The Extractive Industries and Society 17 (2024) 101410

Contents lists available at ScienceDirect

The Extractive Industries and Society

journal homepage: www.elsevier.com/locate/exis

Original article

Transitioning towards sustainability in artisanal and small-scale gold mining: A case study from Tanzania

Oliver Daniel Tomassi

Department of geography and geology, University of Turku, Vesilinnantie 5, 20500, Turku, Finland

ARTICLE INFO

Keywords:
Mercury
ASGM
Sustainability
Innovation
Tanzania

ABSTRACT

The extensive use of mercury in the artisanal and small-scale gold mining (ASGM) sector has long been a major challenge environmentally. Over the past decade, the rapid proliferation of cyanide leaching has shown potential as a substitute for mercury in ASGM. However, this has not led to a decrease in the use of mercury. Cyanide is frequently employed after applying mercury, rather than used as a substitute for it. While this challenge is acknowledged in research, empirical insights into the dynamics of this integration and the underlying transition to sustainability remain limited. To address this gap, this article investigates how cyanide leaching practices are being integrated with mercury use practices in Tanzania, the location of one of the largest ASGM sectors in sub-Saharan Africa. This study reveals that different organisational practices lead to variations in mercury use, which has important implications for sustainability.

1. Introduction

Transitioning towards sustainable development has emerged as a fundamental challenge of our time. This translates into the need to transform current practices of production and consumption in order to achieve environmental and socio-economic sustainability in all stages of production, including natural resource extraction in the Global South (Giurco et al., 2022; Köhler et al., 2019; Smith and Raven, 2012). This is particularly pertinent in the African context, where a significant proportion of the world's natural resources are located and a large number of people are involved.

In this context, innovations, technological change, and mechanisation have provided both new opportunities and challenges for sustainable development (Geenen et al., 2022; Nkuba et al., 2022; Jauhiainen and Hooli, 2019). One of the sectors most profoundly affected by increased mechanisation is artisanal and small-scale mining (ASM). Although ASM has long been considered a low-technology and labour-intensive mineral processing and excavation activity (Hilson, 2009), the last two decades have witnessed a surge in mechanisation (Geenen et al., 2022; Kabunga and Geenen, 2022; Nkuba et al., 2022; Veiga et al., 2014; Verbrugge et al., 2021) . A prominent example of the technological advancement is the adoption of cyanide leaching in artisanal and small-scale gold mining (ASGM). The efficiency gains introduced by this technology have led to its widespread adoption throughout Africa (Geenen et al., 2022; Merket, 2019; Verbrugge and Geenen, 2020).

Furthermore, cyanide leaching has been lauded as a more environmentally sustainable alternative for extracting gold compared to mercury (UNEP, 2019). Mercury amalgamation has long been the most common practice in ASGM for gold extraction, primarily due to its relatively low price and accessibility (Martinez et al., 2021; Veiga et al., 2014). However, mercury is toxic to both humans and the environment, posing one of the greatest threats to the environmental sustainability of this sector (UNEP, 2019; 2018).

Despite cyanide technology eliminating the need for mercury amalgamation, the latter remains prevalent. Existing research suggests that cyanide technology has been integrated into the gold extraction chain alongside mercury amalgamation (UNEP, 2019; 2018; Verbrugge et al., 2021). One primary environmental concern arising from this integration involves the widespread practice of implementing cyanide leaching on waste tailings already processed through mercury amalgamation (UNEP, 2018). This process produces the toxic compound methyl-mercury, which is easily absorbed by humans and the environment (UNEP, 2018). Consequently, it remains ambiguous whether the application of cyanide technology can reduce the use of mercury and steer ASGM towards a sustainable transition.

Examining organisational practices (OPs) in ASGM can yield valuable insights in understanding the potential of cyanide leaching for a sustainability transition. OPs encompass the common practices of organisations, and the individual actions, hierarchies, and agreements

E-mail address: oliver.tomassi@utu.fi.

https://doi.org/10.1016/j.exis.2024.101410
Received 25 October 2023; Received in revised form 15 January 2024; Accepted 15 January 2024
Available online 20 January 2024

through which they are formed (Jønsson and Fold, 2009). Some research has explored the relevance of OPs in ASGM (Conteh and Maconachie, 2021; Jønsson and Fold, 2009; Verbrugge and Geenen, 2020). However, empirical insights into the dynamics of this integration and the underlying motivations and consequences for sustainability remain limited. Moreover, limited knowledge exists regarding how OPs are influenced by the introduction of radically new technology, such as cyanide. This article addresses this gap by investigating how cyanide leaching practices are being integrated into the practices of mercury amalgamation in Tanzania.

This research is guided by the following research question: How do OPs linked to cyanidation impact the extent of mercury amalgamation and sustainable development in Tanzania's ASGM sector?

Feedback from semi-structured interviews (SSI), participants, observations (PO), and survey data were used to answer this question. The data were analysed using a multi-level-perspective (MLP) and a sustainability transition (ST) framework for socio-technical transitions. The MLP focuses on the evolution of socio-technical systems over time, resulting from the interplay of elements such as technology, economy, society, and politics (Geels and Schot, 2007). Consequently, the MLP is employed in this article to elucidate how socio-technical systems in Tanzania's ASGM evolve. Furthermore, the ST framework enables the examination of whether these changes result in more or less sustainable outcomes (Kivimaa et al., 2021; Loorbach et al., 2017). One limitation of the MLP and ST framework is their predominant focus in the Global North (Loorbach et al., 2017; Nesari et al., 2022). To address this gap, this research presents Tanzania as a case study from the Global South.

The results of this research are that the establishment of different OPs leads to variations in mercury use in ASGM. Although cyanide technology has proliferated rapidly and can technically be performed without mercury amalgamation, the latter is still central to most OPs for livelihood creation. This is because the high expenses of carrying out cyanide leaching motivates entrepreneurs to create OPs through which they can access more affordable resources. For example, entrepreneurs find it more convenient to buy the waste tailings produced through mercury amalgamation by miners, rather than extracting and processing the ore directly with cyanide.

The article is structured as follows; the following section discusses the opportunities and challenges in mechanisation within the framework of the socio-technical and sustainability transitions. These address some of the main challenges in the mechanisation of ASGM. Subsequently, the methodology section outlines the data collection and the analysis as well as the ethical considerations. After this, the findings are presented under four section headings: aspirations for mechanisation, organisational practices, agency, and niche development. Finally, the article concludes with remarks on how policy and future research can contribute to fostering a more sustainable ASGM.

2. Transitioning to more sustainable socio-technical systems

2.1. The multi-level-perspective

Transitioning towards sustainable development is a process occurring within landscapes of fast-changing technology, regulations, and practices. To understand and keep pace with these transformations, the sustainability transition (ST) framework has emerged in research. The ST framework examines how interactions between different elements on various scales can drive shifts in socio-technical systems (Loorbach et al., 2017). These systems encompass the interplay between policies, practices, technology, and people (Geels and Schot, 2007).

Investigating these interactions is pivotal to comprehending the transitions, particularly in the context of the rapid innovations in Africa (Jauhiainen and Hooli, 2019). For instance, investigations into institutional, financial, and technological aspects have revealed some of the barriers hindering the transition of Tanzania, Nigeria, and South Africa to cleaner energy (Aly et al., 2019; Nwaiwu, 2021).

Within the ST framework, there is a growing emphasis on understanding the role of innovations and technological change in shifting from one socio-technical system to another (Köhler et al., 2019). This necessity is met by the multi-level perspective (MLP), which offers a valuable approach to addressing these dynamics (Geels and Schot, 2007). The MLP examines the technological aspects of transitions while highlighting their co-evolution over time with society and agency (Loorbach et al., 2017).

The MLP identifies three levels within socio-technical systems: niches, regimes, and landscapes. Niches represent emerging, unstable, local novelties, while regimes encompass dominant societal orders, including existing national infrastructures, practices, institutions, and science. Finally, landscapes are the external global structures, such as market forces and environmental and political challenges (Geels and Schot, 2007; Loorbach et al., 2017). The ST framework views socio-technical transitions as a process in which niches develop and challenge the existing regime, potentially leading to a reconfiguration of the socio-technical system in favour of a new regime. Often, this transformation occurs under pressure from the landscape for more sustainable outcomes. This process is not linear, but rather unfolds as a continuous struggle and learning process among actors within the incumbent regimes, emerging niches, and landscapes (Ingram et al., 2015; Loorbach et al., 2017).

These shifts do not solely result from technological improvements but also involve changes at multiple levels, including aspects that are social, economic, and political (Kivimaa et al., 2021; Köhler et al., 2019). Socio-technical transitions can take decades to unfold due to resistance from incumbents, slow niche development, and the extensive reconfiguration of socio-technical systems (Kivimaa et al., 2021; Geels and Schot, 2007; Köhler et al., 2019). While there is a need to accelerate these transitions (Kivimaa et al., 2021), hasty adoption of new practices without addressing the various levels, groups, or outcomes may result in unjust transitions or produce unintended consequences (Loorbach et al., 2017).

Niche development is a pivotal component within the MLP. It represents the process by which novel innovations emerge, grow, and gain the capacity to challenge and potentially replace the established regime (Smith and Raven, 2012). One catalyst for niche development is niche-regime interaction, which fosters a space for mutual learning (Ingram et al., 2015). During this phase, some niches can leverage the structures, supply chains, or knowledge of the existing regime (Andersen and Wicken, 2021; Ingram et al., 2015). Interestingly, the success of a niche in supplanting the established regime does not solely depend on the radical nature of the innovation (Loorbach et al., 2017), in fact niche-regime compatibility can bolster the emergence and consolidation of niches (Ingram et al., 2015). Compatibility pertains to the extent to which the niche aligns with the practices and regulations of regimes and the extent to which it utilises existing supply chains (Ingram et al., 2015). For instance, in South Africa, those firms that were already familiar with in-situ geological knowledge and international supply chains for mining equipment gained an advantage due to the unique geology and mineralogy of the region. This knowledge outweighed the advantages held by outsiders with more sophisticated and radically different technology (Andersen and Wicken, 2021).

2.2. Mechanisation

Innovations and transitions often follow technological improvements or mechanisation. This is because they offer new possibilities and enhance land and labour productivity (Aryal et al., 2021). Mechanisation may emerge as a niche and then become transformative, especially in labour-intensive sectors. This is critical for the Global South, particularly in rural areas where agriculture and mining are the main economic sectors. Even minor technological enhancements can lead to substantial improvements in production, supply chains, and holistic sustainability (Geenen et al., 2022; Verbrugge et al., 2021). Such improvements are often incremental rather than radical, as they result from the co-evolution between existing problems and problem-solving solutions (Coccia, 2017). This is particularly true for mining, where incremental innovations offer economically safer alternatives than radical, new technology (Giurco et al., 2022).

In addition to gains in efficiency, mechanisation can also offer up-stream and down-stream employment opportunities, such as, the provision of equipment, the repair of machinery, and employment creation in other sectors; this can also have positive impacts on adjacent rural and urban areas (Geenen et al., 2022; Ma et al., 2021). Moreover, these factors may motivate individuals to remain in rural areas, potentially slowing down overpopulation in urban areas (Aryal et al., 2021).

However, there are concerns that mechanisation may reduce labour demand and employment, particularly as these sectors employ a large workforce in the rural areas of the Global South where employment opportunities are few (Aryal et al., 2021; Geenen et al., 2022). Therefore, mechanisation has the potential to instigate socio-technical transitions, but each case must be evaluated individually to assess its impact on holistic sustainability (Aryal et al., 2021; Geenen et al., 2022; Ma et al., 2022) .

2.3. Organisational practices and agency

While the availability, enhancement, and application of technology are crucial in socio-technical transitions, focusing solely on the introduction of technology is limiting. Instead, examining agency, or the ability to act on intentions (Grillitsch and Sotarauta, 2022), will provide more insight into the challenges of sustainable development (Pedersen et al., 2022). Agency is influenced by beliefs and motivations, which crystallise into different OPs, despite the availablility of similar technology. (Nkuba et al., 2022; Verbrugge and Geenen, 2020; Veiga et al., 2014). OPs encompass common practices within an organisation shaped by individual actions, relationships, hierarchies, roles, and agreements (Jønsson and Fold, 2009). OPs have proven significant in rural areas in the Global South, particularly with the rise of mechanisation (Aryal et al., 2021). Exploring the emergence and establishment of OPs can explain how regional growth paths can create lock-in effects which eventually become difficult to change (Grillitsch and Sotarauta, 2022).

3. Materials and methods

Data collection took place between July and September 2023 in the Geita and Shinyanga regions of Tanzania (Fig. 1). This was preceded by an explorative two-month fieldwork period in 2022, which proved essential for the case study selection. Data collection was enhanced outside of this the fieldwork period through a continuous exchange between the researcher and those involved in the field. This research has employed a mixed methods approach, incorporating both quantitative and qualitative methods to triangulate data and achieve both breadth and depth in the research. Quantitative methods formed the foundation upon which the qualitative methods were built.

The quantitative dataset comprised 116 survey responses. These surveys were completed by mining stakeholders, including 84 workers and 32 entrepreneurs. The surveys were conducted through purposive sampling in the Kahama district of the Shinyanga region. While this method does not yield a representative sample, it allows for the investigation of differences that emerge among various stakeholders in the industry. The surveys consisted of 36 questions in Swahili, which the research assistants read out to the respondents. These questions covered a range of topics, including the respondents' background information, perceptions, attitudes, behaviours related to mercury and cyanide use, motivations, OPs, access to capital, learning, changes, challenges, and future aspirations. Although the surveys primarily consisted of closed-ended questions, respondents were given the option to provide other

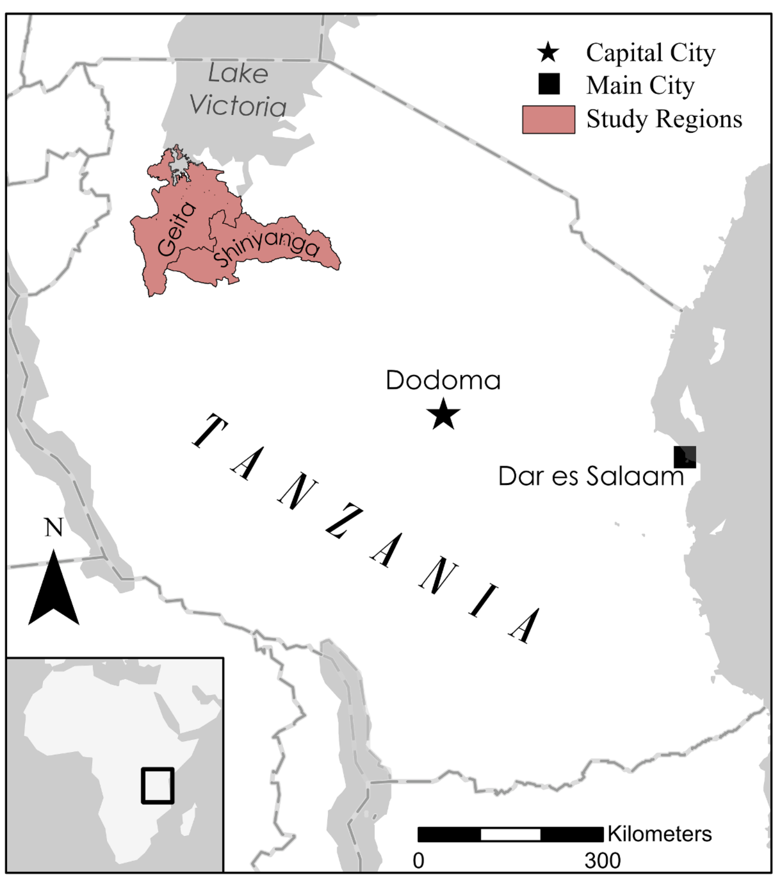

Fig. 1. Study regions within Tanzania. Created with data from the World Bank (2018) through ArcGIS PRO.

responses through the "Other" category. To expand upon the answers given in the surveys, some respondents were invited to participate in follow-up Semi-Structured Interviews (SSIs).

The qualitative data collection encompassed 73 semi-structured interviews (SSIs), two focus group discussions (FGDs), and participant observation (PO). These addressed similar topics to the quantitative data collection. The respondents selected for the SSIs included: twenty-one miners and operators; sixteen entrepreneurs; eight public officials, including mining commissioners, and regulation and enforcement officers; four NGOs, seven miners' associations members; three brokers and four miners' relatives. These were complemented by five interviews with geologists and five engineers with experience in the field. Sixty interviews were conducted in Swahili with the assistance of local aides, while the remaining interviews were conducted in English by the researcher. FGDs were conducted with four miners and three miners' association members each. PO was employed continuously throughout the fieldwork and interviews. Simultaneously, PO was also carried out at the ten mining and eight processing areas, along with the mineral markets, elution plants, and equipment shops. This enabled a more spontaneous interaction with informants, enabling a better in-depth understanding of their practices. This information was recorded in hand written notes and transcribed into field notes at the end of each day.

The data have undergone thematic analysis. Initially, interview and PO data were coded into themes related to mercury use, cyanide use, and the combined use of mercury and cyanide. This enabled the grouping of data related to similar practices; this resulted in common patterns emerging which have then been classified as the four OPs. In a second phase, the OPs were further categorised based on their potential for employment and mercury and cyanide use. These further categories served as proxies for socio-economic and environmental sustainability respectively. In a third phase, the themes of agency and aspirations for mechanisation were added to depict the reasons motiving the development of the OPs. Direct quotations have also been included to illustrate the respondents' rationales for participating in and developing OPs.

This research underwent an ethical review, and the necessary local research permit was obtained from the Tanzania Commission for Science and Technology (COSTECH). Data collection and analysis closely followed the European Union's General Data Protection Regulation (GDPR) and the TENK (2019) ethical guidelines provided by the Finnish National Board on Research Integrity. Consequently, respondent identities were anonymised, and the names of survey respondents were not collected.

Additionally, the research prioritised respectful, reciprocal, and transparent interactions with the respondents. Interviews were structured as a mutual learning process rather than following a traditional researcher-respondent hierarchical structure, fostering a co-production of knowledge. Efforts were made to incorporate local epistemologies and engage with post-colonial practices to prevent the perpetuation of Western perspectives (Thambinathan and Kinsella, 2021). Among other strategies, this was achieved by applying critical reflexivity and engaging with the informants beyond the data collection. Moreover, local research assistants had direct experience with the ASGM activities. Subsequently, their interpretations of the field were valued and have added further meaning to the data collected. This approach allowed for the emergence of meaningful perspectives that might otherwise have been concealed and which has significantly enriched this research.

This open and explorative approach has also been crucial to addressing a theme such as sustainability. Although the concept of sustainability is adopted by Tanzanian institutions (URT, 2020), it usually has little meaning for miners (Fisher et al., 2023). Consequently, this research has endeavoured to include the local narratives driving change which may differ from sustainability as understood in Western and institutional epistemologies.

4. Mercury, cyanide and sustainability in organisational practices in ASGM

4.1. ASGM in Tanzania

ASGM is a large sector in Tanzania, engaging over one million individuals, while indirectly supporting the livelihoods of an estimated seven million people (URT, 2020). The sector has also been shown to have positive effects on poverty alleviation and employment creation (Hilson, 2009; Jønsson and Fold, 2009). These benefits contrast with the more mechanised large-scale mining (LSM), which is less labour-intensive and benefits fewer individuals (Langston et al., 2015).

One of the main challenges to sustainability in ASGM is mercury amalgamation, which has been one of the earliest methods to extract gold from the ore (Veiga et al., 2014). Mercury is a toxic heavy metal that becomes detrimental when bio-accumulating in the human body and ecosystem (UNEP, 2019). ASGM accounts for the largest percentage of global mercury emissions, estimated at 37.7 %, placing miners and the environment at substantial risk (UNEP, 2018). Despite its limitations in extracting only approximately 30 % of gold from the ore, mercury amalgamation has remained the preferred practice for gold extraction in ASGM due to its accessibility and relatively low cost (Martinez et al., 2021; Veiga et al., 2014). The longevity and wide distribution of this practice make it the incumbent regime within the Multi-Level Perspective (MLP) framework. International efforts have been made to destabilise this regime and to reduce mercury use in ASGM, this was done in alignment with the United Nations Minamata Convention on Mercury proclaimed in 2013 (UNEP, 2019). In line with this convention, Tanzania unveiled a National Action Plan in 2020, intending to significantly reduce or eliminate mercury use in ASGM by 2025 (URT, 2020).

The urgency of transitioning from mercury to more sustainable practices has led to the introduction of various innovations in recent decades, including the borax method, retorts, and magnets (Appel and Na-Oy, 2012; Jønsson et al., 2013). However, most of these top-down innovations have failed to become mainstream technologies due to higher costs, geological factors, local beliefs, and insufficient knowledge or equipment (Davies, 2014)

In contrast, gold leaching through cyanide has emerged, to some extent, as a bottom-up innovation. Although it has been used in LSM since the late nineteenth century, it only appeared recently in ASGM (Verbrugge and Geenen, 2020). This is because for a long time it was discounted as an alternative to mercury amalgamation in ASGM due to its requirement for extensive large volumes of ore, knowledge, and capital (Appel and Na-Oy, 2012). Nevertheless, it surfaced in the late 2000s and has since proliferated rapidly (Merket, 2018). Two of the main Tanzanian regions where this method evolved are Geita and Shinyanga, and these were chosen as case studies for this research (URT, 2020).

This rapid expansion was driven by a substantial increase in efficiency, as it can extract between 60 % and 90 % of gold from the ore (Drace et al., 2016; Hiji and Maganga, 2015; Veiga et al., 2014). This efficiency enhancement positions cyanide leaching as part of ASGM's trajectory towards mechanisation, along with ball mills (locally referred to as 'karasha'), excavators, and jaw crushers (Geenen et al., 2022). Within the MLP framework, cyanide leaching and these technologies are niches, as they represent novelty within ASGM.

After the initial phase in which cyanide technology proliferated informally, it became increasingly recognised, regulated, and even supported by public institutions (Kinyondo and Huggins, 2020). This support has been part of a set of policies aiming at strengthening resource nationalism and economic rent capture (Kinyondo and Villanger, 2017). Although mainly targeting LSM, some policies have also promoted formalisation and transparency in ASGM (Pedersen et al., 2021; Kinyondo and Huggins, 2019). These policies have translated into the establishment of formalised mineral markets and demonstration centres (Kinyondo and Huggins, 2020). The aim of the demonstration centres is to train miners in the safe and efficient use of mining technology, including cyanide leaching (Kinyondo and Huggins, 2020). Despite these efforts, most miners have not been able to access such centres, due to legal and economic constraints, which has contributed to maintaining the informality practiced in a large portion of ASGM (Hilson, 2020; Kinyondo and Huggins, 2021). Similarly, formal access to capital is highly restricted, as most miners lack the geological information and physical collateral required by financial institutions, making it difficult to afford the high costs of leaching technology (URT, 2020).

Notwithstanding its relative efficiency, the use of cyanide leaching in mining has also been controversial. This stems from the highly toxic nature of the sodium cyanide utilised in the process, posing risks to both human health and wildlife. In certain LSM operations in the past three decades, improper disposal into water bodies of cyanide-polluted tailings has resulted in significant harm to wildlife and ecosystems (Drace et al., 2016). Consequently, this has prompted the emergence in the last two decades of movements and regulations in some European countries explicitly banning the use of cyanide in gold mining (Bocse, 2021). Furthermore, sodium cyanide may produce hydrogen cyanide gas under certain conditions, adding a further layer of concern (Drace et al., 2016). Actually, hydrogen cyanide does not persist in the environment for extended periods, as it is broken down easily by chemical and biological processes (Manzila et al., 2022; Drace et al., 2016). However, it creates some compounds by interacting with other substances, including mercury, which may persist for longer durations (Drace et al., 2016).

While these issues are also pertinent to ASGM, it has been argued that the implementation of safe disposal methods is feasible if appropriate measures are taken (Manzila et al., 2022; Drace et al., 2016; Veiga et al., 2014). Despite these challenges, many scientists consider cyanidation as a lesser evil than mercury amalgamation methods (Manzila et al., 2022; Drace et al., 2016; Veiga et al., 2014).

Recent evidence suggests that cyanide processing has not replaced mercury amalgamation but instead has complemented it. In many cases, cyanide leaching is applied to the ore after it has been amalgamated with mercury (UNEP, 2019; 2018; Verbrugge et al., 2021). This process promotes the creation of methylmercury, one of the most toxic forms of mercury, as it is more easily absorbed and bio-accumulated by humans, animals, and the environment (UNEP, 2019). This increases risks to the environment and humans, and has therefore been identified as one of the most detrimental practices in ASGM (UNEP, 2019, Annex C). In light of these developments, ASGM in Tanzania serves as a critical case study for transitioning toward sustainability, offering valuable insights not only into this specific context but also for other cases undergoing similar transitions.

4.2. The aspirations of mechanisation

The growth in mechanisation is consolidating existing socio-economic hierarchies. Stakeholders can be divided into two groups: entrepreneurs and miners. Those benefitting most from mechanisation are the entrepreneurs, many of whom entered the sector as affluent outsiders and have been involved in mining for numerous years. Some entrepreneurs may own land or hold primary mining licenses (PML), which are only granted to Tanzanian citizens for prospecting and small-scale mining activities. Smaller entrepreneurs may own pits, gold plants, or machinery, although they usually do not engage directly in excavation activities. They make decisions and direct most mining activities as they are the only stakeholders interested and able to afford expensive technology such as cyanide leaching. In contrast, miners are often seasonal workers, mostly performing low-skilled tasks, such as, rock breaking, digging, mercury amalgamation, operating machinery, and washing the ore. The miners are paid either a small portion of the output or daily wages. The survey responses helped to distinguish between the entrepreneurs and miners. Entrepreneurs consistently answered '*I can make good money*' as their primary reason for becoming involved in ASGM, whereas miners mostly answered '*I have no alternative to making money*' and '*I have to support the family*'.

Mechanisation is threatening some miners' livelihoods, as processes previously carried out by human labour are increasingly being mechanised. This is further evidenced in the survey data, which indicated that 51 % of the miners surveyed considered finding work as one of their main challenges in ASGM.

At the same time, mechanisation has expanded the ambitions of the miners, and particularly the entrepreneurs in ASGM. The interviews revealed that entrepreneurs are continuously seeking technological improvements to increase profitability, reduce accidents, and decrease reliance on miners who they may consider untrustworthy. These motivations are reflected in the following quotes by the entrepreneurs:

> *"It's nonsense to amalgamate those* [tailings] *with mercury! how long would it take? And it only gives you a little gold. if you want to make money, you have to go the* [gold] *plant".*

> *"I used to send the miners down those pits, but it's not safe, we had many accidents, someone died down there. But with the excavator… no need to have miners risking their lives and I will get less trouble for following security standards".*

> "*This* [while pointing to an excavator] *changed everything, now we don't need so many miners […] You cannot trust miners. But the machine will never steal from you".*

These quotes reveal that mechanisation has not only become central as a means of enhancing profitability, but is also used as a catalyst to re-arrange OPs. Mechanisation means reducing reliance on the miners and also the entrepreneurs' responsibilities towards them.

Nevertheless, most entrepreneurs cannot afford to mechanise all stages of production, which also prevents them from upscaling production. As a result, human labour remains central as it is a more accessible and cheaper alternative. A small entrepreneur confessed this challenge in the following quotation while pointing to another entrepreneur's jaw-crusher:

> *"With that jaw-crusher, he only needs one day to crush all those rocks. But it's expensive… Instead employing the women to crush the rocks with these local tools is much cheaper, I only need to pay them 2000 shillings (*~0.80 USD*) per* 25 kg *bag. But it takes a whole week".*

4.3. Emerging organisational practices in ASGM

Individual motivations and aspirations drive the continuous interactions between stakeholders in ASGM. These interactions can be viewed as niche-regime interactions that temporarily crystallise into various OPs. These practices build upon the pre-cyanide OPs, many of which continue in a considerable number of areas despite the availability of cyanide. Therefore, realising how these practices have evolved is essential to understanding the current landscape of the OPs.

In pre-cyanide ASGM, the production process unfolded as follows: after ore extraction, the ore undergoes crushing and subsequent washing. The washing step is pivotal, as it determines whether the ore should be directed towards mercury amalgamation or cyanide leaching. This washing process involves placing the crushed ore on an inclined panel, which is typically covered with a cloth. The ore is mixed with water and slides down the inclined panel. In this process, the coarser gold particles are captured by the cloth, owing to gravity. In contrast, the finer gold particles slide down the panel, accumulating in a pond. Subsequently, only the ore captured by the cloth is amalgamated with mercury. During this process, mercury forms an amalgam with the gold, which is then burnt, leading to the evaporation of mercury and purifying the gold. Since mercury is added only after crushing and washing stages, it is applied only on a more concentrated ore. This means that whole ore amalgamation, considered an action to eliminate in ASGM (UNEP, 2019), does not occur in the visited mining areas, as only part of the ore undergoes mercury amalgamation.

This production process generates two distinct quantities of material: one batch of tailings already amalgamated with mercury and one batch of unprocessed ore. Just over a decade ago, the tailings were considered waste. However, due to the inefficiency of this process, the tailings left behind still contain gold, which can subsequently be extracted through the VAT leaching process. VAT leaching is conducted in gold plants, where tailings and ore are processed in large tanks using cyanide and lime, and the gold is absorbed through carbon. Following this technological improvement, miners now accumulate and mix the two piles of tailings and ore, and these are then both leached with cyanide. This demonstrates how the introduction of cyanide as a niche is compatible with the existing regime of mercury amalgamation methods.

While it is technically possible and environmentally desirable to bypass the mercury amalgamation phase and directly leach the ore with cyanide, the high costs associated with cyanide leaching render it inconceivable for most involved in ASG operations Many entrepreneurs report consuming approximately one kilogram of mercury per month, at the cost of 480,000 shillings (~192 USD). Cyanide leaching incurs substantially higher costs; the most prominent being the renting of gold plants amounting to thousands of USDs per month or the construction of gold plants amounting to tens of thousands of USDs. Other expenses include procuring chemicals and carbons and paying wages for operators. Consequently, entrepreneurs require a considerable quantity of tailings or ore to make VAT leaching economically viable. This leads to the common practice of accumulating tailings over time until the required volume is attained.

As a result, many entrepreneurs engage in mercury amalgamation methods to reduce production costs, either out of necessity or opportunity. Entrepreneurs engage in different ways with mercury amalgamation, leading to the emergence of diverging OPs in different mining areas. This article categorises these OPs into four main groups: outsourcing, concessions, pooling, and insourcing. Distinguishing and classifying OPs is crucial when endeavouring to address sustainability challenges, as each has a distinct impact on the extent of mercury amalgamation and employment.

This classification also aids in identifying how OPs are evolving over time in ASGM. Empirical evidence suggests that some entrepreneurs and miners are shifting from practices highly dependent on mercury amalgamation, such as outsourcing, towards more independent ones, like pooling mercury-free or insourcing. This gradual socio-technical progression has been possible through education, resources and capital accumulation. This shift is evidenced by the fact that many entrepreneurs reported conducting outsourcing before transitioning to pooling or insourcing. Moreover, most entrepreneurs engaging in pooling affirmed that they are willing to engage with pooling mercury-free if certain conditions are met, such as greater access to capital. These challenges preclude many miners from taking part in this transition. Consequently, pooling mercury-free and insourcing demonstrate the possibility of this niche evolving into mercury-free practices, in contrast to any certainty that they will replace OPs using mercury amalgamation methods. This is further indicated by the data, as pooling mercury-free and insourcing were observed in only four mining and processing areas. Consequently, the pathways of mercury and mercury-free OPs seem to co-exist, as illustrated in Fig. 2. These pathways are likely to persist in the absence of significant shocks or disruptions, such as new mineral discoveries, or external intervention. This co-existence is expected to endure as long as different processing methods respond to different necessities. Thus, introducing cyanide technology does not radically transform ASGM, rather it is an incremental innovation, adding a possibility and a further stage to ore processing. Below, the characteristics of each OP are outlined, along with the critical features for sustainability, as summarised in Table 1.

4.3.1. *Outsourcing*

Outsourcing is the earliest OP to develop since the introduction of cyanide leaching. This emerged as an opportunity for entrepreneurs who realised the potential of using cyanide to reprocess waste tailings left by miners after mercury amalgamation. This method has brought success to many entrepreneurs who could initially collect tailings for free from the miners. One of such entrepreneurs expressed their excitement with this process:

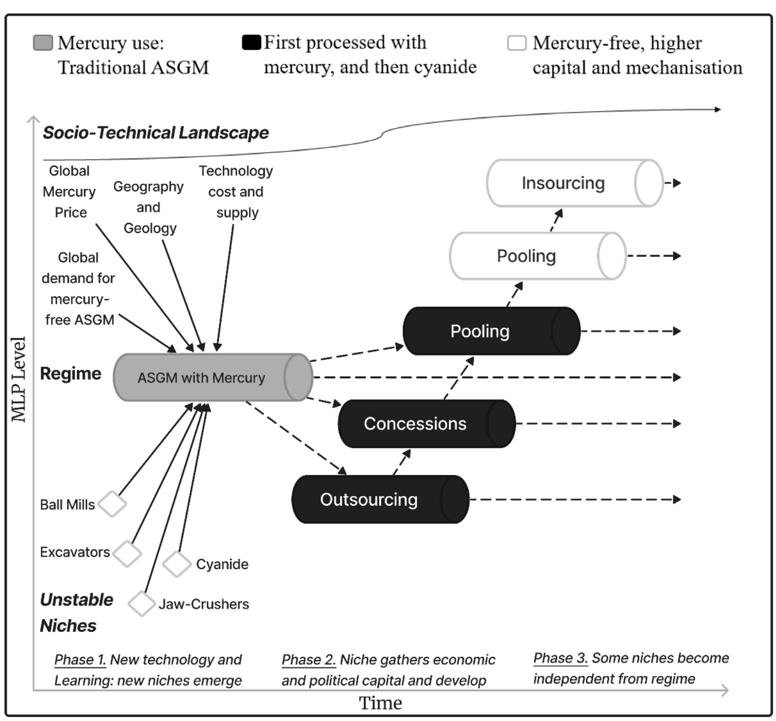

Fig. 2. The incremental evolution of OPs within the MLP framework. As niches emerge and interact with the ASGM regime with mercury, new OPs emerge and co-exist. Outsourcing emerges first, which evolves incrementally into the other OPs: Concessions, Pooling, and Insourcing.

Table 1
Expected sustainability per each organisational practice, compared to pre-cyanide ASGM.

Organisational practice	Frequency in visited areas	Mechanisation levels	Processing strategy	Expected sustainability outcome (compared to pre-cyanide ASGM)
Pre-cyanide ASGM	–	Low	Mercury	–
Outsourcing	8	Medium	Cyanide–Mercury	Lower environmental sustainability
Concessions	7	Medium	Cyanide–Mercury	Lower environmental sustainability
Pooling	15	Medium	Cyanide–Mercury	Lower environmental sustainability
Pooling (Mercury-Free)	3	Medium	Cyanide	Higher environmental sustainability
Insourcing	1	High	Cyanide	Higher environmental, lower socio-economic sustainability

"Those miners get a little gold through mercury amalgamation, but most gold is still there, in the tailings. But with VAT leaching, we could get those waste tailings [for free] *and transform them into gold!"*

As miners began to recognise the value of tailings, a market for this waste emerged. Entrepreneurs now purchase these tailings from miners, transporting them to gold plants for further processing.

Outsourcing does not disrupt the existing ASGM regime using mercury amalgamation, but rather creates demand for its waste. However, apart from not reducing the use of mercury, this process has been identified as one of the practices that needs to be eliminated in this sector. This is because leaching tailings with cyanide after they have been amalgamated through mercury may produce methylmercury, one of the most toxic forms of mercury (UNEP, 2019).

4.3.2. Concessions

Following the success of outsourcing and the resulting increase in the market price for tailings, entrepreneurs sought alternative OPs to enhance profitability. A further reason driving this shift was the uncertainty entrepreneurs felt towards the content of tailings and the consequent fear of being deceived. "Concessions" emerged in response to these challenges. In this OP entrepreneurs allow miners to excavate and extract the gold through mercury for free on their licenses and land. Often, entrepreneurs also provide basic equipment for digging, washing and amalgamation, including mercury. Miners obtain gold as explained in Section 4.3.

This practice allows miners to obtain gold at little or no cost, except for their labour. In exchange for the concession, miners must leave the waste tailings for the entrepreneur. After accumulating a sufficient quantity of tailings, entrepreneurs process them further through VAT leaching. This practice enables entrepreneurs to save on the costs associated with excavating, crushing, and washing ore. Mercury serves as the means to conduct business and determines how revenues are shared between miners and entrepreneurs. Additionally, this OP preserves the individualistic and entrepreneurial nature of ASGM, where trust is limited. Similar to outsourcing and pooling, this practice does not discourage mercury amalgamation and is one of the practices identified as needing to be eliminated by the UNEP (2019).

4.3.3. Pooling

During the fieldwork, pooling emerged as the most common OP. Extraction is carried out using pre-cyanide methods involving mercury amalgamation, as explained in Section 4.3. In this practice, most costs are borne by the entrepreneurs, who either employ miners or compensate them with a share of the gold or the ore. Once a sufficient quantity of tailings is accumulated, they are transported to gold plants for cyanide leaching. However, as entrepreneurs do not own the gold plants in this OP, they must be rented. According to the survey and the interview respondents, tailings are typically transported to gold plants between two to six times per year, depending on the quantity of tailings collected and the availability of capital for cyanide leaching.

Gold obtained through mercury amalgamation is crucial for the day-to-day livelihoods of miners and entrepreneurs, as compared to the sporadic, though much larger, revenue from cyanide leaching. One entrepreneur explained the challenges of mercury amalgamation compared to cyanide leaching:

"You can process this ore with mercury, but much gold will remain in that pile… Sometimes, if I make good money, I will rent a gold plant and process them there, but it costs 5 million per month [~2200 USD]. If I do not have enough money, I will keep the tailings until I get capital, or even sell them if the opportunity arises".

As with outsourcing and concessions, the development of pooling does not reduce mercury use, as the same ore is amalgamated with mercury before being undergoing cyanide leaching. However, pooling mercury-free was also observed in three different mining areas. The small subset of entrepreneurs engaging within this category omit the mercury amalgamation phase and processes the ore directly through cyanidation. The main motivations behind this shift are related to the availability of capital, payment arrangements, and the length and cost of mercury amalgamation.

Firstly, entrepreneurs in this category produced larger amounts of ore, enabling them to carry out cyanide leaching every one or two months, thus decreasing the interval between revenue times. This also requires higher entrepreneurial skills and a stricter planning process. Secondly, workers are paid as waged labour, rather than using gold obtained through mercury amalgamation as a means of payment, as occurs in concessions and pooling. Once these conditions have been achieved, entrepreneurs no longer see the need to employ mercury amalgamation, and consider it a redundant cost. The difference between pooling and pooling mercury-free can be further understood through one entrepreneur's experience, engaging simultaneously with pooling in one area and pooling mercury-free in another. In the words of the entrepreneur:

"In this business [employing pooling] *we don't have enough capital, we just use mercury to get small gold so to get money to keep the mining going and give something to these miners…. But in that business* [employing pooling mercury-free] *I am a shareholder, and these entrepreneurs I work with have capital and they don't want these small amounts of money which we get through mercury amalgamation".*

This quotation not only indicates the importance of capital and payment arrangements but also the opportunities arising from pooling resources as a means of generating capital. It must also be noted that most entrepreneurs engaging in outsourcing, concessions, and pooling affirmed in the interviews that they were willing to engage in pooling mercury-free if they had adequate access to capital. Thus, further research is needed to expand and investigate those factors enabling or preventing the occurrence of pooling mercury-free.

4.3.4. Insourcing

Only the most successful entrepreneurs achieve the scaling-up of production. The larger capital at their disposal allows them to involve an increasing number of miners in their value chains, working on daily wages rather than being compensated with quantities of ore, a share of the gold, or access to technology. Consequently, in this OP mercury amalgamation loses its attribute as a means of sharing revenue.

In insourcing, entrepreneurs accumulate ore and tailings at a much faster rate than in other practices, enabling them to leach the ore with cyanide more often and receive revenues once or twice a month. Moreover, leaching with cyanide directly saves on mercury expenses. In comparison to pooling mercury-free, insourcing exhibits higher levels of mechanisation. For instance, excavators are often used to dig the ore, converting pits into open-cast mines. This makes insourcing the most mechanised practice, increasingly resembling LSM, with fewer miners being employed.

Another important change from the miners' perspective is the transition from being self-employed to employed. Although employment is present in other OPs, in insourcing it is more established. A miner experiencing this transition explains:

> *"For now, I prefer to be employed. If I'm employed, am sure that at the end of the month, I get something. Sometimes those self-employed get more money than me for the same job, but they are not sure that they will get it daily or monthly but for me, am sure".*

This quotation highlights the up-scaling of insourcing as well as the transfer of risk from smaller to larger entrepreneurs. It also portrays how being employed brings greater security to miners rather than being exposed to the risks of self-employment.

Although cyanide technology has become widespread in the sector, there is little evidence to suggest a reduction in mercury use and a clear path to more sustainable ASGM. Overall, of the outlined OPs, only mercury-free pooling and insourcing are free of mercury use, making them the only practices that are more environmentally sustainable than pre-cyanide ASGM (Table 1). In terms of employment prospects, no significant changes are expected in outsourcing, concessions, and pooling, as they do not directly involve further mechanisation. In insourcing, although higher mechanisation rates can lead to reduced work-related accidents, it is associated with lower labour demand and decreasing employment prospects. As a result, insourcing has been classified as having lower socio-economic sustainability than pre-cyanide ASGM. Therefore, the only OP which does not affect the socio-economic sustainability and has a higher environmental sustainability is mercury-free pooling.

4.4. The agency in cyanidation

The existence of diverse OPs stemming from similar technologies underscores the significance of agency within ASGM. Agency, in the form of decision making and implementation, plays a key role in determining how OPs are designed. In this process, a noticeable disparity exists in the distribution of agency between entrepreneurs and miners. The survey data indicates that while entrepreneurs can assert their involvement in decision-making processes and the shaping of OPs the miners face constraints in influencing these practices. All respondents in the lower echelons of production reported that they had never owned either machinery or tailings and had never participated in the cyanidation process. These findings were corroborated by the interview data.

This inequality in agency also manifests in the differing priorities between these two groups. Entrepreneurs are primarily concerned with acquiring advanced technology to enhance their operations. In contrast, miners are preoccupied with day-to-day struggles aimed at securing a livelihood. As one miner lamented:

> *"During the rainy season, we work on the farm… but I need to provide for my family during the dry season as well. So, I have no choice but to find work, and crushing these stones is the only thing I can find, year after year. […] You never know if you'll be paid at the end of the day, or if a stone will injure your eye… but there is no alternative for feeding my children in this season".*

This inherent inequality in agency has solidified within the configuration of the new OPs, which are often established unilaterally by entrepreneurs. Consequently, these OPs function as power structures that not only consolidate but also perpetuate existing inequalities. As a result, some entrepreneurs wield greater agency when transitioning from less sustainable to more sustainable OPs. However, it is important to note that their larger agency is mostly devoted to increasing the business' profitability rather than providing employment or safeguarding the environment.

5. Conclusion: cyanidation - a transition towards sustainability?

Reducing mercury use has been on national and international agendas for many decades (UNEP, 2019). However, although the pursuit has led to a plethora of top-down alternatives most have failed to yield significant results. In contrast, cyanide leaching has emerged and proliferated largely as bottom-up innovation in ASGM and has since gained increasing support from the State. Although the literature on cyanide leaching in ASGM is growing, little attention has been given to how it is being integrated within the existing ASGM production chains through the use of mercury amalgamation. This article has investigated this gap, by addressing the impact of cyanide's introduction on mercury amalgamation and thereby the sustainability processes within ASGM in Tanzania. The examination revolves around the question of whether cyanide is being embraced as an alternative to mercury amalgamation. To analyse the empirical data's complexity, this research leveraged the Multi-Level Perspective (MLP) and Socio-Technical (ST) frameworks. Although public intervention and external factors are influencing this transition, this article focuses on niche development and niche-regime interactions. In the context of ASGM, informal niche-regime interactions have facilitated the expansion of cyanide-based niches, illustrating that compatibility with existing regimes can prove more valuable for niches than radical innovations.

Niche-regime interactions serve as a fundamental lens through which to scrutinise the integration of cyanide within mercury amalgamation in gold mining value chains. This article has adopted these frameworks to identify the continuously evolving OPs, which are crucial for determining the industry's sustainability. Pre-cyanide OPs were structured around ore excavation, crushing, washing, and subsequent mercury amalgamation. Acknowledging the inherent inefficiencies of this process, a significant amount of gold remains locked in waste tailings. Consequently, processing these tailings further with cyanide leaching has emerged as a lucrative economic opportunity for entrepreneurs. Despite the environmental risks associated with this method, it demonstrates the compatibility of these two technologies, rather than their mutual exclusivity.

This compatibility has empowered entrepreneurs and miners to continually reconfigure production and OPs in search of optimal alternatives, which can be seen as the ongoing interaction process between the niche and the regime. Consequently, OP configurations have been transformed, and now exhibit notable distinctions. These differences encompass employment structures and the use of technology, including both mercury and cyanide. This research has classified OPs in ASGM in Tanzania into four categories: outsourcing, concessions, pooling, and insourcing. In addition to serving as an illustration of their purpose, the categorisation of OPs has also elucidated the evolutionary trajectory of OPs over time and their impact on socio-economic and environmental sustainability (Fig. 2). From this evolutionary vantage point, it becomes evident that ASGM is progressing towards mechanisation, however, it is less clear whether this means increased sustainability.

In outsourcing and concessions, mercury amalgamation serves as a means to generate income for the most economically disadvantaged miners. Entrepreneurs gather or purchase their waste tailings and extract further gold through cyanide leaching. Alternatively, entrepreneurs enable the poorest miners to extract gold through mercury amalgamation to reduce production costs. In pooling, entrepreneurs decide whether to employ mercury amalgamation before cyanide leaching. In insourcing, mercury amalgamation is omitted, as the higher levels of mechanisation and capital make mercury amalgamation unnecessary. While this approach may lead to improved working conditions and safety measures, concerns remain that it will upscale the sector into something resembling LSM, which is characterised by lower employment rates and benefits. Notably, pooling mercury-free stands out as the only OP where mercury amalgamation is omitted while maintaining similar employment opportunities. Although most of the entrepreneurs interviewed affirmed that they were willing to change to pooling mercury-free, only a small number have succeeded in doing so. Factors such as poor access to capital hinder the widespread adoption of this mercury-free approach. This underscores that there is potential for transitioning towards mercury-free ASGM, although is unlikely to occur universally without significant external support.

The creation and arrangement of OPs is predominantly steered by the entrepreneurs, who, owing to their greater resources, wield greater agency in enacting decisions and formulating OPs. They are driven by aspirations to increase mechanisation for profitability, while miners are driven by the need to make a living. This emphasises the fact that the proliferation of cyanide and the resultant shift in socio-technical transitions are not primarily motivated by sustainability as understood in Western epistemologies. Rather, they are shaped by narratives of economic opportunities and the exigencies of daily life, which support the entrepreneurs' business feasibility and long-term profitability and the miners' immediate concerns, rather than long-term effects on their health and the environment. Although the concept of sustainability may have little meaning for entrepreneurs, their efforts in investing in mechanisation provide the means through which they visualise improving not only their own but also their children's livelihoods.

Based on these findings, this article recommends policy measures to support the emergence of mercury-free value chains, such as pooling mercury-free, while discouraging pathways where cyanide is applied on tailings amalgamated with mercury. This must be accomplished while considering the potential impacts related to employment changes due to higher mechanisation levels. One approach could involve providing more affordable and inclusive access to technology, including cyanide, to incentivise miners and entrepreneurs to opt for this technology over mercury amalgamation. Additionally, stimulating the establishment of a transparent market for mercury-free ore could result in a more sustainable outcome. This would enable miners to sell ore to entrepreneurs for higher prices rather than mercury-amalgamated tailings. However, beyond technical challenges, it must be acknowledged that most informants expressed low trust in miners they did not know personally, potentially posing an obstacle to this strategy. Nevertheless, these efforts must be accompanied by substantial efforts to enhance the safety of cyanide leaching.

Given the ongoing transformations, there is ample room for further research. It is imperative to delve deeper into the motivations behind entrepreneurs' decisions to establish OPs, particularly those influencing the application or omission of mercury, especially in the OP of pooling. Moreover, there is a need to address how external factors and State interventions are transforming the scale and inclusivity of production. Both these issues are critical to an understanding of how they are supporting or hindering a shift towards pooling mercury-free. Future research should also explore how mining knowledge is acquired, applied, and transferred among entrepreneurs and miners. These approaches could prove crucial in identifying the persistence of mercury amalgamation even in cases where alternatives are available. Overall, these avenues of inquiry represent valuable endeavours in further supporting ASGM's course toward more sustainable trajectories, while preserving the sector's critical contribution to local development.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used Open AI's ChatGPT to improve the text's readability and language. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Funding

This work was supported by the Finland-Africa Platform for Innovation (FAPI) global network. The funding source was not involved in the research process.

CRediT authorship contribution statement

Oliver Daniel Tomassi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

None.

Acknowledgements

I am particularly grateful to my informants, who dedicated their time to participate in this research. I would like to extend my thanks to my research assistants and translators, Fatma Andersson, Charles Shimba and Joyce Nkaina, for their contribution during the data collection process. I would like to express my appreciation to Professor Jussi Jauhiainen and Dr. Abel Kinyondo for their support in the research design, data collection and writing stages. I would like to extent my thanks to Roosa Wingström, Mia Jaatsi and two anonymous reviewers for their valuable comments to earlier versions of this manuscript.

References

Aly, A., Moner-Girona, M., Szabó, S., Pedersen, A.B., Jensen, S.S., 2019. Barriers to large-scale solar power in Tanzania. Energy Sustain. Develop. 48, 43–58. https://doi.org/10.1016/j.esd.2018.10.009.

Andersen, A.D., Wicken, O., 2021. Making sense of how the natural environment shapes innovation, industry dynamics, and sustainability challenges. Innov. Develop. 11 (1), 91–117. https://doi.org/10.1080/2157930X.2020.1770975.

Appel, P.W., Na-Oy, L., 2012. The borax method of gold extraction for small-scale miners. J. Health Pollut. 2 (3), 5–10. https://doi.org/10.5696/2156-9614-2.3.5.

Aryal, J.P., Rahut, D.B., Thapa, G., Simtowe, F., 2021. Mechanisation of small-scale farms in South Asia: empirical evidence derived from farm households survey. Technol. Soc. 65, 101591 https://doi.org/10.1016/j.techsoc.2021.101591.

Bocse, A.M., 2021. Hybrid transnational advocacy networks in environmental protection: banning the use of cyanide in European gold mining. Int. Environ. Agreem.: Polit. Law Econ. 21 (2), 285–303. https://doi.org/10.1007/s10784-020-09492-6.

Coccia, M., 2017. Sources of technological innovation: radical and incremental innovation problem-driven to support competitive advantage of firms. Technol. Anal. Strat. Manage. 29 (9), 1048–1061. https://doi.org/10.1080/09537325.2016.1268682.

Conteh, F.M., Maconachie, R., 2021. Artisanal mining, mechanization and human (in) security in Sierra Leone. Extr. Ind. Soc. 8 (4), 100983 https://doi.org/10.1016/j.exis.2021.100983.

Davies, G.R., 2014. A toxic free future: Is there a role for alternatives to mercury in small-scale gold mining? Futures 62, 113–119. 10.1016/j.futures.2013.11.004.

Drace, K., Kiefer, A.M., Veiga, M.M., 2016. Cyanidation of mercury-contaminated tailings: potential health effects and environmental justice. Curr. Environ. Health Re. 3, 443–449. https://doi.org/10.1007/s40572-016-0113-0.

Fisher, E., de Theije, M., Araujo, C.H.X., Calvimontes, J., Twongyirwe, R, 2023. The lifeways of small-scale gold miners: addressing sustainability transformations. Glob. Environ. Change 82, 102724. https://doi.org/10.1016/j.gloenvcha.2023.102724.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Policy 36 (3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003.

Geenen, S., Nkuba, B., Radley, B., 2022. Technologies and transformations. Traces from a collective research project. Extr. Ind. Soc. 12, 101184 https://doi.org/10.1016/j.exis.2022.101184.

Giurco, D., Matsubae, K., & Northey, S. (2022). Technology, minerals and sustainable development An overview. *Routledge Handbook of the Extractive Industries and Sustainable Development*, 209–215. 10.4324/9781003001317.

Grillitsch, M., Sotarauta, M., 2022. Trinity of change agency, regional development paths and opportunity spaces. Prog. Hum. Geogr. 44, 704–723. https://doi.org/10.1177/0309132519853870.

Hiji, M.F., Maganga, S.P., 2015. Application of response surface methodology for optimization of vat leaching parameters in small scale mines: case study of Tanzania. Am. J. Eng. Technol. Soc.

Hilson, G., 2009. Small-scale mining, poverty and economic development in sub-Saharan Africa: an overview. Resour. Policy 34 (1), 1–5. https://doi.org/10.1016/j.resourpol.2008.12.001.

Hilson, G., 2020. 'Formalization bubbles': a blueprint for sustainable artisanal and small-scale mining (ASM) in sub-Saharan Africa. Extr. Ind. Soc. 7 (4), 1624–1638. https://doi.org/10.1016/j.exis.2020.11.001.

Ingram, J., Maye, D., Kirwan, J., Curry, N., Kubinakova, K., 2015. Interactions between Niche and regime: an analysis of learning and innovation networks for sustainable agriculture across Europe. J. Agric. Educ. Extens. 21 (1), 55–71. https://doi.org/10.1080/1389224X.2014.991114.
Jauhiainen, J.S., Hooli, L., 2019. Innovation For Development in Africa. Routledge.
Jønsson, J.B., Charles, E., Kalvig, P., 2013. Toxic mercury versus appropriate technology: artisanal gold miners' retort aversion. Resour. Policy 38 (1), 60–67. https://doi.org/10.1016/j.resourpol.2012.09.001.
Jønsson, J.B., Fold, N., 2009. Handling uncertainty: policy and organizational practices in Tanzania's small-scale gold mining sector. Nat. Resour. Forum 33 (3), 211–220. https://doi.org/10.1111/j.1477-8947.2009.01226.x.
Kabunga, D., Geenen, S., 2022. Work regimes and technology-driven transformations in DRCongo's artisanal and small-scale gold mines. Extr. Ind. Soc. 12, 101142 https://doi.org/10.1016/j.exis.2022.101142.
Kinyondo, A., Huggins, C., 2021. State-led efforts to reduce environmental impacts of artisanal and small-scale mining in Tanzania: implications for fulfilment of the sustainable development goals. Environ. Sci. Policy 120, 157–164. https://doi.org/10.1016/j.envsci.2021.02.017.
Kinyondo, A., Huggins, C., 2020. 'Centres of excellence'for artisanal and small-scale gold mining in Tanzania: assumptions around artisanal entrepreneurship and formalization. Extr. Ind. Soc. 7 (2), 758–766. https://doi.org/10.1016/j.exis.2020.03.011.
Kinyondo, A., Huggins, C., 2019. Resource nationalism in Tanzania: implications for artisanal and small-scale mining. Extr. Ind. Soc. 6 (1), 181–189. https://doi.org/10.1016/j.exis.2018.08.005.
Kinyondo, A., Villanger, E., 2017. Local content requirements in the petroleum sector in Tanzania: a thorny road from inception to implementation? Extr. Ind. Soc. 4 (2), 371–384. https://doi.org/10.1016/j.exis.2017.01.007.
Kivimaa, P., Laakso, S., Lonkila, A., Kaljonen, M., 2021. Moving beyond disruptive innovation: a review of disruption in sustainability transitions. Environ. Innov. Soc. Transit. 38, 110–126. https://doi.org/10.1016/j.eist.2020.12.001.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.
Langston, J.D., Lubis, M.I., Sayer, J.A., Margules, C., Boedhihartono, A.K., Dirks, P.H., 2015. Comparative development benefits from small and large scale mines in North Sulawesi, Indonesia. Extr. Ind. Soc. 2 (3), 434–444. https://doi.org/10.1016/j.exis.2015.02.007.
Loorbach, D., Frantzeskaki, N., Avelino, F., 2017. Sustainability transitions research: transforming science and practice for societal change. Annu. Rev. Environ. Resour. 42, 599–626. https://doi.org/10.1146/annurev-environ-102014-021340.
Ma, M., Lin, J., Sexton, R.J., 2022. The transition from small to large farms in developing economies: a welfare analysis. Am. J. Agric. Econ. 104 (1), 111–133. https://doi.org/10.1111/ajae.12195.
Manzila, A.N., Moyo, T., Petersen, J., 2022. A study on the applicability of agitated cyanide leaching and thiosulphate leaching for gold extraction in artisanal and small-scale gold mining. Minerals 12 (10), 1291. https://doi.org/10.3390/min12101291.
Martinez, G., Restrepo-Baena, O.J., Veiga, M.M., 2021. The myth of gravity concentration to eliminate mercury use in artisanal gold mining. Extr. Ind. Soc. 8 (1), 477–485. https://doi.org/10.1016/j.exis.2021.01.002.
Merket, H., 2019. Mapping artisanal and small-scale mining in northwest Tanzania. A survey on its nature, scope and impact. Int. Peace Inform. Service vzw.
Nesari, M., Naghizadeh, M., Ghazinoori, S., Manteghi, M., 2022. The evolution of socio-technical transition studies: a scientometric analysis. Technol. Soc. 68, 101834 https://doi.org/10.1016/j.techsoc.2021.101834.
Nkuba, B., Muhanzi, A.G., Zahinda, M.F., 2022. How do technological changes in artisanal and small-scale gold mining affect the environment and communities' health? Extr. Ind. Soc. 12, 101178 https://doi.org/10.1016/j.exis.2022.101178.
Nwaiwu, F., 2021. Digitalisation and sustainable energy transitions in Africa: assessing the impact of policy and regulatory environments on the energy sector in Nigeria and South Africa. Energy Sustain. Soc. 11 (1), 1–16. https://doi.org/10.1186/s13705-021-00325-1.
Pedersen, A.F., Nielsen, J.Ø., Mempel, F., Bager, S.L., Jønsson, J.B., Corbera, E., 2021. The ambiguity of transparency in the artisanal and small-scale mining sector of Tanzania. Extr. Ind. Soc. 8 (4), 101004 https://doi.org/10.1016/j.exis.2021.101004.
Pedersen, A.F., Østergaard Nielsen, J., Friis, C., 2022. Gold, friction and resistance in a globalised land system: the case of Tanzania. J. Land Use Sci. 17 (1), 609–628. https://doi.org/10.1080/1747423X.2022.2063958.
Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Policy 41 (6), 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012.
TENK, (2019). The ethical principles of research with human participants and ethical review in the human sciences in Finland. Finnish National Board on Research Integrity TENK guidelines 2019. https://tenk.fi/sites/default/files/2021-01/Ethical_review_in_human_sciences_2020.pdf (accessed 10 October 2023).
Thambinathan, V., Kinsella, E.A., 2021. Decolonizing methodologies in qualitative research: creating spaces for transformative praxis. Int. J. Qual. Methods 20. https://doi.org/10.1177/16094069211014766.
UNEP, 2019. Minamata Convention on Mercury. Text and Annexes. United Nations Environment Programme. United Nations, New York.
UNEP, 2018. Global Mercury assessment. United Nations Environment Programme (online). https://www.unep.org/resources/publication/global-mercury-assessment-2018. accessed: Apr. 3, 2023.
URT, 2020. United Republic of Tanzania, National Action Plan for Artisanal and Small-Scale Gold Mining 2020 –2025. Vice President's Office. February 2020. https://www.vpo.go.tz/uploads/publications/en-1592551170-ASGM%20National%20Action%20Plan_Tanzania_2020.pdf. accessed 10 October 2023.
Veiga, M.M., Angeloci-Santos, G., Meech, J.A., 2014. Review of barriers to reduce mercury use in artisanal gold mining. Extr. Ind. Soc. 1 (2), 351–361. https://doi.org/10.1016/j.exis.2014.03.004.
Verbrugge, B., Lanzano, C., Libassi, M., 2021. The cyanide revolution: efficiency gains and exclusion in artisanal- and small-scale gold mining. Geoforum 126, 267–276. https://doi.org/10.1016/j.geoforum.2021.07.030.
Verbrugge, B., Geenen, S., 2020. Global Gold Production Touching Ground: Expansion, Informalization, and Technological Innovation. Springer Nature.
World Bank., (2018). Tanzania - region & district boundary. https://datacatalog.worldbank.org/search/dataset/0039598 (accessed 10 October 2023).