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Technology, capital, and sustainability: Frontiers in just transitions for African mining

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ABSTRACT

Transitions towards sustainability are crucial in the natural resource sector in Africa, particularly in artisanal and small-scale gold mining (ASGM). This sector is notably characterized by the extensive use of mercury for gold extraction, which poses significant risks to both human health and ecosystems. This study focuses on Tanzania, where international incentives to reduce mercury have led the state to promote alternative methods and scale up production primarily through cyanide leaching—a more mechanized gold extraction technique.

This article examines the implementation of these strategies, identifies the barriers hindering this transition, and explores the resulting inequalities. We employ a mixed methods approach, combining surveys, semi-structured interviews, and participant observation. We adopt the Sustainability and Just Transitions frameworks for the Global South, arguing that applying an in-depth relational approach to the interactions between actors and technologies can illuminate the persistence of environmentally unsustainable practices within the local context. In conclusion, we advocate for international strategies aimed at the Global South to consider the how promoting the eradication of environmentally unsustainable practices can affect livelihood creation mechanisms.

1. Introduction

Globally, the transition towards more sustainable development has gained significant momentum and importance, including in Africa, where such efforts are closely linked to mineral resource extraction. One of the major challenges at the intersection of natural resource extraction and global sustainability is mercury pollution. Mercury is utilized in artisanal and small-scale gold mining (ASGM) to facilitate gold extraction from ore. ASGM is characteriszed by its low capital intensity and labour-intensive nature, employing basic tools and machinery for gold extraction (Hilson, 2009, 2014; Sidorenko et al., 2020). Mercury amalgamation remains the predominant method used in the sector, despite its relative inefficiency, capturing only around 30 per cent of the total gold within the ore. However, mercury is a hazardous heavy metal that poses significant risks. Once released into the environment, mercury can transform into methylmercury, which is readily absorbed and bioaccumulated by humans, wildlife, and ecosystems (UNEP, 2023). This can result in severe health impacts, such as organ failure, and contribute to biodiversity loss (URT, 2020).

The reliance on mercury amalgamation represents a significant barrier to environmental sustainability in ASGM. UNEP, (2019) estimated that ASGM operations contribute to nearly 40 per cent of global mercury emissions (UNEP, (2019), 2023). In Tanzania, it is estimated that mercury use totals approximately 35 tonnes per year, with 25–33 per cent of ASGM miners experiencing moderate to severe mercury poisoning, resulting in neurological damage and birth defects (UNEP, (2019); URT, 2020). To address this issue, UNEP introduced the Minamata Convention on Mercury in 2013, which aims to reduce and, where possible, eliminate mercury use and emissions in ASGM (UNEP, 2023). The Convention mandates that signatory countries eliminate the worst practices in ASGM and promote mercury-free alternatives (UNEP, 2023: Article 7 and Annex C).

Tanzania is one of the African countries with the largest ASGM sectors, employing over a million people and supporting the livelihoods of more than seven million individuals through upstream and downstream linkages (URT, 2020). Often undertaken by disadvantaged communities, ASGM provides significant employment opportunities and potential poverty alleviation (Hilson, 2009, 2014). The sector's development potential is underscored by the substantial income that rural communities derive, typically amounting to 70–80 per cent of the global gold

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price (O'Neill and Telmer, 2017). However, mercury use has also been linked to subsistence and poverty traps, potentially exploited by wealthier and more powerful actors (Hilson and Pardie, 2006).

While some miners may enter ASGM with capital for machinery investment, the majority have limited or no capital, marking a stark contrast to large-scale mining (LSM), which is more mechanized, employs fewer individuals, and offers fewer benefits for local development (Aubynn, 2009; Hilson, 2009, 2014).

In accordance with international objectives to reduce mercury use, Tanzania has ratified the Minamata Convention. As part of the implementation strategy, cyanide leaching emerged as the selected alternative to mercury. More mechanized and efficient, this technology is widely used in LSM. However, its impact on local development and the environment remains contentious, with concerns about potential employment losses and environmental degradation (Drace et al., 2016; Tomassi, 2024). Consequently, governments aiming to reduce mercury use in ASGM face the challenge of balancing higher employment with fostering environmental sustainability.

Yet, it has been suggested that ASGM could be organized following 'co-existence' organizational practices, which could avoid substantial employment loss while eliminating the use of mercury (PlanetGOLD, 2024; Tomassi, 2024; Veiga and Fadina, 2020). In co-existence, rather than processing the ore with mercury independently, miners sell the un-processed ore to larger mining companies or licensed operators that use cyanide leaching, (Aubynn, 2009; Rodríguez-Novoa and Holley, 2023; Tomassi, 2024; Veiga and Fadina, 2020). Nevertheless, mercury amalgamation remains the predominant method in ASGM, and further research is needed to understand the challenges associated with the mercury-cyanide transition. To address this gap, this article seeks to answer the following research questions:

1. What are the primary strategies identified and promoted to transition away from mercury use in ASGM in Tanzania?
2. What factors contribute to the persistence of mercury use in ASGM despite these strategies?
3. How does a more environmentally sustainable and efficient technology, such as cyanide leaching, affect inequalities in ASGM?

This study employs a mixed-methods approach and adopts the Sustainability and Just Transitions framework for analysis. Applying this framework to a Global South context can present challenges due to its technocratic nature (Ghosh et al., 2021; Ramos-Mejía et al., 2018). We address these limitations in the literature by employing a relational approach to reveal the social complexities underpinning technological transformations. This approach can reveal how livelihood creation mechanisms can also be embedded within environmentally unsustainable practices. This demonstrates that the eradication or adoption of such practices involves intricate technical and ethical challenges.

This article is structured as follows: firstly, we examine the significance of sustainability and just transitions in Africa, focusing specifically on the roles of the state, civil society, and poverty. Subsequently, we outline the methodology and contextualize our case study on mercury and cyanide in artisanal and small-scale gold mining (ASGM) within the existing literature. Our analysis firstly addresses state-led strategies that promote cyanide technology, while the second part explores the empirical challenges resisting a just and sustainable transition. We conclude by reflecting on the impact of global sustainability initiatives, such as the Minamata Convention, on fostering sustainable and equitable development in Africa, and how these can be addressed by policy.

2. Sustainability and just transitions in Africa

To address the mercury-cyanide transition, we adopt the Sustainability Transitions (ST) and Just Transitions frameworks for the Global South. This approach allows us to deconstruct the transition from mercury to cyanide through a relational lens, revealing aspects that might remain hidden under a traditional, more technocratic ST approach (Ghosh et al., 2021; Ramos-Mejía et al., 2018).

Transition studies aim to understand and promote shifts towards more sustainable practices in production and consumption (Köhler et al., 2019). These efforts are encapsulated in ST frameworks, such as the multi-level perspective (MLP), which investigate how transitions from one sociotechnical system to another occur. Sociotechnical systems comprise individuals, technologies, practices, beliefs, and the interactions between them (Geels and Schot, 2007). Within these systems, two central concepts are the 'regime' and the 'niche' (Köhler et al., 2019). The regime, originally termed the technological regime, is the dominant societal order, encompassing incumbent individuals, technologies, and practices. In contrast, the niche pertains to emerging technical innovations which if successful, can disrupt and replace the regime (Geels and Schot, 2007). Niche innovations that aim to foster sustainable development are not only desirable but often encouraged, as they may challenge unsustainable practices (Köhler et al., 2019; Ramos-Mejía et al., 2018).

In the context of ST, environmental sustainability, particularly concerning carbon emissions, is more frequently addressed compared to socio-economic objectives (Köhler et al., 2019; Newell et al., 2022; Ramos-Mejía et al., 2018). This approach reflects the strong academic and political influence of Global North priorities and narratives over those of other regions (Ramos-Mejía et al., 2018). Enhancing the validity of ST frameworks beyond Global North boundaries requires integrating perspectives that account for the diverse concepts, challenges, and priorities of different regions (Johnstone and Newell, 2018; Ramos-Mejía et al., 2018; Sovacool et al., 2017).

Investigating justice and inequalities, and understanding how they are reproduced, is central to this endeavour. If ST only prioritize resource efficiency and environmental sustainability, the outcomes are likely to be highly unequal (Ramos-Mejía et al., 2018; Swilling et al., 2016). We conceptualize justice as the distribution of burdens (e.g., externalities and costs) and benefits (e.g., access to technology) across society (Sovacool et al., 2017), emphasising the interconnectedness of justice and inequality. Thus, just transitions in Africa are inclusive STs that not only aim at environmental protection but also build equitable economic systems and institutions, allowing vulnerable groups to access technologies and improve their livelihoods (Otlhogile and Shirley, 2023). This framework conceptualizes justice as encompassing distributional, procedural, recognition, and cosmopolitan dimensions of inequality (Lee and Byrne, 2019; McCauley et al., 2019; Sovacool et al., 2017; Sovacool et al., 2021).

Distributional inequalities refer to the allocation of resources, power, and social capital (Lee and Byrne, 2019; Sovacool et al., 2021). Procedural inequalities pertain to the governmental processes that set rules and resolve disputes (McCauley et al., 2019; Sovacool et al., 2021). Recognition inequalities address the impacts of ST on the most vulnerable groups in society (Leino, 2024). Finally, cosmopolitan inequalities highlight the global scale of disparities across countries and continents (Lee and Byrne, 2019; McCauley et al., 2019; Sovacool et al., 2017; Sovacool et al., 2021).

While this framework is predominantly applied to energy transitions, it is particularly suitable for natural resource extraction sectors (Sovacool et al., 2017, 2021). Disparities in access to technology, land, or mining rights constitute distributional inequalities, while decisions and agreements made by states and institutions can create procedural inequalities by favouring large-scale mining (LSM) over artisanal and small-scale gold mining (ASGM) (Johnstone and Newell, 2018; Kinyondo and Huggins, 2019; Rodríguez-Novoa and Holley, 2023; Sundet, 1997). Such challenges have contributed to the 'resource curse' in resource-rich countries in the Global South, resulting in economic underperformance and environmental degradation. Environmental impacts and externalities, such as pollution from extraction, disproportionately affect disadvantaged rural communities (recognition inequalities), especially in developing countries (cosmopolitan

inequalities) (Sovacool et al., 2017, 2021).

In ASGM, the localized and global effects of pollutants are evident. While gold from ASGM is traded globally, pollution from mercury and cyanide primarily affects the areas where these chemicals are used, disproportionately impacting disadvantaged rural communities. Mercury pollution poses both local and global threats, as the chemical can travel through the natural elements, making it a global concern. In contrast, cyanide pollution is more localized (Drace et al., 2016; Manzila et al., 2022; Stapper et al., 2021). The global dimension of mercury pollution makes it a more urgent concern, often more strongly promoted by Global North actors (Oakley, 2023), compared to the localized effects of cyanide.

Investigating justice and regime change within ST in the Global South requires engaging with a high level of social complexity, where transformations and resistance to change are interconnected with poverty, informality, indigenous knowledge, patron-client relations, rent-seeking behaviour, global linkages, and colonial legacies (Geenen and Bikubanya, 2024; Kinyondo and Byaro, 2024; Lund, 2006; Otlhogile and Shirley, 2023; Ramos-Mejía et al., 2018; Sovacool et al., 2017, 2021). Actors in Global South regimes rarely play clear-cut roles; instead, they pursue diverging needs and objectives (Ghosh et al., 2021; Lund, 2006; Pedersen et al., 2021; Ramos-Mejía et al., 2018). Hence, technologies introduced to bring societal benefits are often reinterpreted by local actors as means for rent-seeking or re-drawing power relationships (Ramos-Mejía et al., 2018). For example, in ASGM in Tanzania, the retort, an instrument that can save up to 95 per cent of mercury, was introduced to mitigate mercury pollution. However, because it reduces transparency in transactions, it allows owners to set the gold price rather than users (Jønsson et al., 2013). Similarly, technology such as cyanide leaching, introduced to deter mercury use, can be interpreted by the state as a means to increase state revenues and resource capture.

Overall, adopting the ST and Just Transitions frameworks through this approach can be invaluable in breaking down complex cases such as the mercury-cyanide transition. In the following sections, we juxtapose the emergence of distributional, procedural, recognition, and cosmopolitan inequalities with critical promoters and opponents to transitions in the context of ST in the Global South and Africa: states, civil society (and their interactions), and poverty.

2.1. The state and civil society in transitions in Africa

The role of the state is pivotal in ensuring distributional, procedural, recognition, and cosmopolitan justice in sustainability transitions (ST) within the natural resource extraction sector. Notably, states in the Global South are not neutral actors; they influence which groups are supported, for example by financing new technologies or protecting incumbent actors through regulation (Johnstone and Newell, 2018). Thus, while states must balance urgent environmental concerns with fostering development, growth, and industrialization, they contend with resource capture, resulting in their ambiguous behaviour (Ramos-Mejía et al., 2018; Swilling et al., 2016). This challenge is compounded by tight budgets and debt burdens, constraining their capacity to implement decisions. External and internal actors also influence state decisions. External influences include global capital, other countries, and international organizations, which can affect financial budgets and direct policy (Ansari, 2022; Bonizzi et al., 2019; Swilling et al., 2016).

Internal influences can be exercised by powerful groups such as civil society organizations (CSOs). These comprise non-profit and non-governmental organizations that promote shared political and economic interests or cultural and philanthropic values, resulting in collective action (Acemoglu and Robinson, 2023; Igoe, 2024; Mlambo et al., 2020; Smith, 2012). CSOs, including trade unions, NGOs, religious groups, and foundations, play essential roles in transitions. They can act as checks and balances to government power, activities, policies, and resource allocation (Mlambo et al., 2020). Their influence often peaks during policy windows, triggered by international pressures or global changes. The dynamics of CSOs in Africa are unique, as they are often intertwined with ethnicity, interpersonal relations, and patron-client networks, influencing their behaviour and alignment with societal interests (Diamond, 1999; Omede and Bakare, 2014). CSOs significantly contribute to defending the rights of disadvantaged communities and filling gaps in state interventions (Mlambo et al., 2020). In Africa, the presence or absence of CSOs can critically impact resource distribution and access. For example, in Côte d'Ivoire, the failure to challenge the economic constraints and path dependence on unsustainable energy consumption models in bakeries and infrastructure is associated with the absence of CSOs (Späth et al., 2022).

CSOs in Africa face challenges in accessing funding, limiting their influence over political or development processes, especially in rural areas. For instance, in Nigeria, CSOs are reported to be influential only in large urban areas, failing to reach the wider, especially rural, population (Odeh, 2012). Fiscal constraints also relate to their lack of unity and independence, hindering their effectiveness (Odeh, 2012; Diamond, 1999; Omede and Bakare, 2014). This often means CSOs cannot set their own agendas and must respond to funders' requests (Igoe, 2003, 2024; Odeh, 2012). External funders are often foreign; for instance, in Tanzania, registered CSOs receive 90 per cent of their funding from foreign sources (Igoe, 2003; Haapanen, 2007). Similarly, some CSOs are funded by the state, such as Tanzania's Federation of Miners' Associations (FEMATA), which depends on state funding for financial survival (URT, 2020).

The lack of economic and political independence among CSOs can undermine the establishment of effective and democratic institutions (Acemoglu and Robinson, 2023). This dependency can lead to the capture of CSOs by the state or foreign funders, preventing them from pursuing their agendas and failing to represent societal interests (Diamond, 1999; Omede and Bakare, 2014). Additionally, some CSOs have been accused of corruption and embezzlement of donor funds, which diminishes trust in them from both the public and African states (Omede and Bakare, 2014).

Overall, acknowledging the scope of CSOs in Africa is crucial in addressing their influence on ST. It is essential not to assume that CSOs inherently work in favour of sustainability or comprehensive societal interests. Instead, they may represent the interests of specific groups, including foreign actors or the state, potentially leading to distributional and procedural inequalities. Moreover, due to financial and social constraints, only a few groups with sufficient support or resources can exert political influence, while vulnerable groups and the poor may lack the means to organize and create influential CSOs, resulting in recognition inequalities (Odeh, 2012; Omede and Bakare, 2014).

2.2. The poor in transitions

Addressing the needs of the most vulnerable individuals, including the poor, is essential when investigating and designing ST to curtail recognition inequalities. The poor, who live in economic scarcity and struggle to meet their daily subsistence needs, are particularly affected. Poverty increases the focus on immediate needs over long-term social and economic planning, such as organising in CSOs (Assan & Kumar, 2009). Consequently, poverty and financial scarcity exacerbate time discounting, a present bias where immediate rewards and consumption are perceived as more attractive than future benefits and gains, which are seen as more uncertain (De Bruijn and Antonides, 2022). Dealing with financial scarcity increases cognitive load, leading to suboptimal and seemingly irrational decisions. These can include time-inconsistent behaviour, intention-behaviour gaps, increased risk aversion, overborrowing, and erratic consumption decisions (De Bruijn and Antonides, 2022). Similarly, financial scarcity may increase risk aversion and hamper the ability of the poor to exploit resources sustainably, leading to the overexploitation of common-pool natural resources, such as land or forests, for livelihoods (Assan & Kumar, 2009; De Bruijn and

Antonides, 2022).

Transforming behaviour in the context of poverty is a complex undertaking and is closely related to the difficulties and expense of accessing capital in Africa. Formal capital is costly, with interest rates reaching up to 30–40 per cent, and access is limited due to unclear regulations and enforcement (Kalemli-Ozcan and Sørensen, 2014). While microcapital is sometimes more accessible for informal economic activities, it relies on social capital and interpersonal relationships, which not all disadvantaged individuals possess (Geenen and Bikubanya, 2024; Kalemli-Ozcan and Sørensen, 2014). Additionally, microloans, a common form of microcapital, are reported to carry high annual interest rates, exceeding 50 per cent in some cases (Kalemli-Ozcan and Sørensen, 2014).

3. Material and methods

Data collection was carried out for a total of three months in July, August, September 2023 and February 2024 in Tanzania, specifically in the Geita and Shinyanga regions and in the cities of Dodoma and Dar es Salaam (Fig. 1). Additionally, a two-month exploratory fieldwork was conducted in August–September 2022 in the same regions, during which the importance of this research topic emerged, and key stakeholders were identified.

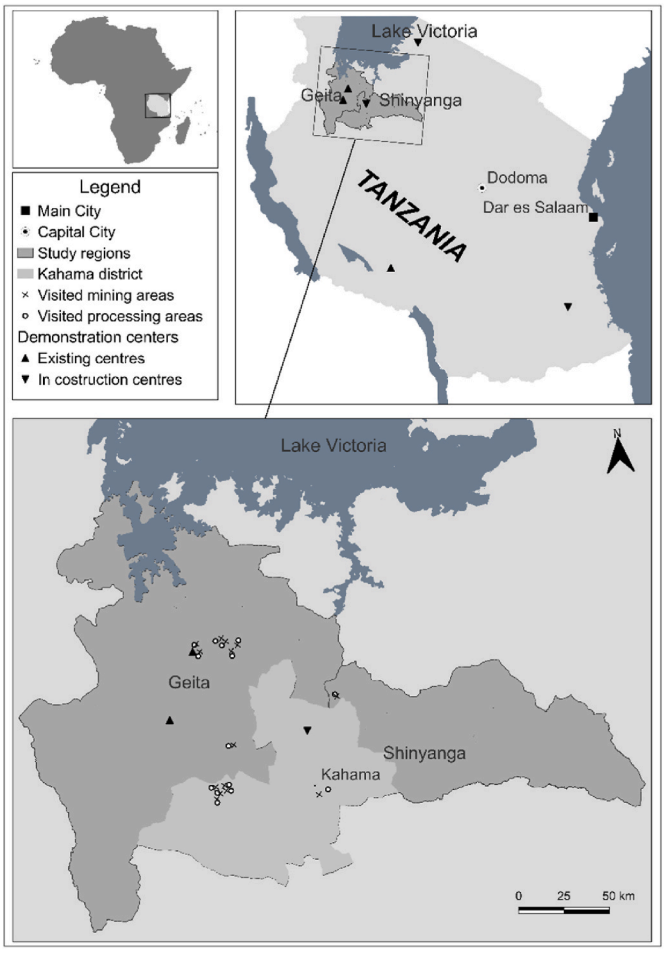

Fig. 1. Study area and demonstration centres
The map shows mining and processing areas visited in Tanzania. It shows the Geita and Shinyanga regions, and the Kahama district (which includes both Kahama township and Kahama, where the survey was conducted). Finally, we highlighted existing and under construction demonstration centres, as well as the cities of Kahama, Dar es Salaam and Dodoma, where interviews with public officials were conducted. Source: Authors' elaboration. Region and country boundaries by World Bank (2018).

This research received approval from the Tanzania Commission for Science and Technology (COSTECH), which provided a research permit. Further approval was obtained from the university's ethics committee by closely following the research integrity guidelines provided by the European Union's General Data Protection Regulation (GDPR) and the Finnish National Board on Research Integrity TENK (2019). We aimed to engage with respondents with reciprocity and transparency. In addition to anonymising all respondents, we interacted with them beyond data collection. This enabled us to comprehend the positionality of different actors and the relationships between them (Ramos-Mejía et al., 2018). We included the interpretations of our research assistants and informants about such interactions and our preliminary findings as part of our data. This field-intensive approach facilitated the emergence of otherwise concealed narratives and insights into relationships, significantly enriching this research.

We adopted a mixed methods approach, combining quantitative and qualitative methodologies, such as surveys and statistical analyses, with participant observation and semi-structured interviews (SSI). Several mining areas and mercury and cyanide processing sites were visited, along with interviews in Dodoma and Dar es Salaam (Fig. 1). The quantitative analysis provided background information and insights, which were further explored through a stronger qualitative analysis. The primary dataset for the quantitative analysis consisted of 116 survey responses from miners in the Kahama district. Given the contextual challenges in creating a representative sample, we followed a purposive sampling strategy, selecting only individuals actively involved in small-scale mining activities (e.g., employment or ownership of mining licences, machinery, or mining shafts). Although this suggests that results may not be generalizable to the whole population, it indicates relationships between variables, which were further investigated through qualitative methodologies. The triangulation of variables (data) and methods rendered validity and reliability to this study (Patton, 1999).

The survey consisted of 36 questions in Swahili, which were read out to respondents. Some questions were multiple-choice, while others were open-ended. From these questions, we created several variables, with the most prominent being that of miners, subdivided into workers (89 respondents) and entrepreneurs (27 respondents). This method allowed for a higher proportion of entrepreneurs against workers, highlighting differences between these groups, as entrepreneurs are a significantly smaller group compared to workers. Other variables were created based on responses related to education, access to capital, challenges in mining, miners' associations, and future intentions. We calculated the percentage of each variable in relation to the entrepreneur-worker variable, and subsequently ran Fisher's exact statistical test to address the statistical significance of the relationship between categorical variables. Following this strategy, we calculate the ensuing two-sided p-value.

Qualitative data collection encompassed 78 Semi-Structured Interviews (SSIs), Participant Observation (PO), and two Focus Group Discussions (FGDs), most of which were conducted in Swahili in Tanzania. Participants in the SSIs, summarized in Table 1, included sixteen entrepreneurs, twenty-one workers, four NGO representatives, seven miners' association officers, three brokers, one chemical distributor, four miners' relatives, and ten public officials. The latter included officials from regulation and enforcement, the Ministry of Minerals, the Ministry of Health, the National Environment Management Council (NEMC), the Geological Survey of Tanzania (GST), and the State Mining Corporation (STAMICO). Additional insights were sought through interviews with five independent geologists and seven engineers, both local and international. PO was conducted continuously throughout the fieldwork, with a particular focus during visits to mining and production areas, supply shops, and mineral markets. Notes taken during this process were used as data. Finally, FGDs were conducted with members of miners' associations. The qualitative data was analysed through thematic analysis, with themes including background information, practices, attitudes, and experiences. These were further divided into sub-

Table 1
Informants' main role for SSIs.

Role		Number
Miners	Entrepreneurs	16
	Workers	21
Public officials	National Environment Management Council (NEMC)	2
	Geological survey of Tanzania (GST)	2
	State Mining Corporation (STAMICO)	3
	Ministry of Minerals	2
	Government Chemist Laboratory Authority (GCLA), Ministry of Health	1
Mining experts	Independent/private geologist (of which local)	5 (4)
	Independent/private mineral processing chemical engineers (of which local)	7 (5)
Other stakeholders	NGO employees	4
	Miner associations officers	7
	Brokers	3
	Distributors (cyanide and other chemicals)	1
	Miners' relatives	4
Total		78

themes such as mercury use, cyanide use, scaling up production, driving change, resisting change, access to capital, gold trade, group-making, miners' associations, trust, production, precarity, poverty, and time-discounting. Subsequently, we explored the relationship between these concepts and the quantitative data, and grouped into the sections for the empirical analysis of this article.

Finally, in Section 4.1, we draw from a comprehensive literature review that includes both academic and grey literature. This section situates technological development within the socio-economic, political, and environmental contexts of Tanzania and Africa. By integrating these perspectives, we aim to unify these discourses and foster a multidisciplinary dialogue. Subsequently, in Section 4.2, we juxtapose our empirical material with the literature, particularly with the Minamata Convention (UNEP, 2023) and Tanzania's official National Action Plan (URT, 2020). This enables us to comprehend the motivations behind the national strategies of Tanzania and to shed light on the discrepancies between the NAP and the Convention with our empirical material. Through this approach, we identified five main strategies adopted in Tanzania to mitigate mercury use and their empirical limitations, which we outline in Section 4.

4. Transitioning from mercury to cyanide: support and resistance

4.1. Context: mercury and cyanide in ASGM in Tanzania

The Minamata Convention requires signatory countries to develop and implement a National Action Plan (NAP) as stipulated by Article 7 and Annex C of the Convention, with the aim of reducing mercury use in artisanal and small-scale gold mining (ASGM). The NAP must outline national objectives that focus on eliminating four harmful worst practices: whole ore amalgamation, open burning of gold-mercury amalgams, burning in residential areas, and the application of cyanide leaching to ore or tailings previously amalgamated with mercury, where mercury has not been removed. The final practice is known to facilitate the formation of methylmercury (UNEP, 2023, Annex C). Additionally, NAPs must promote the formalization of ASGM activities, encourage the adoption of mercury-free alternatives, reduce mercury exposure, develop public health strategies (with particular attention to vulnerable groups), regulate mercury trade, and estimate the quantities of mercury used. It is also crucial that these plans actively involve local communities in the implementation process (UNEP, 2023).

In alignment with the Minamata Convention, Tanzania implemented its National Action Plan (NAP) for 2020–2025, partially funded by a US $14.4 million grant from the Global Environmental Facility (GEF), the funding body of the Convention (URT, 2020). Another significant initiative in Tanzania aimed at reducing mercury use in artisanal and small-scale gold mining (ASGM) include the Sustainable Management of Mineral Resources Project (SMMRP) of the World Bank. Running from 2009 to 2018, this project was financed by a US$75 million credit and sought to improve the socio-economic benefits, governance, and environmental impacts of mining in Tanzania (URT, 2020; World Bank, 2019). Of the total funding, US$2.3 million was allocated specifically to environmental issues, with a strong focus on mercury abatement (Kinyondo and Huggins, 2021; World Bank, 2019).

Over the past few decades, various strategies to reduce mercury use and pollution in ASGM have been promoted, including gravitational methods with borax, magnets, and the use of retorts (Jønsson et al., 2013; Geenen and Bikubanya, 2024). Although more environmentally sustainable, these innovations have not been widely adopted by miners due to perceived or actual economic losses and the inability to universally apply these methods across all types of ores (Jønsson et al., 2013). Conversely, cyanide leaching, introduced by the private sector, has gained traction in ASGM in Tanzania due to its superior efficiency (Tomassi, 2024). Currently, this method is emerging as the primary mercury-free technology for gold extraction, supported by both the NAP and SMMRP.

In ASGM in Tanzania, two main cyanide leaching methods are employed: VAT leaching and Carbon-in-Pulp (CIP). VAT leaching constitutes the majority of cyanide leaching operations. In this process, ore or tailings are deposited into large tanks, where water and chemicals, including sodium cyanide, are introduced. Gold is then extracted using activated carbon and electrolysis technologies. CIP technology follows a similar procedure but is more strictly regulated by the government—requiring, for example, tailings storage facilities (TSF)—and involves more advanced infrastructure, making it more mechanized, efficient, and expensive. Both methods allow for the processing of larger volumes of ore at lower grades, sometimes handling tens or even hundreds of tonnes at a time. These methods are significantly more efficient than mercury-based extraction, with CIP technology capable of extracting up to 90 per cent of gold from ore, compared to approximately 30 per cent using mercury (Drace et al., 2016; Veiga et al., 2014). The higher costs, mechanization, and larger volumes of ore processed through cyanide leaching indicate a shift towards scaling up production. This technology is not profitable at smaller scales, where most ASGM operations have traditionally been situated.

The characteristics of this technology make it a valuable alternative in ASGM, particularly within the context of mining policy in Tanzania, which over the last two decades has focused on resource nationalism and formalization (Kinyondo and Huggins, 2019; Pedersen et al., 2022). Resource nationalism aims to increase state control over natural resources, while formalization seeks to integrate ASGM operations into the legal framework (Kinyondo and Huggins, 2019). Both of these objectives ultimately facilitate the capture of economic rent by the state through taxation (Kinyondo and Byaro, 2024; Kinyondo and Huggins, 2019; Pedersen et al., 2022). Scaling up production through cyanide leaching enhances traceability and taxation, thereby promoting formalization and increasing the ability of the State to capture economic rent (Geenen and Bikubanya, 2024; Huggins and Kinyondo, 2019; Kinyondo and Huggins, 2019).

However, the sustainability of cyanide leaching remains ambiguous, as the technology is associated with reduced employment opportunities and significant environmental harm (Malone et al., 2023; Stapper et al., 2021; Tomassi, 2024; URT, 2020). While job creation remains a priority for Tanzania's ASGM sector, this may be jeopardized if mercury is replaced by cyanide leaching, which is less labour-intensive. Furthermore, without adequate training and equipment, cyanide leaching can cause severe environmental damage and pose serious risks to human health. This concern is highlighted in a UNEP-led report on best practices for cyanide use in ASGM, which discourages the adoption of this technology by artisanal miners, favouring its use in less rudimentary

small-scale operations (Stapper et al., 2021). Moreover, cyanide leaching has been linked to several environmental disasters, such as the Baia Mare incident in 2000, which resulted in substantial pollution and long-lasting effects on the local ecosystem (Drace et al., 2016).

While leaching, cyanide breaks down into various compounds, including hydrogen cyanide. Although highly toxic, hydrogen cyanide is also volatile, meaning it rapidly vaporizes and becomes less hazardous over time, provided there are no other pollutants or heavy metals present (Drace et al., 2016; Manzila et al., 2022). This volatility is a significant advantage compared to mercury, which can persist in the environment for much longer periods.

However, the Minamata Convention focuses solely on mercury, leaving challenges associated with cyanide leaching outside its scope, and there is no equally robust international convention addressing cyanide. In the Minamata Convention, cyanide leaching is only mentioned in relation to mercury, particularly in the section on worst practices in ASGM, where cyanide leaching is conducted on mercury-polluted tailings (UNEP, 2023). While similar recovery rates can be achieved without mercury, this practice often leads to more severe environmental damage than when these methods are used independently (Malone et al., 2023). In Tanzania, empirical research suggests that cyanide leaching is rarely conducted on ore that has not already been processed with mercury. This can be partly explained by the practice of paying workers with gold obtained through mercury amalgamation, while entrepreneurs earn the largest share of profits by reprocessing the waste tailings with cyanide (Tomassi, 2024).

Another environmentally detrimental activity emerging alongside the scaling up of ASGM is the accumulation and storage of tailings. In large-scale mining (LSM), the challenge of safely containing tailings is well-recognized, as failure to do so has frequently resulted in environmental contamination (Drace et al., 2016; Stapper et al., 2021). However, this issue is becoming increasingly prominent in ASGM, driven by rapid scaling up and mechanization, while regulatory measures lag behind (Mutemeri et al., 2024; Stapper et al., 2021). It is estimated that between 1 and 2 million tonnes of tailings, containing up to 64 per cent of the total mercury applied, are produced annually in ASGM in Tanzania(URT, 2020). Moreover, these tailings often contain more mercury than gold (Mutemeri et al., 2024). Without adequate TSF, some mercury evaporates into the atmosphere, potentially affecting distant regions, while the remainder contributes to mercury contamination locally, e.g., in underground drinking water sources (Oakley, 2023; URT, 2020).

Despite these challenges, the 'co-existence' practice aligns with the major objectives of resource nationalism, formalization, mercury eradication, and employment creation. This model involves the co-existence of ASGM miners with conventional mining companies or mining licence holders (Bansah et al., 2018; Malone et al., 2023; Tomassi, 2024; Veiga and Fadina, 2020). For example, in Peru and Colombia, some ASGM miners excavate and grind ore using basic tools, then sell it to conventional, larger-scale miners for processing through cyanide technology (Veiga and Fadina, 2020). Similarly, evidence suggests that ASGM cooperatives in Venezuela could collect ore and process it in smaller cyanide plants provided by mining companies (Veiga and Fadina, 2020). By selling the ore or processing it directly with cyanide, this strategy avoids the use of mercury, thereby significantly reducing the mercury content in tailings. Additionally, by selling the tailings, artisanal miners can avoid direct engagement with cyanide leaching, a process for which they may lack the necessary tools or knowledge to operate safely (Stapper et al., 2021; Veiga and Fadina, 2020).

However, the global applicability of the co-existence model as a one-size-fits-all solution remains uncertain. This model requires changes in organizational capacity, logistics, and capital, which, in turn, demand higher levels of trust—conditions that are not universally present in ASGM communities (Malone et al., 2023; Veiga and Fadina, 2020). In the following section, 'Support for cyanide and ccaling up: state-led efforts in transition,' we outline the implementation strategies for mercury abatement. Subsequently, in 'Resistance of incumbents to scaling up and transition', we discuss the factors preventing these implementations from being successful and analyse how these obstacles perpetuate the use of mercury.

4.2. Support for cyanide and scaling up: state-led efforts in transition

Our qualitative data reveal five strategies through which the Tanzanian state is promoting cyanide leaching, the scaling up of ASGM, and co-existence to reduce mercury use. Most of these strategies are also discussed in the National Action Plan (NAP) and the Sustainable Management of Mineral Resources Project (SMMRP). Some strategies have been long implemented, while others are still in the process of execution. These strategies include: 1) training miners in cyanide technology; 2) fostering co-existence through demonstration centres; 3) providing capital to miners; 4) regulating the mercury market and the price of sodium cyanide; 5) and supporting the formation of groups to achieve economies of scale and co-existence.

The first two objectives emerged from our interviews[1] and resonate within the NAP and SMMRP. These aim at training miners on alternatives to mercury and enabling them to process the ore mercury-free. These objectives have been ongoing since the last decade, especially through the SMMRP, which established demonstration centres to improve productivity and safety, chiefly through CIP (Kinyondo and Huggins, 2020; URT, 2020; World Bank, 2019). Three of such centres are operating in Lwamgasa, Katente and Itumbi, whereas a further three are under construction in Msalala, Buhemba and Lindi (Fig. 1). With the exception of Lindi, which demonstrates salt mining, all others are for gold processing. Such centres are administered by STAMICO through its own funds and chiefly run as private businesses. Revenues ensue from customers, who can bring the ore or tailings already processed through mercury, and have the gold extracted for a fee. This shows how mercury enters the production chain even within such centres, which aim at substituting it. The sufficient quantity of ore/tailings is reached through different sources, for example through ownership of processing areas (both mercury and VAT leaching) or purchasing waste tailings from others.

The accessibility of these larger plants to ASGM miners makes it a form of co-existence between small- and medium-scale mining. The price of the service consists of 115 per cent of the costs incurred for the service, including wages, tailing storage, chemicals, electricity, and water. Half of this amount must be paid before accessing the service. Further costs are incurred in transporting the material across long distances through lorries with capacity 15–18 tonnes, in areas with poor infrastructure.

STAMICO officials sample the ore to ensure profitability before it is transported to the demonstration centre. The minimum accepted load is 10 tonnes with at least a 3g of gold per tonne (3g/tonne) recovery potential (low-grade). However, to increase profitability, customers normally bring up to 100 tonnes with 3g/tonne. Only when the ore is high-grade, with 40g/tonne, they will bring the minimum accepted 10 tonnes. While it was originally estimated that the plants could process 20 tonnes a day, only the recently expanded Lwamgasa demonstration centre has that capacity with the remaining only able to process 8 tonnes per day. This means that the remaining ore and tailings have to be stored in tailing storage facilities which adds to costs which are incurred by customers.

Beyond ore processing, demonstration centres provide other services. For example, Lwamgasa also works as a model mine, teaching miners about safe practices. In addition, demonstration centres in Katente and Itumbi, engage in selling and hiring chemicals and mining equipment, such as cyanide, carbon, lime and gun powder for

[1] Interviews, STAMICO officials, August 2023; February 2024; Entrepreneurs, July–August 2023.

explosives.

Demonstration centres are economically successful, through increasing gold output and tax revenues. The success is also mirrored by demand: waiting time for customers are often over a year due to high demand and this motivated over 10 private businesses following this model.

Consequently, currently only a minority of entrepreneurs engage in the CIP process. A substantial proliferation of these centres is required if all ASGM operations were to employ this technology. This is reflected in our data, where 99 per cent of workers and 73 per cent of entrepreneurs, state to have never received training from state or private initiatives[2] (Table 2). In the follow-up interviews, it emerged that most entrepreneurs were unaware of the very existence of such centres. Most importantly, if demonstration centres are to be considered alternatives to mercury, they must avoid processing tailings containing mercury, which remains the prevalent practice.

3) The third strategy emerged from our interviews,[3] and resonated with the NAP and SMMRP. This consists of the provision of grants and loans to miners enabling scaling up production through improved technology. In 2015, as part of the SMMRP, loans up to US$100,000 were handed out to miners. Moreover, the national action plan of 2020 granted TZN Shillings 7 billion (~US$3 million) to licensed small scale miners through a government grant scheme to 111 miners, which has partly been implemented (URT, 2020). Both these strategies faced significant challenges, due to embezzlements of funds as recipients diverted funds to activities other than mining. Such misappropriation motivated the interruption of these schemes. Although this strategy rightly pointed to the challenge of accessing capital in ASGM, it excludes the day-to-day livelihoods of most entrepreneurs and miners who are unable to access credit.

Table 2
Selected variables against percentage of entrepreneurs and workers and statistical significance (p-value) through Fisher's Exact.

Categories	Selected variables	Entrepreneurs (27)	Workers (89)	p-value
Education	1. I have completed secondary school	44.44%	12.50%	0.001
Training	2. I have never received training from public/state organizations or any other organizations	73.08%	98.88%	0.000
Miners' Associations	3. I do not know miners' associations	22.22%	50.56%	0.014
	4. I feel represented by miners' associations	25.93%	8.99%	0.043
Main challenges I face in mining	5. I have no access capital[a]	7.87%	81.48%	0.000
	6. Occupational challenges[b]	7.41%	69.66%	0.000
	7. Payment challenges[c]	7.41%	50.56%	0.000
	8. Including both variables 7 and 8	7.41%	71.91%	0.000
Access to Capital for mining purposes	9. I have no access to capital[a]	33.33%	89.89%	0.000
	10. If I need capital, I can ask family or a friend	44.44%	6.74%	0.000
	11. I can borrow money from a broker or the mineral market	22.22%	3.37%	0.005
	12. I can borrow capital from banks or other institutions	0%	0%	–
5-year Future Intentions	15. I will continue mining	62.96%	33.71%	0.013
	16. I believe I can have a better role than now in mining	40.74%	14.61%	0.006

The percentage indicates the respondents in each group who respondent positively to the statement.

[a] For or during mining operations.

[b] Include accidents, rudimentary tools.

[c] Include issues related to finding work and being paid late, or not being paid at all, harassment at the workplace. Source: Authors' elaboration.

4) A further state-led initiative supporting cyanide technology emerged from interviews and resonated in news articles.[4] This has been the regulation of the market price of sodium cyanide, the main chemical used in cyanide leaching. In 2022, a shortage of this chemical led to market speculation, causing the price of cyanide to surge from TZN Shillings 400,000 to 1,200,000 for a 50 kg barrel. Following negotiations with ministries and miners' associations, the GCLA set a price cap of 600,000 TZN Shillings per tonne. Despite these efforts, our informants report that distributors are still requesting higher prices for cyanide than the regulated price.

For the first time, regulation of mercury was introduced in the early 2020s, aiming at monitoring its consumption and supply, in accordance with Annex C of the Convention. Although largely smuggled and sold informally, mercury is now available through authorized distributors, albeit few throughout the country, as distributors report being unable to compete with the market price of illegal mercury. Consequently, the informal market for mercury remains predominant. This is also echoed in our data, where only two out of all entrepreneurs knew about the existence of authorized shops selling mercury. Beyond the novelty of these shops in Tanzania, the lack of information can also be attributed to the remoteness of mining areas as well as the blending of formal and informal markets, which can make them unimportant and undistinguishable to customers.

5) The fifth strategy, emerging from interview data[5] and the NAP, aims at increasing the possibilities of co-existence and cooperation: making groups. This aims at challenging a defining feature of ASGM: the limited organizational structures and small number of individuals in each organization in ASGM. Many officials, as well as the national action plan, point to the strategy encouraging miners to group in larger numbers (URT, 2020:21). This would support miners in pooling resources, increase the possibilities of co-existence, share the costs of production and reach economies of scale which are essential for financing larger endeavours such as cyanide leaching operations. This effort is also in line with resource nationalism and efforts to increase formalisation, which present the state with further benefits: higher traceability and tax revenues. A further contribution in this direction has been the support to mining organizations, specifically the FEMATA association, the creation of which was initiated and supported by the state since 1987 and is endowed with the objective of representing interests of miners (URT, 2020). However, this strategy faces pervasive mistrust which hinder their success, as we discuss in the next section.

Overall, these five strategies, demonstrate a high-level commitment by the state to scaling up ASGM under the influence of international organizations and financing to reduce mercury. As such, we observe that the implementation of these strategies also promotes the formalisation of ASGM and in turn rent capture through increased tax revenues, while

[2] Survey: Table 2, point 2.

[3] Interviews: STAMICO, and Ministry of Minerals officials, February 2024 and August 2023.

[4] Interviews: GCLA official, Entrepreneurs, and distributors July–August 2023. News: https://www.thecitizen.co.tz/tanzania/news/national/gold-miners-hit-with-shortage-of-refining-chemicals-4080338.

[5] Interviews: STAMICO and Ministry of Minerals officials, FEMATA officials, July–August 2023.

overlooking environmental challenges, as shown by the perseverance of mercury use. Arguably, economic benefits and resource capture are prioritized against the persistence of mercury in ASGM. Although some of these strategies point to the right direction, they are not providing mercury-free and accessible alternatives to rural communities in Tanzania engaging in ASGM, to which mercury continues to be the best answer despite its environmental consequences.

4.3. Resistance of incumbents to scaling up and transition

Understanding the challenges faced by miners in upscaling production and transitioning towards sustainability necessitates a thorough examination of the existing socio-economic and behavioural structures in which they are embedded. This is essential, as the pro-cyanide strategies are implemented within these contexts, and their compatibility can determine the success of the implementation.

A positive outcome is one where cleaner production is achieved conjointly with local development, poverty alleviation and institutional improvements (Johnstone and Newell, 2018; Köhler et al., 2019; Ramos-Mejía et al., 2018). Hence, a transition towards cyanide technology should aspire to disrupt the use of mercury while introducing cleaner technologies, all the while sustaining or enhancing livelihoods in rural areas, such as co-existence. The subsequent sections delve into the challenges associated with realising these objectives, examining the roles of trust, capital, scale, time, and civil society.

4.3.1. Mistrust

Reaching economies of scale for cyanide production, participating in demonstration centres, and pooling resources requires extensive trust between entrepreneurs, workers, CSOs, and the state. Yet, our data suggests that mistrust is pervasive in ASGM. FEMATA, and the regional sub-associations it breaks into, are often unfamiliar and not trusted by miners and entrepreneurs: only 26 per cent and 9 per cent of entrepreneurs and workers surveyed expressed feeling represented by miners' associations, with 22 per cent of entrepreneurs and 51 per cent of workers stating not knowing about the existence of miners' associations at all.[6]

This relates to the mis-alignment of the needs of the miners against the priorities of miners' associations, whose agenda, including mercury abatement, represents a priority of the state rather than those of miners. Similarly, cooperatives are not seen as representative. This relates to a historical failure on the side of the cooperatives on bringing positive effects on livelihoods, while often accused of fund misappropriation (Nindi, 1978).

Lack of trust also unfolds between miners and entrepreneurs.[7] Entrepreneurs disclosed fearing theft and plants are secured through security officers. Workers also report mistrust towards their employers, as many complain not being paid the agreed amount or at the due time.[8] Fear of deception also prevents potentially more sustainable practices such as co-existence which require trust and cooperation. Miners purchasing tailings often report being deceived by sellers who place high gold PPM content on top of tailings with lower PPM, so their samples will show higher gold content.

Partly, these challenges have their roots in historical reasons and in particular during Tanzania's Ujamaa policies. These entailed the villagization of Tanzania, or efforts in making villages self-sufficient economically through relocation in1973–1977 (Owens, 2014). Although this policy was intended to bring rural development, it led to the embezzlement of government funds (Sundet, 1997). Moreover, it has been argued that these developments have contributed to corruption and fuelling mistrust among Tanzanians (Owens, 2014).

Consequently, scaling up production through collective organization is extremely challenging in ASGM in Tanzania. Only entrepreneurs with economic and political capital can achieve these goals individually. This reflects such entrepreneurs' stronger influence within certain groups, as demonstrated by the objective of lowering the price of sodium cyanide. These extend beyond this, as political capital also allows some entrepreneurs greater access to mining licenses, capital and technology compared to others.

4.3.2. Access to capital

In a context of pervasive mistrust, miners require capital to scaling up production individually or in small groups. Notably, only 4 out of the 27 entrepreneurs interviewed conduct cyanide leaching on ore which has not previously been processed through mercury. Typically, entrepreneurs employ mercury amalgamation before further processing waste tailings through cyanide leaching. In these four cases, capital and access to capital represent the key difference, as it facilitates access to advanced machinery such as ball mills and jaw crushers. The few entrepreneurs engaging in this activity showcase how accessing capital and credit represent a further obstacle in scaling up production.

Formal bank loans are seldom pursued, as lenders require geological assessments, which most ASGM miners do not possess, and consequently consider financing ASGM operations too risky. Survey data corroborate this trend, as none of the respondents reported obtaining credit from such institutions. Instead, family members and brokers serve as the primary lenders in ASGM, albeit in limited instances.[9]

Follow-up interviews[10] reveal that although family members offer informal loans, they often lack the necessary capital to finance substantial mining costs, such as those incurred for cyanide leaching. Consequently, brokers emerge as the primary financiers for cyanide operations. Brokers typically provide loans to individuals within their familial or social networks. Criteria for loan approval include evaluating the viability of the mining venture through metallurgical testing to ascertain ore composition and profitability. Additionally, brokers assess technical factors such as sunk costs, pit depth, machinery availability, and the presence of physical assets that can serve as collateral, such as machinery or cars. Consequently, access to capital remains highly exclusive, limited to entrepreneurs possessing significant social, economic, and physical capital. This resonates with our survey data, indicating that only 22 per cent of entrepreneurs and 3 per cent of workers have access to loans from brokers.[11] Interest rates for these loans typically range from 10 to 20 per cent per operation, lasting approximately between one to four months. For longer periods, interest rates may reach 50 per cent. Often, loan recipients are obliged to pay the interest by selling the gold to the sponsoring broker at lower market prices for gold. An alternative informal credit strategy pertains specifically to mercury, with brokers offering mercury on credit to miners. Subsequently, miners sell the extracted gold to the same broker, thereby settling their debt while hoping to generate income.

This underscores not only the exclusivity of loan accessibility but also the associated high costs. Compared to formal loans, these schemes offer a more accessible avenue for credit. Given the challenges in accessing capital, only few miners succeed in scaling up production.

4.3.3. Inconsistency of time and scale

Despite operating on a smaller scale, mercury amalgamation methods still necessitate capital investment, indicating that there are further factors preventing a ST towards cyanide. In the mining areas visited, the price of mercury ranged from TZN Shillings 380,000 to 520,000 per kilogram [~US$200], with additional costs incurred during excavation, crushing, and sluicing stages. Nonetheless, many miners

[6] Survey, Table 2, points 3–4.
[7] Interviews: Workers, Entrepreneurs, July-August 2023.
[8] Survey, Table 2, point 7.
[9] Survey: Table 2, points 7–11.
[10] Interviews: Brokers, Entrepreneurs, and Families, July–August 2023.
[11] Survey: Table 2, point 12.

effectively manage this production chain. Consequently, it is overly simplistic to attribute the inaccessibility of cyanide leaching solely to its higher costs. Scaling up and access to capital are intricately linked with time: improved excavation and crushing machinery possessed by wealthier miners facilitate faster accumulation of ore/tailings. For instance, the four entrepreneurs employing cyanide technology could accumulate sufficient ore/tailings within one or two months, contrasting with the majority who can only conduct cyanide leaching every three to eight months. Having a shorter investment-revenue time gap facilitates entrepreneurs in covering production costs without necessitating mercury. As expressed by a miner: 'Why bother with mercury? I have capital now; there is no need for mercury; it will just be wasting time and money'.[12] This underscores how some wealthier entrepreneurs view mercury amalgamation as an unnecessary process adding to production costs. This sentiment is shared also among many entrepreneurs currently using mercury, indicating a widespread acknowledgment of the redundancy of mercury. Some entrepreneurs also expressed willingness to omit mercury amalgamation, yet financial scarcity motivates them to persevere in using mercury, as illustrated by the following quote:

> 'All these stages require a lot of money: crushing is money, sluicing is money, amalgamating is money [which you must pay daily]. If I have capital or sponsorship [to cover these costs], I will just take the rocks from the pits, crush, and wash, and later bring everything to the plant [for cyanide leaching]. No wasting time to amalgamate, no wasting money. […] What we get from amalgamation is very little, maybe three million [~US$1,100]; if you already have that money there is no reason for you to use mercury. So, it's shortage of capital that forces us to use mercury. Only few have big capital to do this'.[13]

This quote shows how miners in financial scarcity present intention-behaviour gaps, risk aversion, and time-discounting behaviour: despite being willing, the majority of entrepreneurs prefer short-term revenues compared to uncertain long-term profits. To be profitable at larger scales using cyanide plants, substantial resources and planning are required, including high tonnage of high-grade ore. Renting a gold plant with VAT leaching is costly (TZN Shillings 5 million/month ~ US$2200), which can double when adding the costs of the chemicals. Consequently, entrepreneurs must carefully assess and often speculate whether cyanide leaching will yield higher revenues than expenses. This uncertainty often leads entrepreneurs and miners into applying mercury and accumulating tailings until they are confident of profitable returns by leaching. Again, the uncertainty of profitable returns sometimes motivates miners to sell the tailings instead, which would normally result in lower profits and showing a further intention-behaviour gap. These are expressed in the following quotes:

> 'Today I am happy because I made enough [through mercury amalgamation methods], to feed the family for this week to cover these maintenances of machines, and pay the miners. But I cannot wait six months [to accumulate enough tailings] to feed them!'[14]

> 'You have to accumulate tailings, because the price [for renting the gold plant] if you take only two tanks or all of them is the same. You must accumulate as many tailings as you can. But at the end you have to be lucky, you can pile-up 500 tonnes, but if you have low PPM, you can still get loss!'.[15]

> 'They must accumulate a lot of tailings. The more tailings they have, I will pay higher price per tonne. It's because it's easier to take one sample of tailings from one area. If you take little tailings from different places, it means I don't even know the mineral content of these tailings and how many chemicals I need to add to do the leaching, and it may cost you more than what you get. […] So, at the end of the day, it is much more profit if you accumulate the tailings and do leaching yourself rather than selling.'.[16]

Other than highlighting uncertainty, these quotes demonstrate the interconnectedness between time and scale. In contrast to cyanide, mercury amalgamation, offers a shorter investment-to-output timeframe as little as a few hours compared to several months. The uncertainty and insecurity associated with cyanide contrasts with the routines, regularity, and easily repeatable skills of mercury amalgamation methods. The characteristics of mercury better align with the day-to-day livelihood practices and financial scarcity faced by many within ASGM communities. Other than increasing mercury pollution, these practices contribute to the unsafe accumulation of tailings (containing mercury), with severe environmental implications, as VAT leaching operations lack TSF. Moreover, the urgency of producing fast gold and revenues, creates further tailings which can enhance tailings accumulation by wealthier actors who can access cyanide technology, as well as heightening inequalities.

Overall, the evidence discussed so far highlights how mercury provides miners with easier access to credit and relative security. At the same time, it is largely profits generated through mercury amalgamation which are financing cyanide leaching operations.

4.3.4. *Breaking down production*

Given the uncertainty within ASGM operations, miners and entrepreneurs are known to find creative strategies with existing resources. These aim at sharing risk and output, but also work as means for credit, debit and payments. One of the most prominent occurs after the excavation phase: once the ore is excavated and collected in sacks, it is shared in-kind among the shareholders, the workers (10 to 30 per cent), the license owner (20 per cent) and even tax authorities (7 per cent plus additional charges). Moreover, when taking the ore for mercury or cyanide processing, entrepreneurs often pay part of the service in kind by leaving them tailings (potentially still containing gold) to plant owners. Entrepreneurs, usually receive the largest share in this process, which nevertheless often amounts to less than half of the ore excavated. Many of these sacks are sometimes sold individually to small entrepreneurs, who pay mercury processing centres to extract the gold for them.[17] Naturally, at this scale, mercury amalgamation is the only extraction method that makes economic sense. Although such practices are essential in revenue sharing, they represent a further obstacle in scaling up production.

Overall, organizational practices such as down-scaling production, add to the difficulties in accessing capital, low trust, financial scarcity, and related daily needs which push miners to engage with mercury amalgamation methods to secure their short-term living practices and cover the daily costs of production (Fig. 2). The five strategies supporting cyanide leaching technologies presented in section 4.2, have tackled only part of the elements making mercury amalgamation practices the preferred choices for miners. Consequently, rather than having a ST with a technological transition from mercury to cyanide, the two technologies co-exist, responding to different needs. Moreover, cyanide practices exploit and are largely dependent upon the logistical and financial infrastructures created by mercury amalgamation.

4.4. *Emerging inequalities*

Our data indicate that ASGM in Tanzania is characterized by

[12] Interview: One of the four miners, license owner, July 2023.
[13] Interview: One of the four entrepreneurs engaging in mercury-free practices, July 2023.
[14] Interview: Pit owner, July 2023.
[15] Interview: Pit owner, July 2023.
[16] Interview: Entrepreneur, August 2023.
[17] Interviews: STAMICO, Ministry of Minerals, NEMC officials, Entrepreneurs and miners, July–August 2023.

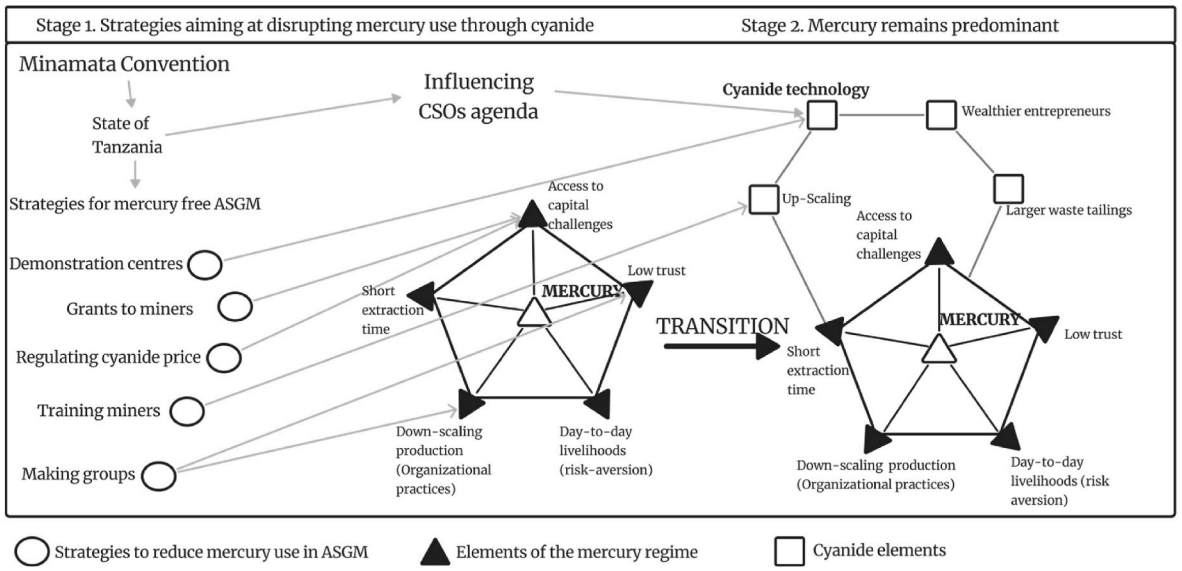

Fig. 2. The challenges in transitioning from mercury to cyanide in ASGM in Tanzania.
This figure shows the attempted mercury-cyanide transition. On the left, the five implementation strategies of the Minamata Convention in Tanzania are illustrated. These aim at tackling the persistence of mercury amalgamation methods within ASGM in Tanzania (stage 1), highlighting the centrality of mercury in sustaining livelihoods within the local context. In stage 2, we see how cyanide, rather than substituting mercury, it complements it. We also depicted the role of CSOs in advocating for the transition. Source: Authors' elaboration on Geels and Schot's (2007) Multi-Level Perspective.

significant fragmentation in terms of power and opportunities. This fragmentation is evident in the disparities between workers and entrepreneurs, as illustrated in Table 2 and supported by our qualitative data. Statistically significant differences in education, social capital (such as seeking financial support from friends and family), access to capital, and resource ownership underscore the distributional inequalities between these two groups.

Workers and less affluent miners rely on mercury for subsistence, whereas entrepreneurs benefit from leaching their waste tailings, allowing them to extract a larger proportion of the output. This aligns with previous research indicating that mercury use can perpetuate subsistence and poverty traps (Hilson and Pardie, 2006). The mercury trap, in turn, can be leveraged by entrepreneurs using cyanide technology to garner higher profits from tailings, while those relying on mercury struggle to meet basic needs.

Such distributional inequalities translate into procedural inequalities, as entrepreneurs exercise greater influence and control over socio-economic and political processes. This includes the ability to influence political decisions through miners' associations or other networks, and to avoid mercury use due to better access to capital. These advantages exacerbate distributional inequalities. This dynamic is further reflected in the statistically significant differences (and reflected in qualitative data) in future aspirations between workers and entrepreneurs, with workers perceiving fewer opportunities for socio-economic advancement.[18] While not captured by the survey, our qualitative data also reveal substantial inequalities among entrepreneurs themselves,

Procedural inequalities relate to the third dimension of inequality: recognition. While some entrepreneurs and powerful actors accumulate wealth, agency, and influence, vulnerable groups—such as workers and the impoverished—are largely excluded from decision-making processes and focus on immediate survival concerns.[19] Table 3 summarizes these distributional, procedural, and recognition inequalities in our case study, alongside the cosmopolitan inequalities discussed in Section 2. Overall, the evidence demonstrates that inequalities, mercury, and cyanide technology are intricately linked. Mercury is crucial for the immediate survival of workers and less affluent miners, while cyanide enables entrepreneurs to maximize profits and shape socio-economic and political processes.

Table 3
Dimensions of inequalities in ASGM.

Distributional	Inequalities in education, social, economic, physical, and political capital, agency between workers and entrepreneurs, and between entrepreneurs.
Procedural	Distributional inequalities enable wealthier entrepreneurs and actors in influencing socio-economic and political processes, and reproducing distributional inequalities.
Recognition	As some entrepreneurs and related powerful actors produce and reproduce wealth, agency, and power, vulnerable groups (i.e., the workers, the poor) are largely excluded from decision making processes.
Cosmopolitan	While gold from ASGM is traded globally, pollution from mercury and cyanide is severe in extraction areas. Miners and adjacent rural communities are disproportionally affected by the extraction. Yet, mercury pollution also has global repercussions.

5. Conclusion

Initiatives for environmental sustainability are driving transformations globally, including in natural resource sectors in Africa. One of these is the Minamata Convention on mercury, which aims at reducing mercury pollution with a large focus on ASGM. The main technology which has gained momentum globally to curb mercury use is cyanide leaching, with many scholars and policy makers advocating for a sustainability transition from mercury to cyanide. Against this background, this research addressed three key questions:

1) What are the main strategies identified and promoted to transition away from mercury use in ASGM in Tanzania? 2) What factors contribute to the persistence of mercury use despite these strategies? 3) How does a more environmentally sustainable and efficient technology, such as cyanide leaching, affect inequalities in ASGM?

1) Our research identifies that significant state-led strategies to reduce mercury use in Tanzania involve scaling up production through

[18] Survey: Table 2, points 15–16.
[19] Survey: Table 2, points 5 to 8.

cyanide leaching technology. Key strategies include establishing demonstration centres, providing grants to miners, promoting associations, training miners, and regulating chemical prices.

2) Despite the implementation of these strategies and the adoption of cyanide, mercury remains prevalent due to its interdependence with securing livelihoods. By delving into the social complexity, we identified the key elements essential in livelihood creation which compose the mercury socio-technical regime resisting a transition, including challenges in accessing capital, low trust, increasing investment-revenue time gap, and organizational practices breaking down production. Mercury is integral to this system, as it is essential to workers and less affluent miners, increasing their perceived security by granting immediate rewards. Similarly, it supports entrepreneurs in covering short-term costs while overcoming the need for more expensive loans, complex organizational structures, or trust. Thus, mercury is interwoven in cultural and socio-economic practices, serving as the medium sustaining and reproducing livelihoods, exchanges and relationships throughout time. Knowledge is another crucial element in this transition, yet it extends the scope of this article. Future research should explore how the increasing complexity of cyanide leaching technology affects both sustainability and inequality.

3) We explored inequalities and justice by weaving our results through the just transitions framework. Breaking down inequalities into distributional, procedural, recognition, and cosmopolitan inequalities and justice enabled us not only to identify how inequalities are distributed within ASGM, but also how they reproduce. These structures entail disadvantaged miners face enormous challenges in climbing employment and societal ladders, whereas the physical, socio-economic capital held by some entrepreneurs gives them greater agency and power in influencing decision making processes. Consequently, only a small subset of miners can bypass mercury by using cyanide leaching. Even when mercury is technically redundant, it enables wealthier entrepreneurs to extract value from the work of less affluent miners, thus also reducing their incentive to halt the use of mercury.

Given the high socio-economic complexity of ASGM, identifying effective policy measures is challenging. Recognising the embeddedness of mercury within the ASGM socio-technical regime highlights the difficulties of technological substitution. In the absence of a less environmentally harmful technology that meets the economic needs of rural communities, providing affordable access to capital could contribute to reduce reliance on mercury. This must be done by making taking loans lower-priced than buying mercury. However, this approach would require substantial enforcement and guidance, as pervasive time discounting, risk aversion, and intention-behaviour gaps need to be addressed.

A more sustainable policy strategy could involve directing resources from scaling up mining technologies towards supporting alternative rural livelihoods, particularly during the dry season when agriculture is not practiced. This responds to the idea that many mining communities engage with the activity as they have no other alternative. This approach could not only provide economic alternatives to mining and mitigate environmental impacts but also reduce inequality and resource capture by selected groups. Additionally, it would support the long-term sustainable development of communities, considering the limits of mineral extraction and its negative environmental impact. Hence, donor and international funding, often focusing narrowly on reducing mercury, could be reconsidered to promote broader sustainable development goals and promote livelihood creation mechanisms as mercury does.

Our case study shows the state plays an ambiguous role in responding, on one hand, to funders, the Minamata Convention, and the interests of powerful actors, while on the other hand addressing the risk of dispossessing miners of their subsistence. This ambiguity results in neither improved environmental sustainability nor achieving justice. This tension highlights the need to rethink how Global North priorities are designed and implemented in the developing world to prevent reproducing inequalities and uneven spatial development. A more sustainable approach could be to attempt to align these priorities, thus preventing such ambiguous outcomes responding to neither challenge.

Finally, our findings suggest that an in-depth relational approach can illuminate the processes shaping sustainability transitions in the Global South. Investigating the interplay between individuals, communities, technologies, and livelihood creation mechanisms is crucial for understanding the persistence of environmentally detrimental practices essential for daily survival. Such an approach can better inform policy development for environmentally sound outcomes and address the implications of technological shifts for justice. Future research addressing technology substitution should consider the complex challenges and contradictions inherent in each case study to enhance our understanding of sustainability and injustices within transitions.

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CRediT authorship contribution statement

Oliver Daniel Tomassi: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abel Alfred Kinyondo:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization.

Declaration of competing interest

None.

Data availability

The data that has been used is confidential.

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