable model over time.

Source: Authors.

28 https://www.brac.net
29 https://finca.org
30 https://grameenbank.org.bd
31 https://goldfinx.com

2.9.3.2 Technological Landscape Evaluation: A gap analysis of access to finance

The current technological landscape reveals a notable gap, with digital infrastructure, tools, and techniques showing limited relevance for ASM operators. However, promising new technologies offer potential solutions. Mobile money, microfinance, and cryptocurrencies have emerged as innovative approaches to democratize financial services. While these technologies can enhance financial inclusion and empower ASM operators, challenges such as telecommunication infrastructure requirements, gendered access issues, the necessity of physical branch visits for microfinance, and potential financial strains associated with cryptocurrency dividends highlight the need for a nuanced and context-specific approach to bridge these financial gaps in the ASM sector.

Policy recommendations to bridge the gaps in technologies for access to finance:

1. **Promote financial inclusion through digital literacy**: Governments and NGOs should implement programs to enhance digital literacy, especially among ASM operators, with a focus on mobile money technologies. This approach can address potential gendered access issues and empower miners to leverage these digital financial platforms for savings, transactions, and access to credit.
2. **Facilitate microfinance outreach**: Policy-makers should work with microfinance institutions to establish outreach programs specifically tailored for ASM operators that include technologies, such as mobile microfinance services, to bring financial services closer to remote ASM communities, addressing the challenges associated with physical branch accessibility.
3. **Develop a regulatory framework for cryptocurrency**: Governments should develop a clear regulatory framework for the use of cryptocurrencies in ASM financing. This framework should ensure responsible and transparent use of digital currencies, protecting ASM operators from potential financial strains while fostering innovation in the sector. Regular monitoring and adjustments to regulations can maintain a balance between financial accessibility and sustainability.

2.9.4 Access to Information

The ASM sector suffers from a critical lack of complete, accurate, and reliable data due to a lack of country-level census data and limited access to a geographically remote ASM community (World Bank, 2019). Filling this data gap will allow for the creation of better policies and formalization processes and improve the ability of governments and development agencies to meet the needs of ASM stakeholders.

Moreover, ASM operators suffer from a chronic lack of good practice information, which can result in the use of unsuitable mining methods (World Bank, 2023). This may, in turn, lead to the use of inappropriate techniques and tools, which can cause environmental damage, decrease productivity and efficiency, and result in unsafe working conditions.

Table 15 lists the access to information methods and products available to ASM operators, differentiating some of those used by mechanized, better-capitalized small-scale operations from those used generally in ASM.

TABLE 15. Current trends in informational products in ASM

Types of technology used for accessing information in ASM			
	Relevance for artisanal mining		Relevance for capitalized small-scale mining
	Informal mining	Formal mining	
Digital infrastructure	• Information sourced from the Internet • Information dissemination through mobile devices	• Information sourced from the Internet • Information dissemination through mobile devices	• Information sourced from the Internet • Information dissemination through mobile devices
Tools	n/a	n/a	n/a
Techniques	• Word of mouth • On-the-job training	• Word of mouth • On-the-job training	• Word of mouth • On-the-job training

Source: Authors.

2.9.4.1 New Technologies for Access to Information

Access to information will facilitate the collection and disbursement of information to ASM populations that are typically in remote places with limited infrastructure. Appropriate technological advancements with a wide geographic reach, such as mobile messaging services, digital networking platforms, and online knowledge hubs that are purpose-driven for the ASM landscape, can aid in overcoming these challenges, as detailed in Table 16.

TABLE 16. Access to information technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Knowledge hub	An online knowledge hub is a digital platform offering curated information and resources on specific topics, facilitating easy access to educational materials and fostering information-sharing.	• **PlanetGOLD Knowledge Repository** – planetGOLD, global[32] • **Mercury-Free Technology Atlas** – University of the Witwatersrand, South Africa[33]	It offers improved access to best practice information to reduce the use of mercury in ASM.	A certain level of literacy, data availability and internet access, and digital infrastructure are needed.
Mobile messaging	Mobile messaging is the real-time exchange of text or multimedia messages through mobile devices, using applications or SMS for instant communication.	• **Interactive Voice Response** – Solidaridad, Ghana[34] • **Quipu** – Ulula, France[35] • **Matokeo** – Ulula, France[36]	Messaging enables the collection and aggregation of information provided by miners and ASM communities. It can be used to record and remediate grievances and provide information about environmental and work-safety practices and other important information.	Miners and ASM communities could be resistant to providing information. Miners are mobile and often change their numbers.

32 https://www.planetgold.org/resources
33 https://mercuryfreetechnology.org
34 https://www.solidaridadnetwork.org/news/accessible-technology-for-artisanal-miners/
35 https://ulula.com/updates/project/ulula-joins-the-inaugural-amazon-colab-to-develop-and-test-technology-to-protect-the-amazon-rainforest/
36 https://ulula.com/updates/project/data-collection-asm-mining-eastern-drc/

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Digital networking platforms	Digital networking platforms are online spaces where individuals connect, share information, and build relationships.	• **ASM WhatsApp Groups** – miners and communities, globally • **The Delve Exchange** – University of Queensland/ World Bank, globally[37]	Connecting miners to other miners, buyers, dealers, and equipment suppliers is a way for them to create a network, share information, and access markets.	A smartphone or computer is needed, and data and internet access are required. A level of literacy is required.

Source: Authors.

[37] https://www.delvedatabase.org/delve-exchange-en

2.9.4.2 Technological Landscape Evaluation: A gap analysis of access to information

Access to information faces substantial challenges marked by a critical lack of accurate data and limited dissemination channels. The absence of comprehensive country-level census data and the remoteness of ASM communities contribute to this information gap, hindering the development of effective policies for formalization. ASM operators also grapple with a chronic deficiency in good practice information, leading to the adoption of unsuitable mining methods and tools that result in environmental damage and unsafe working conditions. Current information access methods primarily rely on informal channels, such as word of mouth and on-the-job training. Emerging technologies, as exemplified by knowledge hubs, mobile messaging services, and digital networking platforms, offer potential solutions to bridge these gaps, fostering improved communication, knowledge-sharing, and market access. However, challenges that include literacy requirements, resistance from ASM communities, and the need for digital infrastructure underscore the complexity of achieving widespread implementation and impact in the ASM sector.

Policy recommendations to bridge the gaps in access to information:

1. **Establish national data infrastructure for ASM**: Establish a comprehensive national data infrastructure specifically designed to gather, analyze, and disseminate accurate information about the ASM sector. Collaborate with relevant government agencies, mining associations, and international organizations to conduct country-level census data collection, focusing on remote ASM communities. Implementing a standardized and centralized data repository will not only provide policy-makers with the necessary insights for effective decision making, but it will also contribute to bridging the information gap by ensuring that reliable data is readily available. This infrastructure should prioritize accessibility, data security, and the integration of modern technologies for efficient data collection and dissemination.
2. **Technology-driven information access initiatives**: Introduce targeted initiatives leveraging technology to enhance information access for ASM operators. Develop and deploy knowledge hubs, mobile messaging services, and digital networking platforms tailored to the unique needs and constraints of ASM communities. Provide training programs to improve digital literacy among ASM operators, ensuring they can effectively utilize these technologies. Collaborate with local NGOs, international organizations, and private sector entities to support the implementation of these initiatives. Additionally, incentivize the use of digital platforms by offering financial and technical support. Regularly assess the effectiveness of these initiatives, seeking feedback from ASM communities to address challenges and make necessary adjustments. This approach will not only empower ASM operators with valuable information but also foster a culture of continuous learning and responsible mining practices within the sector.

2.9.5 Full-Suite Technological Offerings for ASM

The final category of technologies for ASM that are examined in this section is full-suite technology offerings. These technologies are vertically integrated mine-to-market solutions that seek to solve a number of the challenges or constraints associated with ASM. These transversal technologies include a number of components, namely access to finance and markets, traceability, ethical and responsible mining practices, and due diligence verification.

The technologies in Table 17 have been developed to advance and support the formalization of the sector.

TABLE 17. Full-suite technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Full stack	A full-stack technology involves a comprehensive set of software tools covering both user interface and back-end development. It integrates various components to provide a complete solution for addressing challenges and improving efficiency in ASM.	• **Product Passport** – Minespider, Germany[38] • **Minexx** – Minexx, United Kingdom[39] • **Gemfair** – Gemfair/ De Beers, United Kingdom[40]	Vertically integrated mine-to-market solutions offer a full suite of solutions, including access to capital, traceability, and supply chain verification.	It could potentially exclude ASM miners who do not meet stringent requirements and create higher barriers for them to formally participate.

Source: Authors.

In conclusion, addressing the cross-cutting issues in ASM through technological advancements is pivotal for the sector's sustainable development. The next section will explore the positive impacts, potential opportunities, and policy considerations associated with the increasing role of new technologies in ASM.

38 https://www.minespider.com/product-passports
39 https://minexx.co
40 https://www.gemfair.com

3.0 Unpacking the Positive Impacts, Potential Opportunities, and Policies Linked to the Rise of New Technologies in ASM

3.1 Impacts on Productivity

Drawing insights from labour-intensive industries such as agriculture, textiles, and industrial mining, technology holds the potential to enhance productivity (Kapelko & Oude Lansink, 2015; Kim et al., 2020; Ramdoo et al., 2021). In ASM, increased mechanization and the adoption of basic mining technologies, such as sluice boxes, dredges, and water pumps, have elevated operational efficiency. This mechanization trend could propel artisanal operations toward small-scale mining, marking a significant shift in operational scale.

Utilizing technology like aerial photos, light detection and ranging (LIDAR), satellite imagery, and digital mining cadastres for mapping and allocating mineral-rich land reduces the costs associated with exploration and prospecting. When authorities define suitable mineralized land for ASM extraction, it not only reduces monetary and opportunity costs but also promotes productivity, higher yields, and improved economic outcomes.

Enhanced financial access through ASM-specific solutions like Product Passport, Minexx, GemFair, and digital platforms like mobile money and microfinance institutions can positively impact productivity. ASM operators, often deprived of access to capital, can benefit from these solutions, leading to the acquisition of productivity-enhancing equipment and, consequently, safer and more efficient mining techniques.

Similarly, increased information access through ICTs like ASM WhatsApp groups, Delve Exchange, Mercury-Free Technology Atlas, or Solidaridad's Interactive Voice Response service can enhance productivity. By providing best practice information and advice, these technologies contribute to refining methods, techniques, and technologies used by ASM miners.

As ASM operations progress toward greater automation and mechanization, transitioning from artisanal to small-scale mining, there is a noticeable decrease in dependence on manual, labour-intensive methods. This transition fosters operational efficiency, increases output, and enhances economic sustainability.

Digitization, technology adoption, and mechanization, including the use of basic mechanized tools, can impact labour markets. The traditionally labour-intensive nature of ASM may see a reduction in required manpower, potentially leading to displacement and conflicts for other roles along the value chain.

Policy recommendations:

1. **Encourage mechanization and technology adoption**: Incentivize and recognize the adoption of basic mining technologies and mechanization in ASM operations. Formulate policies and programs that facilitate the introduction of efficient tools, fostering collaboration between government bodies, research institutions, and industry stakeholders.
2. **Implement digital land mapping and allocation**: Integrate digital technologies for mapping and allocating mineral-bearing land for ASM activities. Define guidelines to ensure equitable access, optimizing productivity and economic outcomes for ASM miners.
3. **Foster financial inclusion and access**: Develop and support ASM-specific financial solutions and digital platforms, collaborating with microfinance institutions to provide accessible credit. Explore innovative financing mechanisms to enable ASM operators to purchase equipment and enhance productivity.
4. **Manage labour market transitions**: Anticipate and manage labour market transitions resulting from increased automation and mechanization. Develop policies that address potential job displacement, offering training and reskilling programs while promoting alternative livelihoods and opportunities.

3.2 Potential Sources of Supply for Critical Minerals

Technological innovations empower ASM operators to extract and process higher-value materials, positioning ASM as a significant player in critical mineral development (Hendriwardani & Ramdoo, 2022). The global demand for “critical minerals” currently outstrips supply, driven by the transition to less carbon-intensive energy products and the transformative impact of the Fourth Industrial Revolution (Hendriwardani & Ramdoo, 2022).

While ASM already contributes significantly to the worldwide production of key critical minerals, including 15%–35% of cobalt and 25% of tantalum globally, access to productivity-enhancing tools and advanced technologies could amplify this (Hendriwardani & Ramdoo, 2022). Improved access to information and enhanced mining techniques could enable ASM operators to engage with minerals traditionally reserved for more technologically equipped industrial miners.

Policy recommendations:

1. **Invest in technology adoption for ASM**: Allocate substantial funding and resources to support the adoption of advanced technologies and productivity-enhancing tools by ASM operators. Establish targeted programs providing financial incentives, training, and access to cutting-edge technologies for critical mineral extraction.

3.3 Impacts on Processing Techniques

Processing ore to extract higher-value minerals is economically beneficial for ASM operators, but it often involves harmful techniques like mercury amalgamation and cyanidation. Adopting appropriate technologies that enable safe processing without harm to human health or the environment has positive impacts on the sector.

Since the global embrace of the Minamata Convention on Mercury Pollution in 2013, there has been a heightened emphasis on eradicating mercury usage in ASM. This commitment has spurred the creation of mercury-free technologies, exemplified by innovations like Cleangold, which are tailored explicitly for ASM. These advancements not only alleviate environmental and health repercussions but also contribute to enhanced recovery rates (Stoffersen, et al., 2018).

Responsible processing techniques facilitate market access through traceability schemes. Technologies like blockchain, used by Virtu Gems, ensure responsible mining practices, providing access to fair and regulated markets. Cleaner processing technologies also reduce environmental harm and enhance recovery rates.

However, the adoption of new technologies, mechanization, and digitization may negatively impact labour dynamics, especially for women. Job displacement and environmental concerns, such as water pollution and reliance on non-renewable energy sources, are challenges associated with technology adoption.

Policy recommendations:

1. **Promote safe mineral processing technologies**: Implement policies and initiatives promoting the development and adoption of safe and environmentally friendly mineral processing technologies. Allocate funding for research and development that aims to eliminate harmful substances like mercury and cyanide.
2. **Facilitate market access through responsible processing**: Encourage responsible processing techniques and technologies by establishing incentives for ASM operators adhering to ethical mining practices. Integrate traceability technologies like blockchain in processing and supply chain management to ensure mineral provenance.
3. **A gender-inclusive technological transition**: Implement policies addressing gender-specific impacts of technological advancements in ASM. Develop programs to empower women through training and skills development, ensuring equitable participation and preventing displacement.
4. **Regulate environmentally sustainable processing technologies**: Enforce regulations promoting environmentally sustainable processing technologies within ASM. Conduct environmental impact assessments for technologies involving water and power sources to prevent pollution. Collaborate with environmental agencies and ASM communities to ensure the responsible use of processing technologies.

3.4 Impacts on People

Mechanization, digitization, and technology adoption in ASM can positively transform the lives of the workforce and host communities. These advancements democratize access to information, reduce market impediments, enhance value chain linkages, and potentially decrease economies of scale, making ASM more competitive.

Access to information through technology not only boosts productivity but also aids in achieving better economic outcomes for ASM miners. Technology like Quipu enables miners to access international market prices instantly, ensuring fair compensation.

Financial technologies empower ASM operators to purchase productivity-enhancing equipment, leading to increased efficiency and higher production rates. Higher returns, when invested back into mining operations, can improve practices and working conditions, stimulating local economies.

The adoption of technologies enhances worker safety and mitigates environmental and health impacts. Innovations like Picoyune and Solidaridad's Interactive Voice Response platform provide real-time information on safety practices, reducing risks of mercury intoxication and promoting responsible mining.

However, technology can also threaten potential negative impacts on labour, particularly for women. Job losses, driven by mechanization and technology adoption, can disproportionately affect women in ASM, potentially forcing them out of jobs and creating economic disparities within communities.

Policy recommendations:

1. **Inclusive technological adoption and skill development**: Formulate policies encouraging inclusive technology adoption in ASM while addressing potential negative impacts on labour, especially for women. Implement training programs bridging the gender digital divide and equipping women with necessary skills.
2. **Financial and infrastructural support for artisanal operators**: Develop programs that provide financial and infrastructural support tailored to artisanal operators. Introduce subsidies or grants to facilitate the acquisition of technology, making advancements accessible for smaller operations.
3. **Balance efficiency and inclusivity**: Enact policies balancing efficiency and inclusivity in ASM. Recognize diversity within ASM communities and prevent the concentration of resources among larger entities. Encourage technological advancements without disproportionately disadvantaging smaller operations.
4. **Regulatory frameworks for ethical technology use**: Establish frameworks governing the ethical use of monitoring and enforcement technologies in ASM. Safeguard against misuse of technologies without due consideration for livelihoods. Ensure the responsible use of monitoring technologies, striking a balance between environmental conservation, human rights protection, and socio-economic well-being.
5. **Encourage gradual transition and capacity building**: Encourage gradual transition to advanced technologies in ASM through capacity-building programs. Develop phased policies considering varying technological capacities, fostering collaboration to create a supportive ecosystem for a sustainable and equitable technological shift.

3.5 Impacts on the Environment

Utilizing aerial photos, LIDAR, drones, satellite imagery, geological information management systems, and mining cadastres enhances environmental management in ASM areas. Governments can establish ASM zones to prevent activities in protected areas, conservation zones, forests, wetlands, or biodiversity hotspots. Monitoring and enforcement technologies like Project Inambari and ASMSpotter, employing satellite data and artificial intelligence, enable swift regulatory responses to unauthorized ASM activities. ASMSpotter was used by Guyanese authorities to monitor and mitigate ASM encroachment into the rainforest.[41]

Technologies like Micromas 2.0 and Dram counteract the negative environmental impacts of ASM. Dram, deployed as Nidee-Nabe in ASM locations in Peru, removes metals from wastewater using natural bio-waste, passively extracting valuable materials and eliminating contaminants. The main barrier for environmentally conscious ASM operators is access to capital and equipment. The subscription-based Nidee-Nabe model supports logistics, installation, and transportation, and channels a portion of sales from recovered waste metals back to ASM operators.[42]

Community-led monitoring tools like the Remote Environmental Monitoring Application by Timby assist governments, NGOs, and conservation organizations in real-time tracking of environmental impacts from ASM activities. The application enables stakeholders to act swiftly to ensure proper management.[43]

However, technology can generate negative environmental impacts, with productivity-enhancing tools leading to overmining, pushing ASM activities into protected areas or farmlands and causing land degradation, biodiversity loss, and water system impacts. Mechanized tools, typically powered by generators, contribute to air pollution and fuel spills.

Policy recommendations for leveraging technology for better environmental management:

1. **Strategic zoning and technological enforcement**: Implement policies leveraging geospatial technologies for ASM zoning, designating specific zones away from protected areas, conservation zones, and biodiversity hotspots. Enforce monitoring technologies for the swift detection of unauthorized ASM activities.
2. **Promote sustainable environmental technologies**: Enact policies that endorse the integration of environmentally sustainable technologies. Employ subscription-based models that offer logistical assistance and allocate a percentage of sales back to ASM operators, effectively tackling financial impediments.
3. **Community-led monitoring and reporting**: Advocate for policies promoting the use of community-led monitoring tools, integrating them into regulatory frameworks to enhance transparency and effectiveness in environmental management in ASM areas.
4. **Mitigate the negative environmental impacts of technologies**: Formulate regulations addressing potential negative environmental impacts from productivity-enhancing technologies. Ensure the responsible use of mechanized tools, preventing overmining, land degradation, and pollution. Enforce measures to prevent ASM encroachment into protected areas or farmlands. Establish guidelines for the responsible use of mechanized tools to minimize environmental impacts.

[41] https://www.levinsources.com/what-we-do/case-studies/asmspotter-guyana-asm-developments
[42] Personal communication with founder.
[43] https://www.artisanalminingchallenge.com/innovation/community-led-monitoring

3.6 Impacts on LSM That Have Ripple Effects on ASM

The mining sector has traditionally embraced mechanization, digitization, and technology as a means to boost efficiency and drive productivity. Many mines have adopted disruptive technologies: mining operations are using advanced analytics and machine learning to optimize mineral recovery, and mines are using sensors coupled with advanced learning models to boost chemical recovery from the extraction process, saving the mine millions and reducing the amount of chemicals in the tailings (McKinsey & Company, 2018). Some mines are using digital twinning—a computer-generated virtual model that allows operators to review all aspects of the mine at a granular level. This model enables the early detection of problems to ensure that all aspects of the mine are operating optimally, saving the mine time and money (Khawaja, 2022). The most transformative use of technology in mining is the deployment of robotics and autonomous equipment in mining operations, as they have far-reaching impacts on both the efficiency and cost of the mine and manpower. Mines use autonomous haulage systems, autonomous bulldozers, and autonomous blast hole drills; underground mines use tele-remote load, haul, and dump machines (McKinsey & Company, 2018). Technological adoption has improved the efficiency and productivity of mines, improved worker safety, reduced delays, and extended the lifespan of the mine (Ramdoo et al., 2021).

The use of technology can also have negative impacts. Some technologies require highly skilled operators and, as a result, will displace low-to-medium skilled labour. Resulting local job losses could adversely impact the local procurement of goods and services, and the socio-economic impacts of technology adoption will have greater impacts on less diversified mining countries that cannot reallocate labour to other industries (Ramdoo et al., 2021). This section examines the impacts that the adoption of technology in LSM could have on the ASM sector.

Due to the interconnectedness of LSM and ASM, the adoption of technologies in large-scale operations could have consequences that reverberate through the ASM sector. LSM technology use for ASM could cause the retrenchment of low-to-medium skilled mine employees, leading to an influx of new ASM participants, as these ex-mining labourers could transfer their skillsets and knowledge to ASM (Cosbey, 2019). A dramatic increase in ASM operators would have far-reaching consequences: it would increase competition for resources, resulting in conflicts between miners and local communities, as well as between ASM miners and LSM operations due to the higher possibility of encroachment. The struggle for mineral-bearing land could cause a higher rate of environmental degradation, as ASM miners may venture into protected areas in search of minerals. LSM is primarily male-dominated, and men would constitute the large majority of the redundant workers. The introduction of a considerable number of semi-skilled men into the ASM value chain will skew the gender balance and could result in the displacement of women. Government authorities in many ASM-hosting countries already struggle to monitor and enforce ASM activities, and an influx will make it harder for the already limited capacity of regulators to deal with the socio-economic and environmental fallout. Higher yields created by productivity- and efficiency-enhancing technology could negatively impact international market prices due to rising levels of supply (Ramdoo et al., 2021). Lower market prices will detrimentally impact ASM miners, many for whom mining is a source of subsistence.

Technological adoption in the LSM sector could also positively impact the ASM sector. Due to co-existence initiatives, many mining companies engage with ASM on a number of issues related to mining, including technical assistance, capacity building, and training. The adoption of technologies by LSM operators could result in opportunities for technology transfer. The redundant equipment and technologies that have been replaced by new disruptive technologies could be sold, leased, or given to ASM operators. The use of pre-owned equipment and technology by ASM could result in better, more responsible mining and eradicate the need for the use of toxic chemicals like mercury. In addition, the relatively small number of suppliers of pre-owned equipment may also be in a position to absorb some of the workers that are retrenched by LSM operators, reducing the numbers entering ASM. As evidenced by GemFair and Moyo Gems, the use of cleaner, more responsible mining methods also opens up markets to ASM, including the option to sell minerals to nearby LSMs.

Policy recommendations:

1. **Skill transition and job retention programs**: Establish comprehensive skill transition and job retention programs in collaboration with both LSM companies and ASM associations. These programs should focus on providing training and support for low-to-medium-skilled mine employees facing retrenchment due to technological adoption in LSM. By facilitating the transition of these workers into other sectors or supporting skill development relevant to evolving technologies, governments can minimize social and economic disruptions caused by job losses. Additionally, incentivize LSM companies to contribute to skill transition programs and provide resources for retraining initiatives.
2. **Enhanced regulatory capacity for ASM monitoring**: Strengthen regulatory frameworks and build the capacity of government authorities to effectively monitor and enforce ASM activities. Given the potential influx of new participants into the ASM sector due to retrenchment in LSM, increased regulatory capacity is crucial for managing environmental and socio-economic impacts. Leverage technology, such as remote sensing and data analytics, to enhance monitoring capabilities. Collaborate with international organizations and leverage best practices to develop robust regulatory systems that can adapt to the changing dynamics brought about by technological adoption in LSM.
3. **Promote responsible mining practices**: Encourage LSM companies to adopt responsible mining practices and consider the environmental and social impacts of technological adoption. Promote technology transfer initiatives where redundant equipment and technologies replaced by new innovations in LSM can be made available to ASM operators. Support cleaner and more responsible mining methods, reducing reliance on harmful substances like mercury. Establish incentives for LSM companies to engage in co-existence initiatives, fostering partnerships with ASM on issues like social closure, technical assistance, capacity building, and training.
4. **Market access and diversification for ASM**: Facilitate market access and diversification for ASM operators by encouraging collaboration between LSM and ASM. LSM companies can play a role in opening up markets for ASM by purchasing responsibly mined minerals or engaging in co-selling arrangements. Explore mechanisms to ensure that pre-owned equipment and technologies from LSM are accessible to ASM operators. Implement policies that incentivize responsible mining, creating a positive economic environment for both LSM and ASM. Consider tax incentives or other financial support mechanisms to encourage responsible practices.
5. **Gender-inclusive programs**: Recognize and address potential gender imbalances resulting from the influx of semi-skilled men into the ASM sector. Develop gender-

inclusive programs that support women in ASM, providing training, resources, and opportunities to ensure their continued participation in the sector. Collaborate with ASM associations and women's groups to design initiatives that empower and protect women in the face of changing dynamics brought about by the adoption of technology in LSM.

The emergence of advanced technologies in ASM has the capacity to substantially enhance productivity, ensure a stable supply of critical minerals, and promote environmental sustainability. Policy-makers ought to enact comprehensive and inclusive strategies that promote responsible adoption of technology, address gender-specific impacts, and encourage collaboration between ASM and LSM for a well-rounded and sustainable future.

4.0 Conclusions

The integration of technology and mechanization is observable throughout the ASM value chain, transitioning from rudimentary tools, like homemade sluice boxes, to advanced tools like pneumatic drills and water pumps. The primary aim of incorporating these tools and technologies in ASM is to amplify productivity and operational efficiency, ultimately yielding higher returns. However, the current methods employed along the value chain yield suboptimal results, compounded by challenges such as a lack of geological data, limited access to finance and markets, concerns regarding worker health and safety, and the prevalence of irresponsible practices impeding the sustainable development of the ASM sector.

Embracing digitization and adopting technology is a promising solution to address these challenges. Aerial photos, satellite imagery, remote sensing, and UAVs can assist governments in mapping, allocating, monitoring, and enforcing ASM areas. Replacing analogue mining record-keeping systems with digital platforms enhances natural resource governance. Software solutions utilizing satellite imagery and artificial intelligence can efficiently monitor and detect illegal ASM activities, saving governments both time and money while aiding formalization initiatives and curbing environmental degradation. Blockchain-based mine-to-market solutions that trace ASM mining activities connect ASM miners to international markets, increasing profit margins and promoting responsible practices.

Access to credit and capital solutions empowers miners to advance operations through investments in equipment and technology, potentially generating higher revenues and addressing challenges like low productivity and unsafe working conditions. Improved access to information and equipment enhances the environmental record of ASM miners, with accessible mercury-free technologies and best practice information helping mitigate environmental impacts. Solutions facilitating governments in soliciting feedback from hard-to-reach ASM communities enhance service provision and policy making. The increasing role of technology presents opportunities for ASM participation in critical mineral value chains.

TABLE 18. Key findings on the adoption of new technologies in the ASM sector

Issue	Finding
Operational diversity	Operational modes, tools, and techniques vary significantly across ASM.
Technological advancements	Advancements in tools correlate with capitalization, influencing efficiency and output.
Enforcement challenges	Monitoring and enforcement face hurdles due to limited state capacity.
OHS	There are persistent concerns about the limited adoption of advanced technologies.
Financial access challenges	Enhancing financial accessibility continues to be a formidable challenge, notwithstanding the proposed solutions involving mobile money and cryptocurrencies.
Financial solutions	Financial access can improve through digital solutions like Product Passport and mobile money.
Information gaps	Information gaps hinder ASM, and technological offerings may contribute to exclusion.
Potential positive impacts	Efficiency can be enhanced through mechanization and technology adoption.
Exploration cost reduction	Digital mapping and allocation can reduce exploration costs.
Labour market dynamics	Negative impacts involve labour displacement, especially for women.
Critical mineral contributions	With better technology, ASM can significantly contribute to critical mineral development.
Regulatory streamlining	Streamlining regulatory processes and investing in technology adoption are recommended.
Mercury-free technologies	Positive impacts include mercury-free technologies and responsible processing.
Gender disparities	Negative impacts involve potential gender disparities due to technology adoption.
Information access	Positive impacts include access to information, financial empowerment, and enhanced safety.
Environmental management	Environmental management can be enhanced through technologies like LIDAR and drones.
Negative environmental impacts	Potential negative impacts involve overmining, land degradation, and pollution.

Issue	Finding
Job retrenchment in LSM	Negative impacts include job retrenchment due to technological adoption in LSM.
Technology transfer opportunities	Positive impacts include opportunities for technology transfer to ASM.
Inclusive policies	Policy recommendations must focus on inclusive technology adoption, financial support, and balancing efficiency with inclusivity.

Source: Authors.

However, the widespread use and dissemination of technology in ASM also pose potential negative impacts. Mechanization may lead to labour displacement within ASM and LSM, resulting in conflicts for roles along the value chain. The disproportionate impact on women, who predominantly occupy lower-earning, labour-intensive roles, raises concerns. Technology could elevate the cost of ASM mining, potentially crowding out rudimentary operations in favour of more efficient and productive technologies. Monitoring and enforcement technologies may threaten the livelihoods of illegally operating ASM miners and secondary supply chains associated with mining. Due to suboptimal production levels, ASM actors might face competition from industrial miners who are expanding their interest in a broader range of minerals, driven by the global demand for critical minerals.

In conclusion, while the adoption and dissemination of new technologies in the ASM sector offer numerous positive outcomes, it is crucial for ASM-hosting governments to develop comprehensive policy frameworks and interventions. These frameworks should ensure that technology use aligns with sustainable development goals and does not disrupt the livelihoods of the millions of people deriving economic benefits from ASM.

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Appendix A. Technical Approach and Methodology

The research aims to unpack incoming technologies and how they will impact the artisanal and small-scale mining (ASM) sector. Incoming technologies refer not just to newly developed technologies, techniques, and methods but also to recent innovative applications of pre-existing methods.

The findings may eventually be used to inform guidance on government policy-making relevant to optimally managing and leveraging the impacts of new technologies for ASM.

A1 Data Collection

The data collection was conducted in two phases. First, a desktop review identified and assessed emergent technologies and prospective key informants. Phase 2 used the findings from the literature review to conduct remote or online interactions with key stakeholders and informants. As part of this evidence-generation process, a data collection matrix was used to assess many data points in an organized manner.

A1.1 Data Collection Matrix

The data collection matrix is made up of structured data points used to collect and organize data. It comprises data points that guide data collection and analysis. Table A1 presents the overarching framework that underpinned the data collection matrix.

The basis of the matrix is the mining value chain and aspects that characterize ASM, drawing from challenges in the sector and/or areas that need intervention to support the transformation of the sector's activities. The identification of forthcoming technologies was conducted in accordance with the stages of the mining value chain and cross-cutting sectors. In collating the list of technologies, their features were then populated by the data points.

TABLE A1. Conceptualization of the data collection matrix

Mining value chain	Cross-cutting issues
• Exploration • Mining • Mineral processing • Value addition • Marketing & sale • Rehabilitation & mine closure	• Financing • Legalization • Skills & training • Traceability & certification • ASM & just transition • Governance & enforcement • Health, safety, environmental impacts
Forthcoming technologies in ASM Guiding question: What technologies are emerging in ASM in the various areas?	
• Name of the technology • Category of technology • Description of the technology • Intended applications of the technology in ASM • Who developed the technology? • Who supplies the technology? • When was the technology developed? • Where is the technology being used (case study examples of application)? • Benefits of the technology • Downsides of the technology • Main users of the technology • Requirements of using the technology (i.e., skills and training, production information, infrastructure) • Is the technology used alongside other technologies? • Is the technology used in other sectors (i.e., large-scale mining)? • Is the technology replacing and existing practices? • Cost of technologies	

Source: Authors.

A2 Key Informant Interviews

Interviews were conducted with various respondents involved in the development and dissemination of technologies in ASM, namely from

- research institutions known to be involved in mining technologies,
- developers and providers of technology,
- regulatory bodies (e.g., those responsible for mining, environment, and technology and skills development),
- the private sector, and
- development agencies active in technology development and dissemination.

A3 Data Analysis

The data organized in the data matrix was analyzed to extract evidence in the following areas:

- Analysis of the current global technology trends in the context of the ASM sector, including formalization, access to finance, responsible supply chains, skills provision, de-risking, and opportunities for job creation for women and the youth.
- Analysis of the technologies, looking at the constraints and opportunities from both demand and supply perspectives

Appendix B. Exploration and Prospecting

Although both artisanal and small-scale operators engage in prospecting and exploration activities, these aspects receive less emphasis in the main body of this report. However, for those seeking detailed insights into this step of the value chain, comprehensive information is available in this appendix.

Table B1 lists the exploration and prospecting methods, techniques, and technologies used in ASM, differentiating some of those used by mechanized, better-capitalized small-scale operations from those used generally in ASM.

TABLE B1. Current trends in exploration and prospecting

Types of technology used in exploration and mining			
	Relevance for artisanal mining		**Relevance for capitalized small-scale mining**
	Informal mining	**Formal mining**	
Digital infrastructure	Geographic positioning systems (GPS) inbuilt in smart devices (mobile phones and tablets)	• GPS built into smart devices (mobile phones and tablets) • Mining cadastres	• GPS built into smart devices (mobile phones and tablets) • Mining cadastres • Handheld GPS • Handheld X-ray fluorescent spectrometer (XRF)
Tools	Metal detectors	Metal detectors	Metal detectors
Techniques	• Local prospectors/ explorers • Observation of mineralization in rock outcrops • Dowsing or divining (with a stick or coat hanger) • Trenching and pitting • Panning to check for the presence of high-density minerals • Manual dredging for diamonds	• Local prospectors/ explorers • Observation of mineralization in rock outcrops • Dowsing or divining (with a stick or coat hanger) • Trenching and pitting • Panning to check for the presence of high-density minerals • Manual dredging for diamonds • Geological maps	• Local prospectors/ explorers • Observation of mineralization in rock outcrops • Trenching and pitting • Panning to check for the presence of high-density minerals • Manual dredging for diamonds • Geological maps

Source: Authors.

Many resource-rich countries have yet to conduct adequate geological mapping to determine their mineral resources. Where geological information is available, the coverage of the available geological data is limited to areas that have already been prospected, explored, or allocated to large-scale mining (LSM) operations. Access to geological data is important for a number of reasons. From a governmental perspective, it can assist with the allocation and enforcement of ASM areas. From the perspective of an ASM operator, having access to usable geological data can save time and money and take the guesswork out of prospecting. Having access to geological data can reduce encroachment on LSM concessions, decrease environmental degradation, and result in better economic outcomes for miners.

FIGURE B1. A metal detector being used in Mali

Credit: Nellie Mutemeri, 2014.

Countries that have embraced the potential of ASM have used geological mapping to create designated ASM Zones. For example, the Democratic Republic of the Congo, Ghana, Indonesia, Mozambique, the Philippines, Tanzania, and Colombia have made provisions for the creation and management of delineated ASM as part of their mining codes and cadastral systems (Steinmüller, 2017).

Miners without governmental support may use more traditional prospecting methods. Many ASM miners rely on geological information passed on from local explorers, known as *gambusinos* in Mexico or *pirquineros* in Chile. Others use the centuries-old practice of dowsing or divining with a stick or a metal coat hanger to look for underground ore bodies.

ASM operators with the capital to buy equipment will use metal detectors (see Figure B1) and gold detectors to find ore bodies. This method of prospecting is common in West Africa. In ASM, prospecting and exploration are typically conducted at the same time, and they involve a fair amount of guesswork. Miners can look for mineralization in rock outcrops, follow other miners to "rush" areas, or shadow LSM activities. ASM operators will dig trenches and pits in the bedrock to sample the area and reveal ore bodies. These techniques are labour intensive and involve digging holes that can be as large as 3–4 m.

When looking for alluvial minerals, the miners will pan to check for the presence of high-density minerals. The pans are usually fashioned out of metal or plastic; in South America, some miners still use a traditional *batea*, which is made out of wood; and in many African artisanal small-scale gold mining (ASGM) countries, miners use a calabash to pan for gold. In diamond-bearing areas, miners will manually dredge for diamonds as part of their exploration activities and use manual hand jigs to check for the presence of diamonds in the sampled material. It has been recorded that extremely well-financed operations have used handheld XRF to assess the metal content of samples.[44]

Due to budgetary constraints and the low importance of ASM as a development area, many countries have not conducted adequate geological mapping; however, there are various technologies, such as aerial photographs, light detection and ranging (LIDAR), drones/unmanned aerial vehicles (UAVs), and satellite imagery (see Table B2) that can reduce the time and manpower needed to generate geological data. Even though some of these may not necessarily be new technologies, their application in ASM is recent.

[44] Personal communication with interviewees.

TABLE B2. Exploration and prospecting technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Territorial mapping/ geodata production	It involves using technology to collect, analyze, and visualize geographic data, creating detailed maps and spatial datasets. It utilizes sources like satellite imagery and GPS for data collection, employs geographic information system tools for spatial analysis, and results in organized geodatabases. The applications span various fields, aiding in urban planning, environmental monitoring, disaster response, and informed decision-making for resource management and infrastructure development.	• **Aerial photography** – private companies, globally • **LIDAR** – private companies, globally • **Drones/UAVs** - private companies, globally • **Satellite-based remote sensing** – private companies, globally	It generates geographical data needed for exploration, prospecting, and resource allocation relatively inexpensively.	It requires technical expertise to analyze the data and would be expensive for the average ASM user to afford.

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Digital mining cadastre systems (DMCSs)	DMCSs are digital platforms that integrate geospatial data, legal frameworks, and administrative processes to efficiently manage mining rights. These systems facilitate spatial data integration, transparent licensing processes, real-time monitoring of mining activities, and conflict resolution. DMCSs enhance transparency, public access, and data security while streamlining administrative procedures for mining permits and licences.	• **DMCSs** – governments, globally	A publicly accessible geoportal displays the country's mineral resources and is used for the allocation and management of natural resources.	It requires political will and an active administrator. The accessibility and usability of the data can be difficult for the average ASM operator.

Source: Authors.

Appendix C. Mine Closure: Waste management, remediation, and restoration

Table C1 lists mine closure methods, techniques, and technologies used in ASM.

Table C1. Current trends in mine closure

	Relevance for artisanal mining		Relevance for capitalized small-scale mining
	Informal mining	Formal mining	
Digital infrastructure	n/a	n/a	n/a
Tools	n/a	n/a	n/a
Techniques	• Settling ponds • Backfilling	• Settling ponds • Backfilling	• Settling ponds • Backfilling • Reforestation/ revegetation

Source: Authors.

ASM operators often lack the capital and capacity to manage their waste appropriately or to perform remediation and restoration activities, such as soil replacement, shaping and amelioration, revegetation and bio-diversity reestablishment, and other mine closure activities. Many ASM miners are migratory and move to the next mine site, looking for new opportunities, leaving behind open pits, uncovered uncontained tailings ponds, and dumps. ASM tailings are generally released into waterbodies or dumped at the mine site in open areas. On rare occasions, miners may construct concrete settling ponds (see Figure C1), and the tailings may be periodically emptied onto a dump.

However, there are positive examples of governments and development agencies conducting restoration and remediation activities on ASM sites. In Liberia, the U.S. International Development Property Rights and Artisanal Diamond Development program taught ASM stakeholders to backfill with overburden during the mining process to ensure that the mined-out land regains its shape for non-mining activities. In Sierra Leone, Ecuador, and Mongolia, land rehabilitation was conducted using economically valuable plant species (Butler et al., 2014). Another example is the World Bank Climate Smart Mining initiative, which developed *A Forest-SMART Artisanal Mining Standard*.[45]

[45] http://documents.worldbank.org/curated/en/099235104252220988/P1722450cd79500c30bca0078f7496c1e66

FIGURE C1. A full settling pond in Guinea

Credit: Nellie Mutemeri, 2021.

C1 New Technologies for Mine Closure: Waste management, remediation, and restoration

Environmental mismanagement is caused by bad practices and irresponsible mining methods, inappropriate tools, and little to no waste management. With skills development, training, equipment, and appropriate technologies (as highlighted in Table C2), ASM miners can be empowered to mine more responsibly and limit the impacts of their activities.

TABLE C2. Waste management, remediation, and restoration technologies

Type of technology	Description of the technology	Examples of the technology	Impacts of the technology	Potential challenges
Waste management	Waste management technologies in ASM focus on removing mercury from contaminated tailings, allowing for responsible reprocessing or disposal.	• **Copper Plates** – Pure Earth, Colombia	Removing mercury from contaminated tailings allows the tailings to be reprocessed or disposed of properly.	Cost barriers and a lack of incentive for ASM operators to use waste management techniques present challenges. ASM operators will also need to safely store and/or dispose of mercury recovered.
Bio-remediation	Bioremediation involves the application of specialized microorganisms or plants to naturally degrade or absorb contaminants, such as heavy metals, from mining-impacted sites, offering an environmentally sustainable approach to mitigate pollution while promoting ecosystem restoration.	• **DRAM Technology** – SEM Energy Ltd, UK • **Micromax 2.0** – Wipa Codesarrollo Socioambiental and Bioxlab, Peru	Removing heavy metals and toxins from effluent and wastewater reduces the adverse impacts of ASM on the environment and human health.	Challenges include cost barriers and a lack of incentive for ASM operators to use remediation techniques.

Source: Authors.

Appendix D. Mineral Processing

D1 Gold

The gold recovery process includes the comminution, mineral separation, and refining.

D1.1 Comminution

Comminution involves a combination of crushing, milling, and pulverizing with different levels of mechanization to liberate the gold. This process is meant to liberate the gold from the gangue (waste minerals/material) and may be unnecessary for alluvial and eluvial ores. The equipment commonly used includes jaw crushers, stamp mills, and ball mills. On the most rudimentary end of the spectrum, some miners manually grind ore using mortars and pestles or a large stone (see Figure 6). These rudimentary comminution practices are typically inefficient and are linked to low levels of gold recovery.

D1.2 Separation

Separation involves removing the gold from the gangue and may involve a variety of different combinations of the following methods: screening, gravity concentration, mercury amalgamation, cyanidation, and smelting to produce gold doré. Advanced ASGM operations tend to use cyanide leaching systems and froth flotation techniques, which increase gold yields.

D2 Gravity Concentration

Gravity recovery involves using the gravity differential between gold and gangue minerals to separate them. This method works because gold settles faster than sand in water due to its higher density. The oldest form of gravity separation is panning, which has a good recovery rate and is the cheapest form of gravity concentration. However, due to the size of the apparatus, miners can only process a small amount of ore at a time. Miners often use other gravity separation techniques, like sluices and shaking tables, which can be mechanized or manual to pre-concentrate the gold before panning. Sluices efficiently separate gold from waste minerals and have a higher throughput, increasing the amount of gold that miners are able to recover. However, the methods generate a lot of waste, which is often not properly managed, leading to negative impacts on water systems by introducing silt to natural water bodies and inducing turbidity. Better-financed operations will sometimes use centrifugal concentrators; however, these concentrators require more infrastructure for electricity and water supply.

D3 Mercury Amalgamation

Mercury amalgamation has been used for a long time to recover silver and gold from ores and concentrates. Its use is widespread today and expanding, largely because mercury is relatively inexpensive and easily sourced. ASGM miners use whole-ore amalgamation, where large amounts of mercury are added to 100% of the ore during milling.[46] The amalgam created is

[46] Note: This is considered one of the worst practices by the Minamata Convention on Mercury Pollution (United Nations Environment Programme, 2021).

recovered through copper plates and gravity separation for eventual burning to recover the gold. Whole-ore amalgamation is an inefficient practice as its gold recovery is low, and the process results in major losses of mercury to the tailings (Veiga et al., 2006). This mercury is eventually released into the environment, resulting in long-term environmental impacts. In addition, miners exposed to mercury will suffer long-term irreversible health impacts.

FIGURE D1. A miner using fume hood in Guyana

Credit: Nellie Mutemeri, 2019.

The other method used by ASGM miners is concentrate amalgamation, where mercury is only added to the gravity concentrates to capture the gold. The amalgamation process can be done in a panning dish, and sometimes, an amalgamation barrel is used (see Figure 7). In most cases, the gold is then recovered from the amalgam by burning off the mercury using a blowtorch, an open fire or even a stove. On the lower end of the scale, the mercury vapours are released into the atmosphere. However, more knowledgeable and better-resourced miners try to capture the mercury using retorts and work in fume hoods (see Figure D1) to reduce emission releases into the environment. This reduces the exposure of workers and communities and reduces impacts on the wider environment.

D4 Cyanidation

An alternative to mercury use is the chemical leaching of gold, with cyanide as the most common lixiviant. Cement-lined tanks or vats are used to batch leach the mineralized ore. An alternative method is heap leaching, where a heap of the ore is drenched with a cyanide solution that percolates through the heap as it leaches out the gold. The leachate is captured for eventual removal of the gold using various methods, including activated carbon and zinc. Miners utilize cyanide to recover gold efficiently. However, it is a hazardous and highly toxic chemical, and if it is not handled with care, it can cause fatalities in humans and animals.

Due to its high recovery rate, cyanidation is often used to reprocess tailings with low gold grades. However, it is important to note that the cyanidation of tailings from material that was initially processed using mercury results in the creation of cyanide complexes that make mercury more bio-available and hence able to enter food systems more easily. This practice is considered a "worst practice" under the Minamata Convention.

D5 Smelting

Smelting may be carried out as the next step after the high-grade concentration of free-milling gold that has been produced by gravity methods. It may be the final step of producing a cleaner doré from the gold sponge recovered after mercury volatilization from the amalgam. Chemicals such as borax are used as fluxes to enhance the smelting.

D6 Tin, Tantalum, and Tungsten

Like gold processing, ore processing techniques for tin, tantalum, and tungsten (3Ts) will depend on the type of deposit. For hard rock ore, this will be comminution and followed by gravity mineral separation. ASM miners produce a gravity pre-concentrate through single- or multi-stage ground sluicing using dug channels, earth or concrete basins, or, on rare occasions, sluice boxes (Schuette & Naeher, 2020). The second phase of separation may involve hand picking, panning, manual magnetic separation, and air blowing. More capitalized miners may use equipment such as jigs, shaking tables, spirals, and centrifugal concentrators for mineral separation. Since the 3Ts commonly occur together in mineral deposits, concentrates from some deposits will need further steps to separate the 3Ts from each other. This process involves more sophisticated techniques, such as froth flotation or magnetic and electrostatic separation, well beyond the means of most artisanal miners and is usually conducted by mineral traders who act as aggregators.

Appendix E. Gap Analysis

The gaps identified in this study include the following:

- Technologies, initiatives, and interventions tend to focus on better-financed formalized ASM miners, leaving out the informal marginalized miners (such as women) who desperately need assistance. This exclusion may further degrade their already precarious livelihoods and aggravate the state of poverty.
- ASM suffers from a critical lack of actionable data. In order to actually meet the needs of ASM stakeholders, disaggregated baseline data, survey data, and situational data need to be gathered and analyzed. Technologies that enable the crowdsourcing of data is a gap in the technology stack that urgently needs filling.
- Even when data and information are available, such as in geological maps, they might not be accessible to ASM operators who either do not have the necessary hardware to access the information or lack the capacity to analyze the data and turn it into knowledge products. Technologies that make mining data and information available in an accessible format for ASM users are pivotal to ASM actors deriving better economic outcomes from ASM.
- Mining and ore extraction are the central activities of ASM operations; however, there is a lack of attention to technologies that reform or disrupt traditional mining methods. Often, methods, techniques, and technologies used in ASM are co-opted from LSM operations, and many of the advanced innovations being deployed in LSM, such as autonomous systems and artificial intelligence, are wholly unsuitable for ASM activities, particularly as they could undermine one of the key advantages—job creation—of ASM over LSM. As the gulf between ASM and LSM gets bigger, new technologies that aim to transform ore extraction will have to explicitly account for the conditions under which ASM operates.
- Transportation related to ASM activities has also seen no technological innovation. There is probably no impetus to create new technologies to enhance transportation in ASM, and there is a general lack of infrastructure to support the creation of new technologies.
- There have been no technological developments in the beneficiation stage of the value chain, possibly as a consequence of the idea that beneficiation is delinked from ASM activities. However, beneficiation is key to extracting higher value from mining, so the development and adoption of technologies that allow ASM to do so is important. This is particularly true for ASM in "development minerals."
- For mechanized equipment and technologies that require a power source, if ASM operators do not have access to electricity, they typically use diesel or petrol generators, which can harm the environment and human health. This harm could be mitigated through technological solutions with alternative energy sources, such as a centrifuge that uses solar panels. There is currently a gap in the provision of lower-carbon technologies in ASM.
- In recent years, there has been a boom in ASM-focused technologies. At present, however, they do not seem to have been disruptive enough to transform the sector or enable ASM to leapfrog, either because the technologies have not been impactful enough or they have been poorly adopted (for many reasons).

E1 Demand-Side Challenges

The demand-side challenges associated with technology in ASM include

Affordability – Many ASM operators are cash strapped and struggle to afford new equipment or technologies. Similarly, many resource-rich governments and non-governmental organizations (NGOs) working in the ASM sector have limited finances and cannot afford expensive innovations.

Capacity – Potential users (governments, ASM operators, NGOs) may lack adequate capacity to use new technologies. Challenges include literacy, language barriers, a lack of infrastructure, and limited access to phones, data, and the Internet.

E2 Supply-Side Challenges

The supply-side challenges associated with technology in ASM include

Reach – ASM often occurs in remote areas that lack sufficient infrastructure. As a result, technology developers find it hard to reach them to distribute and maintain their technologies. Additionally, limited reach inhibits access to the end-user, making it hard to create and test appropriate solutions.

Design barriers – Innovations that are being deployed in ASM may not have been developed for ASM, which can lead to low uptake or limited scalability and create apathy among ASM users.

Cost – As affordability is a key challenge for end users of ASM technologies, it is difficult for developers to commercialize their technologies. The limited commercial viability of ASM-specific technologies can disincentivize technology developers and innovators from creating products for the sector.

Insufficient adoption – Even though technological adoption might be beneficial, ASM users are not incentivized to use new technologies. Many ASM stakeholders are content with the status quo. For example, many operators still use mercury because they are not aware of the risks and, as a result, are not motivated to use mercury-free alternatives that will require capital outlay. Poor adoption may also be due to barriers to exiting current methods—for example, where mercury is being supplied to artisanal miners as part of an ecosystem driven by illicit mercury traders and illicit gold traders wanting to secure gold supply.

Funding – Unlike agriculture, where development agencies, national governments, and the technology sector have prioritized and supported the development of innovative, disruptive technologies, funding for technology in ASM has been limited.

E3 Summary of Key Considerations

The development and adoption of new technologies in ASM are constrained by a panoply of challenges. Technology is not a silver bullet, but it can have a number of positive impacts. In order for ASM to reap the benefits of technological innovation, there has to be a concerted push by ASM stakeholders for technological development.

- The key constraint on demand and supply is funding. National governments, multilateral organizations, NGOs, LSM, and other invested parties will have to raise funds for the development and disbursement of ASM-specific technologies.
- Capacity building is key to the successful adoption and scalability of technologies in ASM. The distribution of technologies must be accompanied by skills training and infrastructure development.
- ASM end users and technology developers, alike, must be incentivized to use and make new technologies, respectively. Incentives for ASM operators could include free trials or access to new markets. For technology developers, this could involve the creation of funding envelopes, incubators, or competitions similar to the ASM Grand Challenge or Amazon CoLab, through which developers have access to funds and also direct access to ASM operators to test and develop with.
- A huge barrier to technological development and adoption in ASM is the lack of access to ASM operators and the subsequent inability of technologies to account for the characteristics of ASM and the needs of the sector. As a result, many technologies fail or are unscalable. Many of the operational technologies in this report were co-designed with ASM stakeholders, which is a step in the right direction and crucial for uptake and scalability.

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