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Sustainability Challenges and Opportunities in Artisanal and Small-Scale Gold Mining in The Global Production Chain

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Gold has been one of the most valuable and strategically important metals throughout human history. In the modern global economy, gold remains essential not only as a financial asset and reserve commodity but also as a key material in electronics, medicine, aerospace technologies, and advanced industrial applications. In recent years, the sustained increase in international gold prices has further stimulated exploration and mining activities worldwide. Within this global production system, artisanal and small-scale gold mining (ASGM) represents a critical but complex component of the gold supply chain.[1]

Artisanal and small-scale gold mining contributes significantly to global gold production. It is estimated that ASGM accounts for approximately 15–20% of the global gold supply, while providing direct or indirect livelihoods for more than 40 million people worldwide.[2, 3] These activities are particularly widespread in regions of Latin America, Sub-Saharan Africa, and Southeast Asia, where mining often represents one of the few available economic opportunities in rural communities. Despite its socio-economic importance, the ASGM sector faces substantial challenges in terms of environmental sustainability, occupational health, and technological efficiency.

From a mining and metallurgical engineering perspective, ASGM operations are typically characterized by limited geological knowledge, low levels of mechanization, and inefficient mineral processing methods. Gold extraction often relies on rudimentary techniques such as manual excavation, gravity concentration using simple sluice boxes, and amalgamation with mercury. Mercury amalgamation has historically been favored due to its simplicity and relatively low operational cost; however, it represents one of the most serious environmental and public health concerns associated with artisanal mining.[4]

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Mercury releases during amalgamation processes contaminate soils, rivers, and aquatic ecosystems, leading to bioaccumulation in food chains and posing significant health risks to miners and nearby populations. According to the United Nations Environment Programme,[3] artisanal and small-scale gold mining is currently the largest source of anthropogenic mercury emissions to the environment, accounting for nearly 40% of global mercury releases.[3] These impacts have motivated the development of international policy frameworks aimed at reducing mercury use in mining.

One of the most important international initiatives addressing this issue is the Minamata Convention on Mercury, a global treaty adopted in 2013 that seeks to protect human health and the environment from anthropogenic mercury emissions. The convention specifically recognizes ASGM as a priority sector and encourages participating countries to develop national action plans to reduce and, where possible, eliminate mercury use in artisanal gold mining.[3]

However, regulatory frameworks alone are insufficient to transform the sector. Sustainable improvement in ASGM requires the integration of appropriate technologies, technical training, and socio-economic development strategies. Mining and metallurgical engineering can play a fundamental role in this transition by promoting improved mineral processing techniques that increase gold recovery while reducing environmental impacts.

For example, enhanced gravity concentration technologies such as shaking tables, centrifugal concentrators, and improved sluice systems can significantly improve recovery efficiency compared to traditional methods. These technologies can often reduce or eliminate the need for mercury when properly implemented. In addition, advances in mineral characterization, ore beneficiation strategies, and small-scale processing plant design can contribute to more efficient resource utilization and reduced environmental footprint.[5]

Another key component of sustainability in ASGM is the formalization of mining activities. In many countries, artisanal mining operates under informal or semi-legal conditions, which limits access to financial resources, technical assistance, and regulated markets. Formalization programs aim to integrate artisanal miners into legal and institutional frameworks, allowing governments to implement environmental standards, improve labor conditions, and support technological innovation.[2]

From the perspective of global mineral supply chains, formalization also facilitates the traceability of gold production and supports initiatives for responsible and conflict-free sourcing of minerals. International markets, particularly in the electronics and jewelry industries, increasingly demand transparency and sustainability in raw material supply chains. As a result, responsible sourcing initiatives and certification schemes are becoming more important in the global gold market.[1]

Academic institutions and research centers have a critical role to play in supporting this transformation. Through interdisciplinary research and collaboration with governments, industry, and local communities, universities can develop innovative technological solutions adapted to the specific conditions of small-scale mining operations. Educational programs in mineral processing, environmental management, and occupational safety can also strengthen the technical capacity of artisanal miners and promote safer and more efficient practices.

Given the current high international demand for gold and its growing importance in technological applications, ASGM will likely remain an important component of the global gold production system in the coming decades. Therefore, addressing the environmental and technological challenges of artisanal mining is essential for improving the sustainability of the entire gold supply chain.

In conclusion, achieving sustainability in artisanal and small-scale gold mining requires a multidisciplinary approach that integrates engineering innovation, environmental management, regulatory frameworks,

and community engagement. By promoting responsible mining practices and appropriate technologies, it is possible to transform ASGM into a more sustainable and socially responsible component of the global mining and metallurgical industry.

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