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OF TURKU

# Transitioning Towards Sustainable Development in Tanzania

The case of mercury and cyanide in  
artisanal and small-scale gold mining

Oliver D. Tomassi





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The originality of this publication has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

Cover Image: Fatma Andersson

ISBN 978-952-02-0617-8 (PRINT)  
ISBN 978-952-02-0618-5 (PDF)  
ISSN 0082-6979 (Print)  
ISSN 2343-3183 (Online)  
Painosalama, Turku, Finland 2026

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OLIVER TOMASSI: Transitioning towards sustainable development in Tanzania: The case of mercury and cyanide in artisanal and small-scale gold mining

Doctoral Dissertation, 135 pp.

Doctoral Programme in Biology, Geography, and Geology

March 2026

## ABSTRACT

Artisanal and small-scale gold mining (ASGM) is a vital economic sector supporting millions of rural livelihoods across Africa, offering direct employment and broader income opportunities in regions with limited alternatives. Within this sector, mercury amalgamation has been the dominant extraction method despite its severe impacts on human health and the environment. In recent decades however, ASGM has undergone significant technological change, with cyanide leaching emerging as a prominent alternative that provides higher gold recovery rates, especially as ASGM faces declining ore grades that make mercury amalgamation methods less effective.

This dissertation draws on the case of ASGM in Tanzania and situates it within the Multi-Level Perspective and Just Transitions frameworks of the Sustainability Transitions (ST) field. It investigates how technological change interacts with organizational practices, institutional arrangements, and knowledge systems, and how these interactions shape sustainability outcomes and inequalities within the sector. The study integrates qualitative and quantitative data collected during fieldwork in Tanzania between 2022 and 2024, including 119 semi-structured interviews and 116 survey responses.

The findings show that mercury amalgamation remains predominant not only because it is inexpensive, widely accessible, and requires minimal skills, but also because it is deeply embedded in existing relationships, livelihoods, and extraction practices. While cyanide technology provides a mercury-free alternative and up-scaling of extraction, it demands significantly higher costs and specialized knowledge, restricting its uptake to few entrepreneurs, deepening socio-economic inequalities in ASGM. Overall, these findings raise questions about whether a transition from mercury to cyanide can truly be considered a transition toward sustainable development, and call for policies that ensure an inclusive transition for all ASGM stakeholders while protecting the environment and natural ecosystems.

**KEYWORDS:** Technology, knowledge creation processes, inequality, mineral exhaustion, Africa, global South.

TURUN YLIOPISTO

Matemaattis-luonnontieteellinen tiedekunta

Maantieteen ja Geologian laitos

Talousmaantiede

OLIVER TOMASSI: Siirtyminen kohti kestäväää kehitystä Tansaniassa:

Elohopea ja syanidi artesaani ja pienimuotoisessa kultakaivostoiminnassa

Väitöskirja, 135 s.

Biologian, maantieteen ja geologian tohtoriohjelma

Maaliskuu 2026

## TIIVISTELMÄ

Artesaani ja pienimuotoinen kultakaivostoiminta on keskeinen toimiala, joka tukee miljoonia maaseudun elinkeinoja Afrikassa, ja tarjoaa työllistymis- ja ansaintamahdollisuuksia alueilla, joilla vaihtoehdot ovat rajalliset. Kullan rikastaminen elohopea-amalgaamin avulla on hallitseva kaivostekniikka alueella, huolimatta sen haitallisista vaikutuksista ihmisten terveyteen ja ympäristöön. Viime vuosikymmeninä kaivostoiminta on kuitenkin kokenut merkittäviä teknologisia muutoksia syanidiliuotuksen noustessa menetelmävaihtoehdoksi, joka mahdollistaa korkeamman kullan talteenoton, erityisesti tilanteissa, joissa laskevat malmipitoisuudet heikentävät elohopeamenetelmien tehokkuutta.

Tässä väitöskirjassa tarkastellaan artesaani- ja pienimuotoista kultakaivostoimintaa Tansaniassa ja sijoitetaan se kestävyden siirtymien tutkimusalaan, erityisesti monitasoisen tarkastelun viitekehykseen (Multi-Level Perspective) sekä oikeudenmukaisten siirtymien (Just Transitions) keskusteluun. Tutkimuksessa selvitetään miten teknologinen muutos vaikuttaa organisaatioiden käytäntöihin, institutionaalisiin järjestelyihin ja tietojärjestelmiin, ja miten nämä vuorovaikutukset muokkaavat kestävyden ulottuvuuksia ja epätasa-arvoa sektorilla. Tutkimus yhdistää kvalitatiiviset ja kvantitatiiviset aineistot – 119 puolistrukturoitua haastattelua ja 116 kyselyvastausta – jotka kerättiin kenttätöinä Tansaniassa vuosina 2022–2024.

Tulokset osoittavat, että elohopea-amalgaamin käyttö on hallitseva rikastusmenetelmä edullisuutensa, helpon saatavuutensa ja vähäisten pätevyysvaatimusten takia. Lisäksi menetelmä on olennainen osa olemassa olevia sosiaalisia suhteita, elinkeinoja ja kaivosteknisiä käytäntöjä. Vaikka syanidiliuotus tarjoaa elohopeavapaan ja suuremman tuotantomittakaavaan vaihtoehdon, ovat sen kustannukset korkeammat ja käyttö vaatii erityisosaamista, mikä rajoittaa menetelmän käyttöönoton harvoille yrittäjille ja syventää sosioekonomista epätasa-arvoa artesaani ja pienimuotoisessa kultakaivostoiminnassa. Tulokset kyseenalaistavat voidaanko siirtymää elohopeasta syanidiin todella pitää kestävään kehityksen siirtymänä, ja korostavat tarvetta politiikkatoimille, jotka varmistavat siirtymän olevan oikeudenmukainen ja osallistava kaikille sektoriin kuuluville toimijoille samalla suojellen ympäristöä ja luonnon ekosysteemejä.

ASIASANAT: teknologia, tiedonluontiprosessit, epätasa-arvo, malmin ehtyminen, Afrikka, globaali etelä.

## CHUO KIKUU CHA TURKU

Kitivo cha Sayansi

Idara ya Jiografia na Jiolojia

Jiografia ya Uchumi

OLIVER TOMASSI: Kuelekea mpito wa maendeleo endelevu nchini Tanzania:

Kesi ya zebaki na sianidi katika uchimbaji mdogo na wa kati wa dhahabu.

Tasnifu ya Uzamivu, 135 kurasa

Programu ya shahada ya uzamivu wa Biolojia, Jiografia na Jiolojia

Machi 2026

## MUHTASARI

Uchimbaji wa dhahabu wa kienyeji na mdogo (Artisanal and Small-Scale Gold Mining – ASGM) ni sekta muhimu kwa maisha ya kiuchumi inayosaidia mamilioni ya watu vijijini barani Afrika, kupitia ajira za moja kwa moja na fursa pana za vipato katika maeneo yenye mabadala michache ya kiuchumi. Katika sekta hii, matumizi ya muunganiko wa zebaki yamekuwa mbinu kuu ya uchujaji licha ya athari zake kubwa kiafya kwa binadamu na mazingira. Hata hivyo, katika miongo ya hivi karibuni, ASGM imepitia mabadiliko makubwa ya kiteknolojia, ambapo uchujaji kutumia sianidi umeibuka kama mbinu mbadala inayorejesha kiwango cha juu zaidi cha dhahabu, hasa ukizingatia upungufu wa kiwango cha madini kwenye mwamba, kunakofanya mbinu za zebaki kupungua ufanisi.

Tasnifu hii inachunguza hali ya ASGM nchini Tanzania kwa kujikita katika mifumo ya kinadharia ya Mitazamo ya Nyanja Mbalimbali (Multi-Level Perspective) na Mpito Jumuishi (Just Transitions) ndani ya nyanja za Mpito Endelevu. Utafiti unachunguza jinsi mabadiliko ya kiteknolojia yanavyoingiliana na taratibu za kiutendaji za mashirika, mipangilio ya kitaasisi, na mifumo ya maarifa, pamoja na namna mwingiliano huo unavyoathiri matokeo endelevu na ukosefu wa usawa ndani ya sekta. Utafiti unajumuisha takwimu za ubora na kiasi zilizokusanywa wakati wa kazi ya uwandani nchini Tanzania kati ya mwaka 2022 na 2024, zikiwemo mahojiano 119 ya nusu-muundo na majibu ya madodoso 116.

Matokeo yanaonyesha kuwa matumizi ya muunganiko wa zebaki yanaendelea kutawala si tu kwa sababu ni ya gharama nafuu, yanapatikana kwa urahisi, na yanahitaji ujuzi mdogo, bali pia yamejikita katika mahusiano ya kijamii yaliyopo, mifumo ya riziki, na mbinu za uchimbaji. Ingawa teknolojia ya sianidi inatoa mabadala usiotumia zebaki na unaoongeza uzalishaji sana, inahitaji gharama kubwa zaidi na utaalumu maalumu, hali inayozuia upokeaji wake kwa wajasiriamali wachache na kuongeza pengo la kijamii na kiuchumi ndani ya ASGM. Kwa ujumla, matokeo haya yanaibua maswali iwapo mpito kutoka matumizi ya zebaki kwenda sianidi unaweza kuzingatiwa kama mpito kuelekea maendeleo endelevu, na unasisitiza umuhimu wa sera zitakazohakikisha mpito jumuishi kwa wadau wote wa ASGM huku zikilinda mazingira na mifumo asilia ya ikolojia.

MANENO MUHIMU: Teknolojia, michakato ya uundaji maarifa, ukosefu wa usawa, uchakavu wa rasilimali za madini, Afrika, Global South.

# Table of Contents

<b>Abbreviations .....</b>	<b>8</b>
<b>List of Original Publications .....</b>	<b>9</b>
<b>1 Introduction.....</b>	<b>10</b>
1.1 Research objectives.....	12
<b>2 Analytical Framework: Sustainability Transitions in Africa and the Multi-Level Perspective .....</b>	<b>16</b>
2.1 Sustainability and Just Transitions in Africa.....	18
2.2 Niche: emerging innovations and practices (Article I).....	19
2.2.1 Organizational practices and agency.....	20
2.3 The Regime (Article II) .....	22
2.4 The Landscape: knowledge creation processes and the natural environment (Article III) .....	23
2.5 Theoretical contributions of the thesis: interactions between levels and relational approaches.....	25
<b>3 Materials and Methods .....</b>	<b>27</b>
3.1 Quantitative data & methods .....	30
3.1.1 Design .....	30
3.1.2 Data and data collection.....	32
3.1.3 Data analysis .....	32
3.2 Qualitative data & methods .....	33
3.2.1 Interviews: design .....	33
3.2.2 Interviews: data collection and data.....	34
3.2.3 Participant observation and the go-along: design .....	36
3.2.4 Participant observation and the go-along: data collection and data .....	37
3.2.5 Qualitative data analysis .....	37
3.3 Positioning myself and the research.....	38
3.4 Case studies .....	41
3.5 Limitations.....	44
<b>4 Situating ASGM in Tanzania .....</b>	<b>45</b>
4.1 Technology and practices in ASGM .....	45
4.2 Mercury and cyanide: sustainability and regulations.....	49
<b>5 Empirical Analysis and Discussion .....</b>	<b>54</b>

5.1	Mechanizing ASGM.....	54
5.2	Organizational practices (Article I).....	55
5.3	Pushing and resisting mercury-free gold extraction (Article II).....	58
5.3.1	Transforming the regime: promoting mercury-free ASGM through policy.....	58
5.3.2	Barriers to co-existence models and transitions to mercury-free practices.....	60
5.4	The landscape and the natural environment (Article III).....	63
5.4.1	Learning through the senses .....	64
5.4.2	Learning through trial and error .....	65
5.4.3	Acquiring science- and technology-based knowledge .....	65
5.4.4	Social learning, communities of practice, and adaptation .....	66
5.5	Inequalities.....	67
5.5.1	Agency and inequality .....	68
5.5.2	Knowledge inequalities.....	68
5.5.3	Resulting dimensions of inequality.....	69
<b>6</b>	<b>Conclusions .....</b>	<b>71</b>
	<b>Acknowledgements .....</b>	<b>77</b>
	<b>Declaration of generative Ai in the writing process .....</b>	<b>83</b>
	<b>List of References.....</b>	<b>84</b>
	<b>Original Publications.....</b>	<b>95</b>

# Abbreviations

ASGM	Artisanal and small-scale gold mining
ASM	Artisanal and small-scale mining
CIP	Carbon-in-pulp
CSO	Civil society organization
DUI	Learning-by-doing, using, and interacting
FEMATA	Federation of Miners Association of Tanzania
GCLA	Government Chemist Laboratory Authority
GeoST	Geography of Sustainability Transitions
GST	Geological Survey of Tanzania
JT	Just Transitions
MLP	Multi-Level Perspective
NAP	National action plan
NEMC	National Environment Management Council
OP	Organizational practice
PML	Primary Mining License
SDG	Sustainable Development Goal
SMMRP	Sustainable Management of Mineral Resources Project
STAMICO	State Mining Corporation
STI	Science, technology, and innovation
UNEP	United Nations Environment Programme
URT	United Republic of Tanzania

# List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

- I Tomassi, O. D. Transitioning towards sustainability in artisanal and small-scale gold mining: A case study from Tanzania. *The Extractive Industries and Society*, 2024; 17: 101410, 1–10. <https://doi.org/10.1016/j.exis.2024.101410>
- II Tomassi, O. D., & Kinyondo, A. A. Technology, capital, and sustainability: Frontiers in just transitions for African mining. *Resources Policy*, 2024; 98: 105348, 1–12. <https://doi.org/10.1016/j.resourpol.2024.105348>
- III Tomassi, O. D., Kinyondo, A. A., & Jauhiainen, J. S. Adapting to environmental and technological transformations through knowledge creation: Insights from artisanal and small-scale gold mining in Tanzania. *World Development Sustainability*, 2026; 8: 100260, 1–13. <https://doi.org/10.1016/j.wds.2025.100260>

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# 1 Introduction

*Here, transformation has a scent. It is the bitter almond smell of cyanide, lingering in the air around leaching plants, where mountains of tailings rest along their edges. Cyanide has changed the logic of extraction, unleashing new frontiers of possibility by turning waste into gold. Yet, mercury is far from a relic of the past. It is everywhere, holding the ASGM world together while slowly poisoning bodies, landscapes, and daily life.*

Drawn from fieldnotes,  
*Mwabomba, Tanzania, August 2022.*

This moment from the field exemplifies a broader paradox at the heart of artisanal and small-scale mining (ASM), which serves as the central case study for this thesis. ASM is the low-capital, labor-intensive economic activities that rely on low-tech methods to extract minerals. Within ASM, artisanal and small-scale gold mining (ASGM) is the largest sub-sector and it plays a vital role in supporting livelihoods in rural areas where formal employment and alternative income sources are limited. In Tanzania alone, the sector employs over one million people and indirectly sustains the livelihoods of an estimated seven million others (URT, 2020a).

Mercury (Hg), a highly toxic substance and the only metal liquid at room temperature, remains central to gold extraction in ASGM across Tanzania and many other countries in the global South. Its affordability and ease of use have rendered it a mainstay, despite its well-documented environmental and health risks and low gold recovery rates (Aldous et al., 2024; Davies, 2014; Esdaile & Chalker, 2018; Manzila et al., 2022; Martinez et al., 2021; Stærfeldt & Stacey, 2025; van der Merwe et al., 2025). When released into the environment, mercury can bind with biological matter to form methylmercury—an odorless and invisible compound with severe toxicological effects. In response to these concerns, the Minamata Convention was introduced in 2013 as a global treaty aimed at protecting human health and the environment from mercury’s adverse impacts (UNEP, 2018). A key focus of the Convention is to reduce, and, where possible, eliminate, mercury use in ASGM, particularly by targeting the most harmful practices associated with its application (UNEP, 2018, 2019, 2023).

Several alternatives and policies have been promoted in an effort to replace or reduce mercury use and pollution in ASGM, including the use of retorts, magnets, and gravity concentration integrated with borax smelting, though with limited success in expanding adoption (Appel and Na-Oy, 2012; Davies, 2014; Jönsson et al., 2013). In contrast, cyanide leaching has proliferated rapidly in the last decade, transforming ASGM by increasing extraction efficiency, enabling the upscaling of production through investment, and facilitating the processing of lower-grade ores, crucial as high-grade, easily accessible surface deposits become exhausted (Davies, 2014; McKay, 2025; Verbrugge et al., 2021).

Cyanide also poses environmental and health risks, but it is widely regarded as the less harmful alternative. As such, the transition from mercury to cyanide is often promoted as a more sustainable pathway (Drace et al., 2016; Veiga et al., 2014). However, rather than replacing mercury, cyanide is most often applied to ore that has already undergone mercury amalgamation, which is explained by mercury's poor recovery rates (Drace et al., 2016; Kouadio et al., 2025; Martinez et al., 2021; Veiga et al., 2014). The interaction between residual mercury and cyanide promotes the formation of methylmercury, thereby compounding environmental and health hazards beyond those associated with the use of either substance in isolation (UNEP, 2018; 2019; 2023).

Against this backdrop, this dissertation explores how technological change, and particularly the adoption of cyanide leaching, interacts with organizational practices, institutional arrangements, and knowledge systems, and how these interactions shape sustainability outcomes and patterns of inequality within ASGM.

I explore this by placing the ASGM mercury-cyanide case within the field of sustainability transitions (ST). The ST conceptual approach provides analytical tools to explore whether and how technological and social dynamics contribute to more environmentally and socially sustainable outcomes (Avelino et al., 2016; Binz et al., 2020, 2025; Dzhengiz et al., 2023; Geels, 2019; Köhler et al., 2019; Loorbach et al., 2017). Within this field, the Multi-Level Perspective (MLP) has gained prominence as a key framework examining the role of technological change in sustainability transitions, emphasizing how such shifts occur across levels and in conjunction with evolving societal systems (Loorbach et al., 2017). The MLP distinguishes between three levels of analysis: the niche (protected spaces where emerging innovations and experimental practices develop), the regime (established technologies, institutions, and actors), and the landscape (broader contextual forces such as global markets, political dynamics, and the environment) (Geels, 2002, 2019; Geels et al., 2017; Geels & Schot, 2007; Kiviaho & Hyryläinen, 2025; Quinteros-Condoretty et al., 2020; Runhaar et al., 2025; Smith & Raven, 2012).

Within the thesis, I have adopted the MLP as a key analytical framework. Empirically, cyanide represents a niche innovation—an emerging technology and

experimental practice developing within protected niches. Mercury amalgamation, as the dominant practice and technology, is conceptualized as the regime. Finally, I adopt the expanded interpretation of the landscape concept, which incorporates the natural environment, particularly the material characteristics of the terrain and the ore being mined.

While all articles engage with all levels of the MLP framework, each one has a specific focus: Article I mostly focuses on niche innovations, Article II changing the regime, and Article III the role of the landscape in transitions. Although each article mainly focuses on a distinct MLP level, this division is analytical, as cross-level interactions are addressed throughout and form a central feature of the thesis. This thesis integrates the MLP with the Just Transitions framework, recognizing that technological change often generates new inequalities and redistributes benefits and harms, thereby raising questions of justice in transition processes.

## 1.1 Research objectives

The overarching aim of the thesis is to investigate sustainability transitions in ASGM, with a particular focus on the socio-technical and environmental factors that sustain the use of mercury despite the availability of alternative technologies like cyanide. By generating novel empirical findings and theoretical insights, the research not only deepens our understanding of ASGM but also contributes to the development of a grounded, justice-oriented, and context-sensitive perspective on sustainability transitions in extractive economies of the global South (Avelino et al., 2016; Ghosh et al., 2021; Ghosh & Mguni, 2026; Oates, 2021). Building on this approach, the thesis pursues three core objectives.

The first objective is to analyze the empirical dynamics of sustainability transitions in ASGM, with a focus on the continued use of mercury despite the availability of alternatives such as cyanide leaching. Although numerous studies have documented the harmful effects of mercury and the technical advantages of cyanide, limited research has examined why mercury continues to be used in contexts where cyanide is widely available (Drace et al., 2016; Esdaile & Chalker, 2018; Malone et al., 2023; Manzila et al., 2022; Verbrugge et al., 2021). This reveals a critical gap in the ASGM literature: the socio-technical persistence of mercury use remains poorly understood. Specifically, little is known about how social, organizational, economic, and knowledge systems interact with technologies like mercury and cyanide, and how they sustain their use. This involves identifying socio-technical and economic barriers to technological change and examining their integration into current practices. Moreover, there is a need to examine how these structures shape sustainability outcomes, including their implications for inequality. I address these questions throughout the three articles in the thesis.

Article I assesses how cyanide leaching interacts with existing organizational and socio-economic structures, evaluating its compatibility with mercury-based methods. The guiding questions are: *How is cyanide being integrated within ASGM extraction chains using mercury? How does the integration of cyanide in ASGM extraction practices affect sustainability?*

Article II extends this analysis by exploring regime-level dynamics such as the actors and institutions who support or resist cyanide adoption, including public and private stakeholders, civil society organizations, and policymakers. It examines the strategies employed by these actors and groups to reduce mercury use and how and why actors resist these changes. The guiding questions are: *What are the primary strategies identified and promoted to transition away from mercury use in ASGM in Tanzania?* and *Why does mercury use persist despite the implementation of strategies promoted to reduce its prevalence?*

Article III examines the knowledge creation and learning processes miners engage in to sustain extraction activities. In contexts marked by technological change and shifting environmental conditions—such as declining ore grades—adaptive learning becomes essential. The article explores how miners interact with the natural environment, including gold deposits and the geomorphological features that shape mining possibilities, and conceptualizes these interactions as the knowledge-creation processes through which miners adapt extraction practices. The guiding question is: *What knowledge creation processes do ASGM miners in Tanzania engage in to extract gold?*

Together, these articles provide a foundation for assessing whether cyanide can facilitate a socio-economically and environmentally sustainable transition away from mercury, and how its adoption may reshape social structures. The overarching question is: *What is the impact of socio-technical transformations on sustainability transitions in ASGM?*

The second objective is to examine the socio-economic and environmental inequalities embedded in the mercury-cyanide transition pathways. By identifying factors that enable or constrain technological uptake, the thesis highlights the processes of inclusion and exclusion, particularly in relation to access to knowledge, capital, and technology. It also considers which actors exercise agency in transforming the sector. All three articles engage with questions of inequality and justice, analyzing their relationship to existing hierarchies and power structures. This analysis informs the design of policy interventions aimed at fostering a more inclusive and sustainable ASGM sector in Tanzania and beyond, while minimizing the risk of reinforcing existing inequalities. A cross-cutting question is: *How does the adoption of cyanide leaching reshape socio-economic and environmental inequalities within the ASGM sector?*

The third objective is to address a key limitation in the ST literature: its limited application to global South contexts, where transitions are often conceptualized through technocratic lenses. There is an urgent need for more relational approaches that account for informality, local knowledge systems, and community priorities (Avelino et al., 2016; Balanzó-Guzmán & Ramos-Mejía, 2023; Feola, 2020; Ghosh et al., 2021; Ghosh & Mguni, 2026; Morales & Ramos-Mejía, 2023; Oates, 2021; Ramos-Mejía et al., 2018). This need is particularly acute in sectors such as mining, agriculture, and forestry, which are central to rural economies across the global South and account for a significant share of global natural resource extraction. In Africa, natural resource industries are among the largest employers and contribute substantially to national GDP.

A second area for improvement within ST research is the underexamined role of the natural environment within transitions. While this gap is increasingly being addressed by the geography of sustainability transitions (GeoST), a subfield that integrates spatial and environmental dimensions, including human–nature interactions and natural resource endowments, further work is needed to systematically incorporate the natural environment into analyses of sustainability transitions.

By integrating the three articles and drawing connections between them, this thesis addresses these broader gaps in ST literature (**Table 1**). These objectives are explored through the following research question: *How does the ASGM case study in Tanzania contribute to sustainability transitions research in the global South?*

This thesis is structured as follows. The next chapter outlines the key concepts and analytical framework, introducing the ST frameworks employed in this research: MLP and Just Transitions. It also presents the core concepts that inform these frameworks and support the empirical analysis. Chapter 3 details the data and methodology, including reflections on the selected case studies, ethical considerations, and researcher positionality. Chapter 4 provides background to the case studies, offering a brief overview of current practices, regulatory frameworks, and technologies in ASGM. Chapter 5 presents and discusses the empirical findings. Chapter 6 concludes by addressing the research questions and considering the implications of the findings for future research and policy.

**Table 1.** The three articles' main research questions, concepts, and findings.

<b>Article</b>	<b>1) Transitioning towards sustainability in artisanal and small-scale gold mining: A case study from Tanzania.</b>	<b>2) Technology, capital, and sustainability: Frontiers in just transitions for African mining.</b>	<b>3) Adapting to environmental and technological transformations through knowledge creation: insights from artisanal and small-scale gold mining in Tanzania.</b>
<b>Overall research questions</b>	<p>What is the impact of socio-technical transformations on sustainability transitions in ASGM?</p> <p>How does the ASGM case study in Tanzania contribute to sustainability transitions research in the global South?</p> <p>How does the adoption of cyanide leaching reshape socio-economic and environmental inequalities within the ASGM sector?</p>		
<b>Research Questions</b>	How is cyanide being integrated within ASGM extraction chains using mercury? How does the integration of cyanide in ASGM extraction practices affect sustainability?	What are the primary strategies identified and promoted to transition away from mercury use in ASGM in Tanzania? Why does mercury use persist despite the implementation of strategies promoted to reduce its prevalence?	What knowledge creation processes do ASGM miners in Tanzania engage in to extract gold? How do changes in the natural environment influence sustainability transitions in ASGM?
<b>MLP focus level</b>	Niche	Regime	Landscape
<b>Key concepts</b>	Niche-regime interactions Mechanization Agency in Transitions Organizational practices	Regime resistance, Just Transitions Co-existence	Knowledge creation processes Natural environment
<b>Data</b>	Survey, semi-structured interviews, participant observation	Survey, semi-structured interviews, participant observation	Survey, semi-structured interviews, participant observation
<b>Analysis</b>	Thematic analysis, descriptive statistics	Thematic analysis, statistical tests	Thematic analysis, statistical tests
<b>Key Findings</b>	Cyanide is integrated within gold extraction with mercury, exacerbating environmental damage. Different organizational practices can lead to significantly different mercury consumption and sustainability overall. These are interrelated with miners' agency and inequality.	Cyanide leaching is supported by the Tanzanian State as the most valid alternative to mercury. Yet, mercury persists due to its embeddedness in socio-economic practices, while cyanide adoption widens existing inequalities.	Knowledge creation processes are critical for miners to adapt to less unsustainable technologies, especially in response to environmental and technological change. However, unequal access to knowledge deepens socio-economic inequalities and hinders a full transition towards sustainable development.

## 2 Analytical Framework: Sustainability Transitions in Africa and the Multi-Level Perspective

This doctoral dissertation engages with concepts drawn from the fields of Geography and Sustainability Transitions (ST). The purpose of this chapter is to outline and critically examine the key concepts informing this research by presenting the state of the art in current literature, identifying existing research gaps, and highlighting the theoretical contributions made by the dissertation.

Concepts and frameworks from the ST field are instrumental in unpacking and addressing the most pressing sustainable development challenges, including transitioning away from mercury use in ASGM. Addressing such complexity requires an interdisciplinary approach, as insights from various disciplines can significantly contribute to understanding empirical case studies. This is particularly relevant in the context of resource extraction, where socio-economic, environmental, and technical dimensions are deeply intertwined (Allouche, 2025; Aubynn, 2009; Bryceson & Jønsson, 2010; Saka, 2025; Verbrugge & Geenen, 2020).

ST is crucial in studying and explaining these challenges, as it has gained prominence as an interdisciplinary field exploring how the interplay of elements across different levels can drive changes in socio-technical systems (Avelino et al., 2016; Geels et al., 2017; Loorbach et al., 2017). A ‘socio-technical system’, a key concept within ST research, comprises the interconnected roles of policies, practices, technologies, infrastructures, markets, and individuals (Geels, 2002; Geels & Schot, 2007; Kiviaho & Hyyryläinen, 2025). Increasingly, ST research has focused on how innovation and technological change contribute to shifts within and between these socio-technical and ecological systems (Köhler et al., 2019).

Within ST, various analytical frameworks have been developed, among which the multi-level perspective (MLP) is one of the most widely adopted. The MLP examines the role of technological change in sustainability transitions, emphasizing how such shifts occur in conjunction with evolving societal structures and the actions of different individuals or groups over time (Loorbach et al., 2017).

A key feature of the MLP, is its conceptualization of socio-technical systems across three analytical levels: niches, regimes, and landscapes. Niches are defined as

the spaces where experimental and localized innovations, technologies, and practices emerge. Regimes refer to the dominant societal configurations, encompassing established infrastructures, institutional arrangements, practices, and scientific paradigms. The landscape level includes broader, exogenous factors such as market dynamics, environmental conditions, and political pressures.

According to this framework, socio-technical transitions occur when niche-innovations mature and challenge the dominant regime, potentially leading to a reconfiguration of the system and the emergence of a new regime. These processes are also shaped by pressures from the landscape level, which can enable or constrain change (Geels & Schot, 2007; Hansen & Coenen, 2015; Loorbach et al., 2017). These processes are rarely uniform, on the contrary, progress often occurs non-linearly. Moreover, transitions are complex and contested, involving multiple actors who promote or resist change and who direct transitions towards different objectives and directions (Ingram et al., 2015; Loorbach et al., 2017).

One of the key strengths of the MLP and ST more broadly, is their ability to provide a generalized understanding of transitions by abstracting the main elements and processes within sustainability transformations. They offer a broad, interdisciplinary perspective on the multiple levels, elements, and interactions that drive change—an approach essential for identifying critical questions and challenges within transition pathways. While such frameworks account for many of these dynamics, they have been criticized for being overly technocratic and for insufficiently addressing relational dimensions and agency, which are nevertheless crucial in shaping transitions (Ghosh & Mguni, 2026). Further critiques highlight the predominantly Western focus of this body of research (Ghosh & Mguni, 2026; Kvangraven, 2025; Morales & Ramos-Mejía, 2023; Ramos-Mejía et al., 2018). Consequently, there is a continuing need to refine the MLP and ST approaches by engaging with diverse cases across contexts, timeframes, and perspectives, and by examining their applicability beyond Western settings and epistemologies.

This chapter is structured as follows. First, I review the literature on ST in Africa and introduce concepts and frameworks relating to justice in ST. Second, I examine key themes and concepts from the dissertation articles, organizing them according to the niche-regime-landscape structure. Within each level, I incorporate concepts that have been contextualized to the African setting. Finally, I explore the importance of understanding the interactions between these levels.

Each article concentrates on a different level of analysis: Article I focuses on the niche, Article II on regime change, and Article III on landscape dynamics. However, due to the interconnected nature of these levels, analysis of any one level also requires consideration of the others. For instance, Article I explores niche-innovations development in relation to regime structures, and Article III explores how individuals, communities, and niche-innovations interact with the landscape.

Consequently, the concepts and contributions associated with each level are informed by findings from all three articles. This integrated approach facilitates a more nuanced analysis of the challenges hindering transitions as well as who holds agency within them.

## 2.1 Sustainability and Just Transitions in Africa

The ST approach and associated concepts and frameworks have predominantly been adopted by institutions and scholars in the global North. Consequently, the frameworks within these fields are largely shaped by regional priorities, with a strong emphasis on environmental sustainability, and particularly the reduction of carbon emissions to combat climate change (Köhler et al., 2019; Ramos-Mejía et al., 2018). However, over the past decade, the sustainability transitions literature has increasingly engaged with developing countries (Ghosh & Mguni, 2026; Morales & Ramos-Mejía, 2023; Ramos-Mejía et al., 2018). This engagement necessitates an acknowledgement of the diverse concepts, perspectives, and priorities emerging from different regional contexts (Jenkins et al., 2018; Johnstone & Newell, 2018; Ramos-Mejía et al., 2018; Sovacool et al., 2021).

Transitions in these contexts are often embedded in high levels of social complexity, where practices intersect with informality, poverty, colonial legacies, resource and rent capture, and indigenous knowledge systems (Geenen & Bikubanya, 2024; Ghosh & Mguni, 2026; Lund, 2006; Otlhogile & Shirley, 2023; Ramos-Mejía et al., 2018; Sovacool et al., 2021; Swilling et al., 2016). This doctoral thesis engages with many of these themes and concepts within ST. Specifically, it explores practices and agency (Article I), the role of the state, civil society organizations, and poverty (Article II), as well as local knowledge (Article III).

A further framework within ST guiding this thesis is that of Just Transitions (JT), which places greater emphasis on justice and inequality (Sovacool et al., 2017). Justice and inequality are thus intrinsic to transitions, particularly in Africa, where a stronger focus on poverty and structural disparities is essential (Ramos-Mejía et al., 2018; Otlhogile and Shirley, 2023). A Just Transition refers to the shift toward environmentally sustainable outcomes in which the benefits and burdens are shared equitably across society (Ramos-Mejía et al., 2018; Swilling et al., 2016; Sovacool et al., 2017).

Within the JT framework, justice is conceptualized through multiple dimensions, each offering a lens to unpack specific aspects of inequality. These include distributional, procedural, recognitional, and cosmopolitan justice (Lee and Byrne, 2019; McCauley et al., 2019; Sovacool et al., 2017; Sovacool et al., 2021). Distributional justice concerns the allocation of resources, such as capital, technology, and power, within societies (Lee & Byrne, 2019; McCauley et al., 2019;

Sovacool et al., 2021). Procedural justice refers to the processes through which rules are established and disputes resolved (McCauley et al., 2019; Sovacool et al., 2021). For instance, mining regulations may favor the formalization of LSM over ASM, or vice versa (Huggins & Kinyondo, 2019; Johnstone & Newell, 2018; Kinyondo & Villanger, 2017; Rodríguez-Novoa & Holley, 2023; Sundet, 1997). Recognition justice addresses how transitions impact the most vulnerable individuals or groups, such as rural communities disproportionately affected by fuel price increases (Lee & Byrne, 2019; Leino, 2024; McCauley et al., 2019; Sovacool et al., 2017, 2021). Lastly, cosmopolitan justice links local and global inequalities; for example, while miners may bear the health and environmental consequences of local pollution, economic benefits often accrue elsewhere (Lee and Byrne, 2019; McCauley et al., 2019; Sovacool et al., 2017, 2021).

Currently, most literature adopting the Just Transitions framework relates to just energy transitions. The latter focuses not only on decreasing carbon emissions in the energy sector, but also on ensuring that this process addresses the four dimensions of justice (McCauley et al., 2019; Sovacool et al., 2017, 2021). Nevertheless, this framework is also suitable for other economic sectors, including natural resource extraction. For instance, distributional inequalities can include access to land, technology, and mining concessions, and procedural inequalities can be created by decisions by governments to grant mining rights to large- or small-scale mining companies (Huggins & Kinyondo, 2019; Johnstone & Newell, 2018).

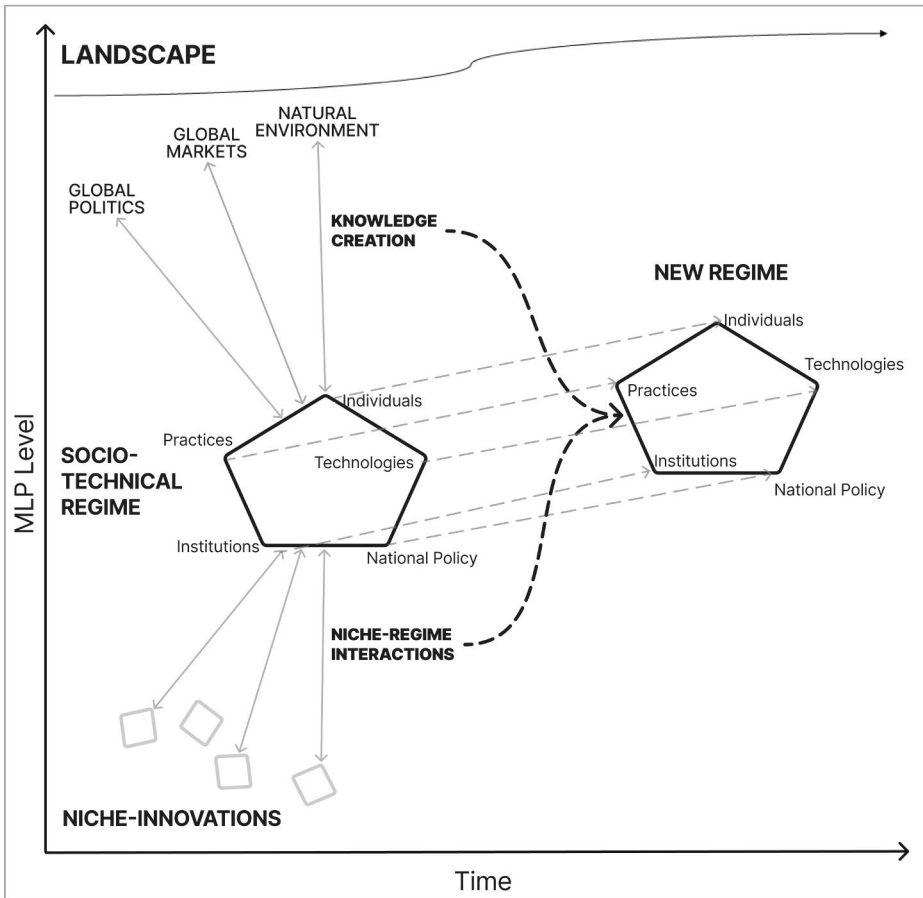
Concepts and frameworks from ST and JT are thus essential for exploring both the environmental and social dimensions of sustainability and inequality within technology transitions in ASGM. The following section provides greater conceptual depth by analyzing transition dynamics across the three MLP levels of niche, regime, and landscape.

## 2.2 Niche: emerging innovations and practices (Article I)

Niches are protected spaces in which emerging and localized innovations develop. If successful, these niche-innovations can contribute to challenging, disrupting, or even replacing the incumbent socio-technical regime (Geels & Schot, 2007; Loorbach et al., 2017; Runhaar et al., 2025; Smith & Raven, 2012).

A key driver of this process lies in leveraging the structures, supply chains, and knowledge embedded within the existing regime and broader socio-technical landscape (Andersen & Wicken, 2021; Ingram et al., 2015). In the mining sector, for instance, this may involve capitalizing on established machinery supply chains, regulatory frameworks, or outputs generated by other mining operations. Access to existing knowledge can offer a significant advantage during transition processes.

Accordingly, a successful niche-innovation is not necessarily one that diverges radically from the prevailing regime, but rather one that effectively integrates and utilizes incumbent infrastructures, knowledge, and technologies (Loorbach et al., 2017; Ingram et al., 2015) (**Figure 1**).



**Figure 1.** Niche, regime, and landscape levels within the multi-level perspective framework interact to shape socio-technical transitions. Successful niche-innovations can disrupt existing regimes and lead to the emergence of new ones. Highlighted in the figure are niche–regime interactions and knowledge creation, two key concepts within this thesis. Author’s elaboration on Geels & Schot’s (2007) MLP.

## 2.2.1 Organizational practices and agency

Although technological innovation plays a central role in transitions, the exercise of agency—the capacity to act on intentions and in this case apply the technologies—is also fundamental in determining the success of an innovation

(Grillitsch & Sotarauta, 2025; Sotarauta & Grillitsch, 2023a, 2023b). Agency can be influenced by values, intentions, and ambitions, and can result in different outcomes for sustainability. A useful strategy to investigate this is through organizational practices (OPs), or the customary practices which shape the functioning of an organization (Jönsson & Fold, 2009). These can also be influenced by hierarchies, agreements, and power relations (Conteh & Maconachie, 2021; Geenen & Bikubanya, 2024; Jönsson & Fold, 2009; Kabunga & Geenen, 2022). In sectors of the global South marked by informality, uncertainty, and insecurity, such conditions further shape OPs. In these contexts, OPs should not be understood merely as technical or managerial routines, but as strategies and livelihood mechanisms through which actors seek to generate flexibility, stability, and security in informal settings (Ramos-Mejía et al., 2018). As a consequence, the use and availability of similar technologies can result in different impacts for efficiency and sustainability (Nkuba et al., 2019; Veiga et al., 2014; Verbrugge & Geenen, 2020). The introduction of new technologies can transform hierarchies and re-arrange OPs, potentially disrupting current unsustainable systems, or create new lock-in effects (Arhin & Behuria, 2025; Chlebna & Suitner, 2025; Gaillard et al., 2025; Grillitsch & Sotarauta, 2025; Klitkou et al., 2015; Sotarauta & Grillitsch, 2023a). This is especially relevant for rural economies in the global South, as mechanization can offer productivity increases in labor-intensive sectors while bringing employment restructuring (Aryal et al., 2021; Brown et al., 2021; Geenen & Bikubanya, 2024; Kabunga & Geenen, 2022).

For example, Kabunga and Geenen (2022), in their research on ASM in the Democratic Republic of the Congo, found that mechanization—particularly through cyanidation and the introduction of ball mills—is associated with wealth concentration among a smaller group of entrepreneurs. These entrepreneurs vertically integrate extraction processes, and enables them to reshape labor arrangements and organizational practices to benefit them disproportionately, leading to increased inequality. As a result, the authors suggest the ASM sector might be gradually shifting toward a wage-labor system rather than one characterized by diverse organizational and sharing practices aimed at reducing risk and mobilizing capital. Overall, exploring OPs in global South rural sectors like ASM is essential in understanding the development of regional growth paths and the emergence of path-dependent practices (Gaillard et al., 2025; Grillitsch & Sotarauta, 2025; Nkuba et al., 2019; Sotarauta & Grillitsch, 2023a).

## 2.3 The Regime (Article II)

While the concept of the regime initially referred to the dominant technological configuration, it has since broadened to encompass the prevailing societal order more generally (Geels & Schot, 2007; Köhler et al., 2019; Runhaar et al., 2025). Specifically, the regime can be understood as a constellation of individuals, institutions, practices, and technologies that collectively constitute the incumbent societal order, which must undergo transformation to achieve sustainability transitions (Geels, 2002; Kaya et al., 2025; Loorbach et al., 2017). Although regime actors are often portrayed as powerful incumbents, they can also include vulnerable groups, particularly in the global South, where environmentally unsustainable practices may serve as essential means for short-term subsistence (Assan & Kumar, 2009; Morton, 2024).

Understanding the composition of a regime and resistance to change in a largely informal economic sector like ASGM in Africa requires taking a relational approach. The latter implies unpacking the complex dynamics of informal relationships and hierarchies, poverty, ambiguous institutions, civil society organizations (CSOs), the state, and regulatory structures (Ghosh & Mguni, 2026; Kvangraven, 2025; Lund, 2006; Pedersen et al., 2021; Stein et al., 2024). Thus, technological change does not occur in isolation; on the contrary, it is deeply embedded within these elements, and actors, which can both drive and resist change. Consequently, achieving sustainable and inclusive development requires transformations across these interconnected domains (Gaillard et al., 2025; Geels, 2014; Martínez Arranz, 2017).

Two key elements in this context are the state and CSOs, which can exert significant influence over technological change and sustainability transitions. Through regulation and policy, states in the global South are expected to pursue objectives such as environmental sustainability and economic growth. These goals can be contradictory, leading to ambivalent policy decisions and uneven support for different social groups (Johnstone and Newell, 2018; Ramos-Mejía et al., 2018; Swilling et al., 2016). Moreover, state actions are shaped by interactions with internal and external actors, including CSOs, global capital, foreign states, and other international and local organizations and industries (Ansari, 2022; Bonizzi et al., 2019; Swilling et al., 2016). These can also lead to rent capture, particularly in contexts involving natural resources.

CSOs can influence transitions by shaping political agendas and the allocation of resources (Mlambo et al., 2020). However, many CSOs in Africa face persistent financial constraints, limiting both their independence and effectiveness (Diamond, 1997; Odeh, 2012; Omede & Bakare, 2014). These constraints can render them susceptible to capture by the state, institutions, or foreign donors (Igoe, 2003, 2024; Odeh, 2012).

A further key factor in understanding regimes in the Global South is the accessibility and cost of capital. In Africa, capital is often scarce, and when it is available, interest rates can be prohibitively high, severely limiting the ability of the poor to escape poverty. In the absence of clear regulation, enforcement mechanisms, and collateral, formal access to capital remains out of reach for many (Kalemli-Ozcan & Sørensen, 2014). Although informal microcapital may be more accessible, it often depends on social capital, which is not universally available, and may involve exorbitant interest rates (Geenen & Bikubanya, 2024; Kalemli-Ozcan & Sørensen, 2014).

Finally, the poor form a crucial component of the regime. Resource and financial scarcity often drive the poor into short-term survival strategies that undermine long-term sustainability (Assan & Kumar, 2009; de Bruijn & Antonides, 2022; Morton, 2024; Mullainathan & Shafir, 2013; Ostrom, 1990). These findings are in line with research in behavioral economics, which further shows that poverty can lead to seemingly irrational or economically sub-optimal decisions (de Bruijn & Antonides, 2022; Mullainathan & Shafir, 2013). For instance, households may borrow at high interest rates, spend on immediate consumption such as alcohol or tobacco, or overexploit common-pool resources like forests, fisheries, and grazing lands to meet urgent needs (Assan & Kumar, 2009; de Bruijn & Antonides, 2022).

In economic activities involving multiple stakeholders, such as workers, businesses, the state, and CSOs, trust plays a critical role in shaping productivity and sustainability. Yet lack of transparency, historical legacies, and even poverty can undermine trust, and is reported being a key challenge in many economic sectors across Africa (Acemoglu & Robinson, 2023; Kinyondo & Byaro, 2024; Lund, 2006; Omede & Bakare, 2014). For example, recent research in rural Tanzania found that farmers exhibited lower levels of trust during the lean season, when they are experiencing financial scarcity, than during the abundant season (Agneman et al., 2023). Hence, exploring the role of trust in transitions in Africa can reveal a further layer of relational complexity between the different stakeholders which compose the regime.

## 2.4 The Landscape: knowledge creation processes and the natural environment (Article III)

Although the landscape has received the least attention within the MLP, it remains subject to ontological ambiguity. In its early application, scholars conceptualized the landscape as the broader context encompassing niches and regimes, and as the most challenging level to transform. This broader context has traditionally been interpreted as global politics and market dynamics (Köhler et al., 2019; Loorbach et al., 2017).

Some scholars have argued for incorporating a geographical and spatial dimension into the landscape concept (Hansen & Coenen, 2015). This approach enables the integration of the physical and natural environment as influential factors in shaping transitions (Andersson et al., 2024; Andersen et al 2021) (Article III). This contrasts with earlier transitions research, where the natural environment was often treated as a passive recipient of human influence, rather than an active component of transition processes (Andersson et al., 2024, 2025; El Bilali, 2019; Vermunt et al., 2020). Including the natural environment is particularly important in the African context, where natural resources play a central role and are deeply intertwined with transition processes (Arhin & Behuria, 2025; Ostrom, 1990).

Examining these dimensions reveals overlooked but essential factors that may either hinder or facilitate transitions. Responding to this gap, an expanding body of literature now integrates spatial and geographical perspectives within ST. This has contributed to the emergence of a subfield, the Geography of Sustainability Transitions (GeoST), which more systematically incorporates these dimensions into transition studies, including the role of human–nature interactions and natural resource endowments (Binz et al., 2020, 2025; Hansen & Coenen, 2015; Munro, 2019).

In this regard, and specifically in Article III, the thesis contributes to the literature by examining knowledge creation processes as mechanisms through which humans interpret and engage with their environment during transitions. Previous research often places knowledge within the niche level of the MLP as part of emerging innovations (Keller et al., 2022; Polita & Madureira, 2021). Exploring knowledge creation in relation to the materiality of natural and physical environments can therefore be understood as an instance of niche–landscape interaction (Dumont et al., 2020; El Bilali, 2019; Lutz & Schachinger, 2013). For this reason, I discuss knowledge creation processes in this section, as they cannot be separated from the natural environment and the landscape level.

Knowledge creation underpins all economic and social activities, serving as the means through which individuals and groups engage with one another and with their material environments (Tödting et al., 2009; Ziervogel et al., 2022). Here, the concept of knowledge base is useful in describing how knowledge is created, applied, and shared between individuals and across economic sectors (Asheim et al., 2007). Economic activities are associated with distinct knowledge bases: analytical or science, technology, and innovation (STI) knowledge, synthetic or applied knowledge, and symbolic or cultural knowledge (Asheim et al., 2007). While analytical knowledge is often crucial, it can be costly and time-consuming to acquire. In contrast, disadvantaged communities in Africa tend to rely more on informal and accessible knowledge forms, such as synthetic and symbolic knowledge (von Hippel, 1994).

These knowledge bases can be shared through modes of exchange, such as learning-by-doing, using, and interacting (DUI), where individuals learn through face-to-face encounters and co-presence (Asheim et al., 2007). These are particularly valuable in contexts characterized by informality, where tacit knowledge and sensory engagement play a significant role (Ferry & Ferry, 2019). A related and essential concept is that of knowledge stickiness, which refers to the cost associated with exchanging or transferring knowledge between individuals or groups (Andersen & Wicken, 2021; von Hippel, 1994). Thus, as opposed to general knowledge which is widely applicable, sticky knowledge is closely embedded in specific local environmental and social contexts.

While technologies requiring sticky knowledge have limited applicability across different settings, standardized innovations may take advantage of economies of scale (Andersen & Wicken, 2021; Bresnahan, 2011; von Hippel, 1994). In areas with scarce resources and limited access to knowledge of the local environment and scientific knowledge, technologies and innovations requiring general-purpose knowledge can serve as vital lifelines for communities, especially in rural areas in the global South where individuals directly engage with natural resources for their sustenance. Nevertheless, general knowledge, technologies, and innovations may produce less effective outcomes, especially in terms of productivity and environmental sustainability due to a lack of idiosyncratic knowledge (Andersen & Wicken, 2021; van der Merwe et al., 2025; von Hippel, 1994). This challenge can make localized knowledge essential for successful adaptation and sustainable development.

Overall, examining the knowledge base required as well as modes of knowledge exchange can be key to understanding technological adoption for transitions towards sustainable development. Situating these concepts within the Just Transition framework highlights the need to examine the extent to which unequal access to knowledge bases and exchange mechanisms may reinforce inequalities during transition processes (Arhin & Behuria, 2025). Examining knowledge creation and exchange processes in relation to the natural environment is therefore central to assessing the sustainability of production systems.

## **2.5 Theoretical contributions of the thesis: interactions between levels and relational approaches**

The theoretical contribution of this thesis lies in showing that technological substitution alone is insufficient to explain or achieve a just and sustainable transition, particularly in the global South. A deeper understanding requires examining the underlying socioeconomic and organizational structures operating

across the niche, regime, and landscape levels. While these three analytical levels are often treated separately, their interactions—and the fluid, relational interpretation of the MLP framework—represent its core analytical strength. Novel niche-innovations, for example, do not emerge in isolation but within the broader socioeconomic dynamics of regimes and landscapes. Their ability to learn from, interact with, and leverage existing regimes is crucial to their success (Article I). Likewise, expanding the conceptualization of the landscape to explicitly include the natural environment is valuable. Exploring how actors engage with the landscape through knowledge creation processes sheds light on how such interactions shape practices and influence sustainability outcomes (Article III).

Advancing these theoretical perspectives has necessitated the use of field-intensive methodologies and empirical research to adopt a relational approach that reveals how actors engage with technologies and how these are embedded within complex socioeconomic systems. Such an approach not only uncovers sources of resistance to change and opportunities for transformation but also identifies where transformative agency resides, enabling analysis of both dominant and marginalized actors in transition processes. Ultimately, mapping these relational structures exposes the constellation of elements and relationships that produce lock-in effects—either impeding change or diverting it towards more (or less) just transitions (Article II).

### 3 Materials and Methods

Research methodology is fundamental, as it provides systematic procedures to collect and rigorously analyze empirical data in a transparent manner (Yin, 2006). The choice of methodology is inherently linked to the research questions. Because this research addresses *what* and *how* questions, it has adopted both exploratory (*what*) and explanatory (*how*) approaches (Hay, 2000; Yin, 2006). A fieldwork-intensive, mixed-methods approach—including both qualitative and quantitative methods—was therefore selected. In-depth qualitative methods are advantageous for addressing *how* and *why* questions, particularly through the use of open-ended questions (Cope & Hay, 2021), while quantitative methods are useful in answering *what* and *who* questions by identifying patterns and delineating the occurrence and extent of phenomena (Cope & Hay, 2021; Yin, 2006). Combining these approaches provides both breadth and depth (Ivankova et al., 2006) and allows for methodological triangulation, thereby reducing the potential weaknesses and biases inherent in each individual method (Lund, 2014; Patton, 1999). These complementary methods ultimately strengthen the overall validity of the research (Hay, 2000; Stake, 2005; Yin, 2006).

While mixed-methodologies can be organized in a structured fashion (Ivankova et al. 2006), an inductive and explanatory approach is particularly valuable during fieldwork. This approach permits research themes to emerge from the field rather than being constrained by preconceived ideas (Tsing, 2015). Although it is impossible to completely eliminate preconceptions, I have strived to pursue an inductive approach by following the emerging findings, themes, and priorities from the field (Charmaz, 2012; Clark et al., 2007; Clarke, 2005; Thomas, 2006). As a result, the research process has been “messy” rather than linear, involving a complementary use of methodologies and constant movement between data, methods, and theory to uncover findings from multiple perspectives (Clark et al. 2007:110). This iterative process between empirical material and theory has enabled me to continuously refine the case analysis and enhance the abstraction and generalization of the findings (Lund, 2014).

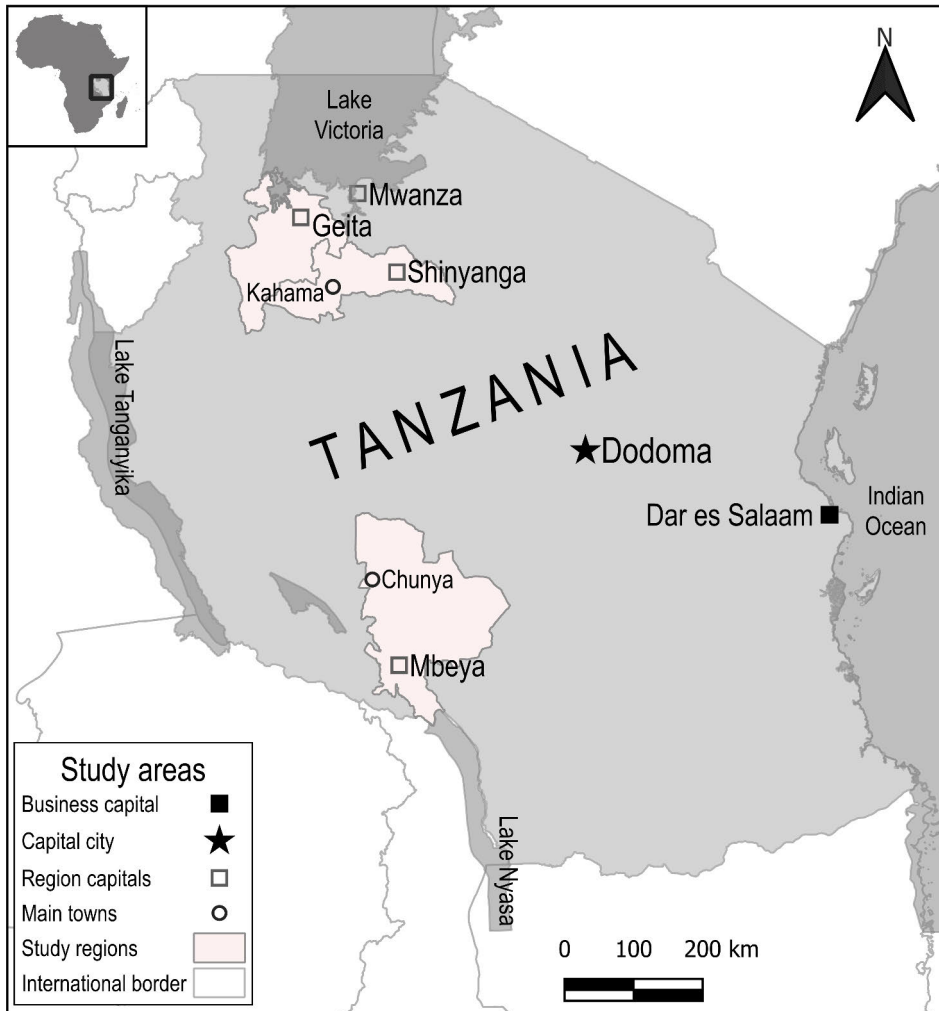
An additional benefit of fieldwork is the possibility to collect novel, first-hand empirical data. This is particularly relevant for qualitative data, which is

constructed through the engagement of the researcher with informants, the field, and the research process (Bryant & Charmaz, 2007). Data on social inquiries are best obtained through day-to-day interactions and by being physically present in situ (Bryant & Charmaz, 2007; Frilund, 2019; Hooli, 2016; Mason, 2001). Such engagement also builds rapport and trust with informants, thereby revealing otherwise concealed narratives through diverse methodologies (Ivankova et al., 2006; Kusenbach, 2003).

The research process for this thesis was organized as follows. Prior to entering the field, I conducted desk research analyzing academic and grey literature on innovations, sustainability, and natural resources and ASGM more specifically in Africa and Tanzania. This also includes literature addressing technical challenges within ASGM, such as the effectiveness of different extraction methods. While this approach was essential in the initial stages, I pursued this approach throughout the PhD period, continuously integrating further literature. While these efforts informed all articles, grey literature was integrated more systematically in Article II. I have acquired further insights through discussions with colleagues, practitioners, and experts who had been undertaking similar work in Tanzania and Africa.

The preliminary literature review was essential for narrowing down the research questions. Concurrently, I focused on ethical research conduct, which resulted in obtaining ethical approval from the University of Turku's ethics committee and a research permit from the Tanzania Commission for Science and Technology (COSTECH).

Fieldwork was conducted in Tanzania (**Figure 2**) over a total of five months in August–September 2022, July–August 2023, and May–June 2024. The 2022 fieldwork was exploratory and instrumental in further narrowing down the research questions, familiarizing me with the field, selecting case studies, identifying key challenges, and building rapport with informants. This background was crucial for designing the subsequent quantitative and qualitative data collection. During the subsequent fieldwork visits (2023 and 2024), I collected qualitative data through semi-structured interviews, participant observation, focus group discussions, and the go-along methodology, and quantitative data via a survey administered in 2023. Specifically, the 2022 fieldwork provided the necessary experience for selecting the case study and sample for the survey more effectively. The qualitative data were analyzed thematically, while the quantitative data underwent statistical analysis (**Table 2**).



**Figure 2.** Study areas in Tanzania. Created with the Humanitarian Data Exchange (2024) data through QGIS. Drawing by Justo Jonas.

In summary, I employed qualitative and quantitative methodologies in parallel, using insights from each method to inform the other. The intervals between field visits provided valuable time to analyze and reflect on the data, plan subsequent research steps, and write the articles. I have selected this approach also to provide the research with a longitudinal dimension (Li, 2014; Pedersen, 2023). This provided me the opportunity to approach the field with different lenses each time, which contributed to identifying key insights and challenges more accurately, as well as observing how phenomena in the field evolve through time. Overall, while selecting this approach combining methodologies with in depth fieldwork is not a novel

approach, it has been an essential strategy to accomplish an inductive, exploratory, and explanatory approach, which enable addressing the research questions and enhance the validity of this research (Cope & Hay, 2021; Lund, 2014; Yin, 2006, 2017).

Although the methodologies were interrelated and employed complementarily, I provide a detailed discussion of each in the following sections. First, I describe the design, data collection, and analysis of the quantitative methodologies. Second, I break down the qualitative methods into interviews (including semi-structured interviews and focus group discussions) and observation methods (participant observation and go-along). While the design and data collection for qualitative methods are addressed separately, the analysis is discussed within the same section. Finally, I reflect on my positionality and the case study selection.

**Table 2.** Summary of quantitative and qualitative data collection, areas, and analysis.

	Quantitative	Qualitative		
Data collection Method	Survey	Semi-structured interviews	Focus Group Discussions	Participant observation
Area	Kahama District	Geita, Shinyanga, Mbeya, Dar es Salaam, Dodoma	Kahama district, Mbeya	Geita, Shinyanga, Mbeya, Dar es Salaam, Dodoma
Data	116 survey responses	119 interviews	2 interviews	Field notes
Analysis	Statistical	Thematic	Thematic	Thematic
Year of data collection	2023	2023, 2024	2023, 2024	2023, 2024

### 3.1 Quantitative data & methods

#### 3.1.1 Design

The quantitative data for this research were collected through a survey conducted in the Kahama District, Shinyanga Region, during July and August 2023. This district was chosen because it is one of the primary areas in Tanzania where cyanide leaching proliferated, and currently hosts a large number of ASGM operations, including those using mercury, cyanide, or a combination of both, as well as other extraction technologies. Moreover, Kahama is a comparatively under-researched area

compared to the more extensively studied Geita District. Section 3.4 *Case studies* further elaborates on the rationale for selecting these areas for case studies.

The survey was structured in three main sections. The first gathered demographic and background information, such as age, gender, education level, area of employment, place of residence, and occupational roles in mining. Based on responses to the latter, I assigned miners either into the ‘workers’ or ‘entrepreneurs’ categories. The entrepreneur category was assigned to miners holding primary mining licenses, or owned pits, machinery or processing areas. The ‘workers’ category was instead assigned to miners whose primary role was performing physical and low-skilled tasks including digging, crushing rocks manually, sluicing, and who are compensated through their work or a small share of the output. The second section focused on behaviors, perceptions, and practices related to mining technologies. This included the frequency of mercury and cyanide use, use of technologies, and knowledge acquisition and sharing. The final section explored economic challenges, respondents’ beliefs—including impacts of mining on human health and the environment—aspirations, and expectations for the future.

Most questions were multiple-choice, with four open-ended questions. Most multiple-choice items included “other” as an option, allowing respondents to elaborate beyond the pre-defined answers (Hughes et al., 2016). Including this option was essential, as it enabled participants to provide insights that extended the scope of the structured responses, offering themes for further exploration in subsequent semi-structured interviews (McGuirk & O’Neill, 2010; Reja et al., 2003).

The survey was originally designed in English and subsequently translated into Swahili by research assistants. To refine the questionnaire, the assistants conducted a small number of pilot surveys, which helped ensure the clarity, comprehensibility, and logical structure of the questions (McGuirk & O’Neill, 2010). These revisions aimed to ensure the survey could be completed within fifteen to twenty minutes. Survey participants were stakeholders in ASGM, primarily miners engaged in various production roles, including license holders and brokers. Due to limitations in time and resources, and the challenges associated with obtaining comprehensive knowledge of the broader population, a representative sample was not pursued. Instead, purposive sampling was employed to ensure the inclusion and representation of specific subgroups within the ASGM sector (McGuirk & O’Neill, 2010; Patton, 2002). While the results are not generalizable to the entire population, they enable the identification of relationships between variables, which can be further examined through qualitative methods.

### 3.1.2 Data and data collection

Following the completion of the survey design, research assistants administered the survey by reading the data statement and individual questions aloud to respondents in Swahili. Responses were recorded manually by the assistants on a survey sheet. To ensure anonymity, no personal identifiers or names were collected. We requested survey participation from 120 miners, of whom 116 provided complete responses. All respondents were based in the Kahama District, including Kahama town and surrounding mining areas.

Participants were primarily recruited through snowball sampling. As miners invited us to different mining areas, we established contacts with potential respondents, who either completed the survey if they were not engaged in work at the time (for example, during breaks in their shifts) or arranged to participate at a later time and at a different location. As data collection progressed, we ensured that different stakeholder groups were represented in the sample. For instance, once in mining areas, we requested to be introduced to workers involved in mercury amalgamation or cyanide leaching activities. Similarly, we actively sought survey responses from entrepreneurs, who constitute a smaller share of the overall mining population. As a result, the final sample included a higher proportion of entrepreneurs (32 respondents) relative to workers (84 respondents) than would be expected in a representative population sample. At the same time, we ensured that the 84 workers were engaged in diverse mining roles (e.g., digging, manual rock crushing, machinery operation, mercury amalgamation, and cyanide leaching). This sampling strategy was adopted to ensure that the perspectives of different groups were adequately captured.

### 3.1.3 Data analysis

After data collection, responses were converted into Excel format and subsequently uploaded to the STATA software for analysis. The primary analytical approach involved the use of dummy variables, created from survey responses, to explore statistical relationships. Fisher's exact test was employed to assess the significance of relationships between categorical variables, with results presented through two-sided p-values. This method is particularly well-suited for analyzing small datasets using two-by-two contingency tables (Freeman & Campbell, 2007). One of the key dummy variables constructed was the entrepreneur–worker distinction. This variable enabled comparisons across various dimensions, including access to capital, knowledge, and perceptions.

The quantitative data and corresponding analysis informed all three articles in the thesis. In Article I, the data informed descriptive statistics serving primarily as background and was complemented by qualitative analysis. By contrast, Fisher's

exact test played a more central role in Articles II and III, contributing directly to the development of the broader thesis.

## 3.2 Qualitative data & methods

Qualitative and ethnographic methods represent the core methodological foundation of this mixed-methods research. These approaches include semi-structured interviews, participant observation, go-alongs, and focus group discussions. These methods are not applied as isolated techniques; rather, they are often employed simultaneously and in combination. As a result, many research interactions cannot be classified under a single methodological category.

For instance, a one-on-one semi-structured interview might evolve into a joint interview if the informant invites others to participate. Similarly, interviews often overlapped with other methods such as go-alongs or participant observation, particularly when informants engaged with their environments or demonstrated mining technologies during the interaction. These overlapping methods were used both before and after the quantitative data collection and analysis. Initially, they contributed to strengthening and validating the survey design. Subsequently, they enabled a deeper, more nuanced exploration of survey responses. This research benefitted greatly from such fluid and informal interactions. Although they blur the conventional boundaries between qualitative methods, these hybrid encounters yielded richer, in-situ insights and ultimately enhanced the quality and depth of the data collected.

Based on this integrated approach, the following section is organized into two main parts. The first addresses interviews, encompassing both semi-structured interviews and focus group discussions. The second focuses on participant observation, which also incorporates the go-along method. In line with the structure used for quantitative methods, each part is further divided into subsections on research design and data collection. Finally, as qualitative data were analyzed collectively and concurrently, a shared data analysis section follows, covering all qualitative methodologies.

### 3.2.1 Interviews: design

I initially designed a tentative structure for the semi-structured interviews and focus group discussions prior to entering the field, acknowledging that this structure would evolve and adapt throughout the fieldwork process. Accordingly, before each interview, I would modify the interview guide to incorporate new information from survey or interview data or adjusting for changes in the role or position of the interviewee. Interview questions focused on themes such as access to capital, mining

challenges, mining techniques and technologies, as well as issues related to change, perceptions, beliefs, attitudes, knowledge, and learning. The goal was to capture a broad range of perspectives by including a diverse array of stakeholders, from miners to government officials, policymakers, and regulators.

### 3.2.2 Interviews: data collection and data

In total, this research is based on 119 semi-structured interviews conducted between 2022 and 2024. Respondents were selected based on their roles, interests, first-hand experience with the research topic, or their ability to provide distinct perspectives on it. This approach enabled engagement with individuals with long-term experience in the sector who could offer in-depth insights, while also capturing a diversity of viewpoints that significantly enriched the analysis. Consequently, informants were drawn from a broad range of experience and roles in relation to ASGM, including miners (both workers and entrepreneurs), public officials from key agencies and ministries, mineral processing engineers and geologists, representatives from NGOs, mining suppliers, leaders of mining associations, brokers, and other relevant actors (**Table 3**).

Miners constituted the central group of informants in this study. Their interviews offered critical insights into perceptions, beliefs, technical know-how, socio-economic challenges, and future aspirations. Interviewing a wide range of miners—spanning different roles within the extraction process, as well as entrepreneurs with differing levels of capital availability—was essential for addressing the research questions from multiple vantage points. Particular attention was given to miners with extensive experience in the sector, as they were able to reflect on the transformations that ASGM has undergone in recent decades.

Interviews with mineral processing engineers, environmental engineers, and geologists provided detailed perspectives on the technical dimensions of mining, including mineral deposits, extraction methods and their effectiveness, and the environmental impacts associated with different techniques. These interviews also contributed to an understanding of the key technical challenges faced by miners from an expert standpoint. Combining expert and miner perspectives was essential for examining mercury–cyanide transitions through a socio-technical-natural approach, allowing for analysis of how the material properties of technologies and mineral deposits shape the behaviors of miners and other stakeholders.

Government officials from multiple agencies and ministries were interviewed to capture the procedural and distributional dimensions of the transition, as well as to gain insight into short- and long-term policy objectives. These perspectives were essential for analyzing how mercury use and cyanide leaching have been supported and regulated.

Overall, the inclusion of this wide range of stakeholders substantially strengthened the research. The diversity of perspectives enabled a more comprehensive analysis of the transition away from mercury in ASGM, which could not have been adequately explored through a single group of informants.

**Table 3.** Semi-structured interview respondents. Elaborated from Article III.

<b>Respondents' main occupations and roles</b>		<b>Number of respondents</b>
<b>Miners</b>	Workers	35
	Entrepreneurs	22
<b>Public officials</b>	Local mining officials	3
	Geological Survey of Tanzania (GST)	2
	State Mining Corporation (STAMICO)	3
	Ministry of Minerals	2
	National Environment Management Council (NEMC)	4
	Government Chemist Laboratory Authority (GCLA), Ministry of Health	1
<b>Experts</b>	Mineral Processing engineers	6
	Environmental engineers	2
	Geologists	9
<b>Private Sector</b>	NGOs and consulting	5
	Mining equipment and chemicals (including cyanide) suppliers and vendors	7
<b>Other stakeholders</b>	Miner associations leaders	8
	Brokers	6
	Miners' relatives	4
<b>Total</b>		119

Most interviewees were primarily identified and contacted through snowball sampling. This method can foster trust by connecting potential informants through mutual acquaintances, thus making them more comfortable (Parker et al., 2019). In addition, in the Kahama district, I also conducted many follow-up, semi-structured interviews after respondents completed the quantitative survey. I conducted semi-structured interviews in various settings, including cafes, local restaurants, informants' homes, public offices, and mining sites. The majority of interview questions were open-ended, which allowed me to guide the conversation around specific themes while enabling respondents to elaborate on their answers freely.

Questions were not asked in a fixed order; instead, follow-up questions were posed to maintain a natural flow of discussion and adhere to an inductive and exploratory approach (Flick et al., 2004; DeWalt & DeWalt, 2010). This flexible

structure allowed respondents to raise important topics and challenges that may not have been included in the initial interview guide. Additionally, informants were encouraged to ask questions about the research. This approach aimed to make the interviewee feel as comfortable as possible and to foster rapport and intimacy. Consequently, many interviews resembled informal, two-way conversations rather than formal, hierarchical exchanges. Engaging with informants beyond the interviews also proved essential, as it facilitated trust-building and provided access to information that might otherwise have remained tacit (Brinkmann, 2013).

Most interviews were conducted in Swahili with translation support from the research assistants, while a smaller number—particularly with government officials—were conducted in English. At the start of each interview, we read the data statement to respondents and sought their permission to record the interview. As a result, most interviews were recorded, though in the cases where recording was not possible, detailed notes were taken. The interviews lasted between twenty minutes and two hours, with the majority lasting approximately one hour.

The same principles applied to the two focus group discussions I conducted, which involved members of miners' associations. These discussions addressed similar themes to the semi-structured interviews. Although focus groups were a relatively marginal method in this research due to the complexities of translating between multiple stakeholders, they provided valuable insights into the interactions and interests of different groups. These insights were further explored during the semi-structured interviews.

### 3.2.3 Participant observation and the go-along: design

Participant observation and the go-along are key ethnographic methods in this research. Participant observation allows the researcher to investigate behaviors, attitudes, cultures, and interactions in situ (Kusenbach, 2003; Dewalt and Dewalt, 2010); while the go-along combines participant observation and interviews (Kusenbach, 2003). In the latter, the researcher interviews informants while they engage in their daily activities, providing insights into the informants' everyday experiences, challenges, and interactions in real-world contexts (Kusenbach, 2003; Pink, 2015).

The advantages of both methods are amplified when used in combination, as they are essential for gathering information that might otherwise remain tacit (Dewalt and Dewalt, 2010; Kusenbach, 2003). These methods are particularly valuable for exploring the skills, techniques, and technologies miners employ in their work, as these elements often involve a high degree of tacit knowledge or are difficult to express verbally (Asheim et al., 2007; Ferry & Ferry, 2019; Hautala, 2018).

### 3.2.4 Participant observation and the go-along: data collection and data

Throughout the fieldwork, participant observation was employed continuously, particularly in mining and processing areas. This approach allowed me to interact firsthand with the participants and their tools, materials, and spaces they had referred to in interviews. For instance, it enabled me to adopt a sensory approach in my third article: by being in situ I could observe firsthand the visual cues, smells, and dangers that are integral to mining (Asheim et al., 2007; Ferry & Ferry, 2019; Pink, 2015). Consequently, while participant observation was essential for all three articles, it was particularly prominent in the third. These sensory cues were especially important in informing me of the processes driving miners' decisions and learning processes. It also allowed me to immerse myself in the sensory experience of the materials and explore the possibilities of learning through interaction with both the materials and the people involved. Combining this method with the go-along proved crucial, as explaining concepts about their work in situ proved a significant advantage, especially for more tacit skills and knowledge. Additionally, this combination enabled me to investigate the relationships between miners, their hierarchies, and their connections to space, the environment, and technologies. Overall, notes were taken during observations and subsequently expanded upon in the fieldwork diary each day.

### 3.2.5 Qualitative data analysis

As part of inductive and exploratory approaches, preliminary qualitative data analysis occurred already during data collection (Bryant & Charmaz, 2007). Additionally, I asked research assistants and selected critical informants to reflect on the data collected, and their reflections were incorporated as part of the data. This allowed me to verify whether their understandings aligned with my interpretation of the field (Lund, 2014).

Following the fieldwork periods, I conducted a systematic thematic analysis of the data. The interview transcripts and notes, along with the fieldnotes from participant observation, were analyzed using NVivo software. Initially, I coded the data based on the context, perceptions, attitudes, and experiences. These initial codes were then refined into field-related themes, corresponding to the research questions of each article.

In the first article, the data were grouped into four main organizational practices related to mercury use that emerged from the fieldwork. This enabled me to examine each practice in terms of its employment potential and the application of chemicals, which in turn informed the sustainability of each practice. In the second article, key themes were divided into the use of chemicals, driving and resisting change, access

to capital, time-discounting behavior, scaling up production, trust, precarity, and poverty. For the third article, I analyzed the data around three central themes: local knowledge, knowledge about mining and the environment, and knowledge creation processes. The themes that emerged from the thematic analysis provided the foundation for each section of the articles.

### 3.3 Positioning myself and the research

Conducting ethnographic research can involve positionality challenges across multiple dimensions, requiring continuous and critical self-reflection. Part of this reflexive work includes both acknowledging how the researcher is perceived by respondents, as well as understanding how the researcher's ways of perceiving and analyzing social realities have been shaped by contexts with different cultural, historical, and epistemic foundations. This section explores both these challenges.

Researcher-informant interactions are shaped by relational dynamics—including race, gender, and professional identity—that influence trust, access, and forms of disclosure (Husband, 2020). In my case, this required acknowledging how being a white male researcher in Tanzania would inevitably shape the relationships I formed and the ways in which respondents understood my presence in the field.

As I entered the field, my physical presence alone inevitably attracted attention, largely due to my skin color. I had anticipated that my presence in gold mining areas would be interpreted by the miners' prior experiences and expectations. For example, I imagined being perceived as affiliated with institutions or corporations seeking to acquire mining areas, or as an inspector evaluating safety conditions. Nevertheless, miners prevalently interpreted my presence as opportunity rather than threat, being perceived as a potential investor for their mining activities, or as an intermediary for investors. As I strived to engage with informants with a transparent approach, introducing myself as a doctoral researcher, I would often face disappointment from some informants, while others would expect of me to bring alternative technologies to persistent challenges like mercury given the research topic of this research.

To navigate this challenge, I employed a strategy of entering mining sites alongside informants who were either well-known local miners, acquaintances of the research assistants, or individuals with connections to government officials. These varied forms of introduction enabled different modes of engagement with respondents, encompassing both top-down and bottom-up approaches. The latter proved particularly effective in fostering trust, while the combination of both approaches offered diverse perspectives and enriched the findings. This complexity illustrates the necessity of continually renegotiating positionality with informants (Egbetokun, 2022; Pedersen, 2023; Thambinathan & Kinsella, 2021).

This second phase—direct interaction with informants—is critical in ethnographic research. I approached this engagement with a commitment to ethical conduct, transparency, and reciprocity. Most interviews were designed as dialogical exchanges, encouraging informants to participate actively, ask questions, and share their perspectives. This method aimed to reduce hierarchical dynamics and create a more comfortable space (Husband, 2020). I also spent extended time with many key informants beyond data collection, participating in everyday activities such as watching football, or sharing a meal or time with the family.

Although often mediated by translation provided by the research assistants due to my limited knowledge of Swahili, these informal encounters enabled a mutual exchange of thoughts and experiences. Striving to establish horizontal relationships was essential to my ethnographic approach, as meaning and qualitative insights are co-constructed through the researcher–informant relationship (Bryant & Charmaz, 2007; Fabian, 2014; Frilund, 2019; Hooli, 2016; Mason, 2001).

In line with a transparent research approach, I consistently explained the purpose of the research and presented data protection and privacy statements before any interviews were conducted or recorded. My research adhered to the European Union’s General Data Protection Regulation (GDPR) and followed the ethical guidelines of the Finnish National Board on Research Integrity (TENK, 2019). To protect informants' identities, names were not collected for the surveys and semi-structured interviews were anonymized after transcription. I also reminded informants of their rights at the beginning of the interviews and surveys, including the right to skip questions, maintain anonymity, and request deletion of data at any point (Husband, 2020). To support this, I shared my contact information with all participants.

A further key challenge in the research process as a white researcher in Africa is engaging in research which leads to mutual benefits and does not result in extractive research. These concerns significantly shaped the design and conduct of my fieldwork. Being acutely aware of the high expectations placed on my positionality, I sought to frame the research as a process of mutual learning, where informants could also derive some value from participation. While mutuality in learning was limited by the scale of interaction—given that only a small proportion of the population participated—certain moments, such as discussions around mercury exposure and health risks, prompted reflection among informants. To avoid creating expectations or distortions in responses, compensation was modest and context-sensitive, such as covering transport or meal costs. This also contributed to acknowledging informants’ time and contribution (Egbetokun, 2022). However, what appeared most valued by participants, especially key informants, was not the provision of information or material compensation, but the time spent together beyond formal interviews. Sharing meals, taking or simply lingering after interviews

helped to foster trust and demonstrated that my interest extended beyond the research. Moreover, maintaining digital contact with informants despite physical distance has further enhanced this aspect. These also provided me with an opportunity to share preliminary results with the informants. Sharing results with informants is an essential component of the research process, and I aim to bring the results back to the communities after the doctoral dissertation defense, by organizing workshops with key stakeholders in Tanzania.

Most verbal interactions during the research were mediated by research assistants, who played a crucial role not only in translation but also in facilitating relationships between myself and the informants. Their involvement extended beyond linguistic support to include cultural mediation and interpretation. To this end, research assistants were thoroughly briefed and closely supervised throughout the research process. I selected assistants who could navigate the physical and social landscape of mining areas.

Building trust and mutual understanding with research assistants was a priority. I engaged in continuous feedback exchanges and sought their interpretations of interactions with and between informants. This helped unpack behaviors, attitudes, and practices, enriching the overall analysis. Additionally, I conducted in-depth interviews with each research assistant before and after every fieldwork period. This approach fostered critical reflexivity within the research process (Thambinathan & Kinsella, 2021).

These exchanges also contributed in building a critical reflexivity which would limit the imposition of the researcher's own epistemologies over the informants' ways of knowing (Thambinathan & Kinsella, 2021). Without careful reflection, these inherited lenses risk misrepresenting the perspectives present in this setting (Frilund, 2019; Gabay, 2018; Hooli, 2016). While it is impossible to entirely shed one's preconceptions, combining these reflexive practices with an inductive methodology supported the emergence of concepts from the field, rather than imposing predefined frameworks (Lund, 2014).

This is particularly relevant to sustainability transitions research, which remains predominantly shaped by Western institutions and scholars (Ghosh et al., 2021; Ramos-Mejía et al., 2018). The concept of 'sustainability' itself may have limited resonance—or even contradictory meanings—within mining communities, requiring researchers to step away from Western-centric interpretations (Fisher et al., 2023; Pedersen, 2023). Although this thesis contributes to the broader, Western-dominated discourse on 'Sustainability Transitions', it also seeks to open alternative understandings of transition processes in Tanzania, Africa, and the global South.

### 3.4 Case studies

Tanzania was selected as the case study for this research. Data collection was undertaken in the gold-mining regions of Geita, Shinyanga, and Mbeya, as well as in the administrative and commercial centers of Mwanza and Dar es Salaam, and in the capital, Dodoma. The fieldwork was organized as follows: in 2022, I conducted exploratory fieldwork in Geita, Shinyanga, Mwanza, and Dar es Salaam; in 2023, fieldwork with extensive interviews and the survey was conducted in the same areas, with the addition of Dodoma; while in 2024 fieldwork was carried out in Mbeya and Dar es Salaam. Accordingly, Articles I and II draw on data collected in 2023, whereas Article III incorporates data from all phases of fieldwork.

The Geita and Shinyanga regions are located in northwestern Tanzania, with Geita bordering Lake Victoria and sharing its southern border with Shinyanga. By contrast, the Mbeya region lies approximately 600 kilometers to the south, within the Southern Highlands, bordering both Lake Nyasa (also known as Lake Malawi) and the Republic of Malawi. While Geita and Shinyanga are among the smallest regions in Tanzania, with surface areas of 21,879 and 18,555 square kilometers respectively, Mbeya ranks among the largest, covering 35,232 square kilometers (URT, 2019a, 2020b, 2020c).

Geita, Shinyanga, and Mbeya are home to approximately 3 million, 2.2 million, and 2.3 million inhabitants respectively (URT, 2022). In all three regions, agriculture dominates the economy, accounting for roughly 80% of employment and 40% of income (URT, 2019a, 2020b, 2020c). Other significant economic activities include mining, livestock keeping, fishing, beekeeping, and forestry (URT, 2019a, 2020b, 2020c).

Nationally, mining and quarrying account for over 10% of national GDP and over 40% of goods exports (URT, 2024). While gold mining has the largest share, the extraction of coal, tanzanite, diamonds, gemstones, gypsum, and construction minerals are also significant (URT, 2024). The case study regions were selected due to their prominence in gold production and their long-standing histories of gold mining (Merket, 2019; Roberts, 1986). Collectively, they employ approximately half of the national ASGM workforce and account for about one-third of the gold produced by ASGM nationally (URT, 2020a) (**Table 4**). Large-scale mining is also significant in these areas, with major operations including Geita Gold Mine (Geita), Buzwagi and Bulyanhulu (Shinyanga), and New Luika Gold Mine (Mbeya). Although gold is the primary mineral extracted, Shinyanga also hosts substantial small- and large-scale diamond mining, while coal mining and construction minerals are extracted in Mbeya (Merket, 2019; URT, 2019a, 2020b, 2020c).

**Table 4.** Key Statistics for ASGM gold production, mercury use, and employment, in the study regions.

Indicator	Geita	Shinyanga	Mbeya	Total (three regions)	Total (Tanzania)
<b>Annual Gold Production (kg)</b>	2,800	910	1,159	4,869	15,261
<b>Share of National ASGM Gold Production (%)</b>	18.35%	5.96%	7.59%	31.9%	100%
<b>Estimated Mercury Use (kg/year) *</b>	4,480	1,456	1,854	7,790	24,416
<b>Estimated ASGM Employment</b>	171,300	138,000	154,000	463,300	932,730**
<b>Share of National ASGM Employment (%)</b>	18.37%	14.80%	16.51%	49.7%	100%

Source: elaborated from the 2020 National Action Plan (URT, 2020a).

\* Mercury consumption estimates are derived from the ratio reported by URT (2020a), which indicates that approximately 1.6 kg of mercury is used for every 1 kg of gold produced.

\*\*This total ensues from the detailed aggregated baseline data collected from a field survey of only 40 ASGM sites across 9 regions (15% of the total national ASGM sites) which explains the discrepancy with the national estimate.

As the leading region in both gold production and ASGM employment, Geita has become a central focus of ASGM-related research in Tanzania (URT, 2020a). While this study includes fieldwork in the Geita region, most fieldwork was conducted in the Kahama and Chunya districts, located within the Shinyanga and Mbeya regions respectively (**Table 5**). These less-studied areas were deliberately selected to provide more original case studies and to avoid contributing to the over-researching of certain groups and locations (Egbetokun, 2022).

The Geita and Shinyanga ASGM sites lie within the Lake Victoria Goldfields (LVG), while the Chunya district of Mbeya region are part of the Lupa Goldfields (Roberts, 1986). A key distinction between these two goldfields is the extent of exploitation. The LVG has been heavily mined—some areas, such as Nyarugusu, have experienced a decline in activity since the 1990s due to the depletion of surface-level minerals (Bryceson et al., 2020). Conversely, in Chunya, gold remains readily accessible near the surface, and alluvial mining continues to be widespread (URT, 2020a).

**Table 5.** ASGM sites visited in Tanzania, organized by region and year of fieldwork.

Region	2022	2023	2024
<b>Geita</b>	Nyarugusu Rwamagasa Nsangano	Masumbwe Segese Nyakafuru Shenda Nyakasaluma Nyambogwe	
<b>Shinyanga</b>	Mwakitolyo Mwime Mwabomba	Mwakitolyo Mwime Mwabomba	
<b>Mbeya</b>			Makongolosi Matundasi Itumbi Ifumbo

The selection of these Tanzanian regions as case studies for ASGM, and ASGM itself as a case study for Sustainability Transitions, has been essential. The sites represent both mature and emerging ASGM operations, offering insights into how transformations unfold across different contexts. Simultaneously, examining similar questions across culturally and geologically diverse areas within Tanzania has provided valuable comparative depth enhancing the validity of the findings and contributing to the identification of novel insights (Marcus, 1995; Yin, 2006, 2017).

Tanzania serves as a critical context for addressing questions related to mercury, cyanide, and sustainability transitions and development. This is due to several factors, including the sector's economic significance and its support of a large segment of the population. Additionally, Tanzania possesses a comparatively mature and formalized legal framework for ASGM relative to other sub-Saharan African countries.

Importantly, this research was conducted during a pivotal period, coinciding with implementation of the National Action Plan by the Tanzanian government (2021–2025) aimed at reducing mercury use, with the upcoming 2030 deadline extension aiming at phasing out its use. ASGM continues to be a vital sector for regional economic development, while simultaneously contributing significantly to environmental degradation.

While evolving regulatory frameworks and technological transformations render each national context distinct, the persistence of mercury use despite the relative maturity of Tanzania's regulatory framework makes it a strategic entry point for understanding how regulatory reform interacts with technological transitions in resource-dependent economies.

## 3.5 Limitations

This section reflects on the methodological and representational limitations inherent in the research design, data collection, and analytical choices adopted in this thesis. The qualitative, mixed-methods, and case-based design prioritizes depth of socio-technical analysis over statistical generalizability or population-level inference to the wider ASGM population in Tanzania. Both the quantitative and qualitative data draw on relatively small samples, and the purposive and snowball sampling strategies employed do not allow for representative inference. However, by intentionally over-representing specific groups, such as entrepreneurs, the research enabled deeper analytical comparison and the identification of relationships and patterns rather than prevalence. Empirically, while the study is limited to a single-country case, it spans multiple regions, mining areas, and stakeholder groups selected to capture spatial, geological, and institutional diversity, supporting analytical rather than empirical generalization.

A further limitation concerns analytical boundaries: the thesis does not evaluate or propose technical or engineering solutions, nor does it directly measure mercury flows, environmental contamination, or extraction efficiency, relying instead on expert accounts for these dimensions. Future research integrating mineral engineering and geoscientific analysis with social inquiry would therefore be particularly valuable.

Finally, the research may have been influenced by my positionality and by language mediation; these challenges were addressed through sustained reflexivity, close collaboration with research assistants and local scholars, and triangulation across methods and actors.

## 4 Situating ASGM in Tanzania

While ASM is broadly understood as a low-capital, labor-intensive activity involving basic technology to extract mineral resources, it often functions as an umbrella term encompassing a wide array of extraction practices, contributing to ambiguity in policy, regulations, and definitions (Hilson & Maconachie, 2020; Hilson & Potter, 2005; Pedersen, 2025). This definitional challenge arises from the heterogeneity of the sector, which spans informal, rudimentary operations to more structured entities with access to capital and machinery (Jönsson & Bryceson, 2009).

This ambiguity is also evident in Tanzanian legislation, where small-scale mining is defined through the holding of a Primary Mining License (PML). The 2010 Mining Act classifies small-scale mining as involving capital investment below US\$100,000 (URT, 2010:11). However, the 2019 amendment revised this threshold to US\$5 million (URT, 2019b:17).

Due to the informality of the sector and varying classifications across countries, the global number of ASM participants remains uncertain. Estimates suggest up to 50 million people are engaged in ASM worldwide, with as many as 20 million in Africa (Fritz et al., 2018; Hilson & Maconachie, 2020; Hruschka, 2025). This stands in stark contrast to large-scale mining, which employs only 2.5 million individuals globally (Hilson & Maconachie, 2020).

ASGM represents the largest subsector within ASM, employing over 18 million people and accounting for approximately 20% of global gold supply (Hruschka, 2025). Tanzania hosts one of the world's largest ASGM sectors, employing over one million people and indirectly supporting the livelihoods of an estimated seven million others. This means around 13% of Tanzania's population benefits directly or indirectly from the sector (URT, 2020a:i).

### 4.1 Technology and practices in ASGM

The economic and sustainability dimensions of ASGM are intrinsically linked to its modes of extraction. Two principal methods are commonly employed: hard rock underground mining and surface extraction of alluvial and eluvial deposits containing secondary ore (Fritz et al., 2018; Mutemeri et al., 2024). In underground mining, gold is typically extracted using chisels, hammers, and, where available,

compressors and explosives. These tools are used to open pits—usually one or two meters squared—that can reach depths of up to 100 meters (**Figure 3**). In more advanced operations, open-pit mining is mechanized through the use of excavators. Once the ore is extracted, it is packed into 25 kg bags and transported for processing.



**Figure 3.** ASGM shaft in Geita featuring a generator-powered electric winch used for hoisting miners and ore. Behind the shaft are bags of ore and sizeable piles of tailings. Author's photo.

Processing begins with coarse crushing, either manually with hammers or using jaw crushers. The ore is then pulverized into fine powder using ball mills. Concentration is achieved through gravity methods such as sluicing, where water and crushed ore are poured down a tilted mat-covered wooden slope. The heavier gold particles become trapped in the mat, while lighter material is washed away. The trapped concentrate is then washed and further refined through panning. At this stage, mercury is introduced to bind with gold particles, forming an amalgam. This amalgam is burned—typically in open air—causing the mercury to evaporate and leaving the gold behind (**Figure 4**). Depending on the characteristics of the ore, this process can recover between 30–40% of the gold, leaving the remaining amount within the tailings (Martinez et al., 2021; URT, 2020a).

In contrast, alluvial operations focus on near-surface deposits (within two meters of the surface), where coarser gold particles or nuggets are present. These operations often bypass the crushing stages and sometimes omit the mercury amalgamation process entirely.

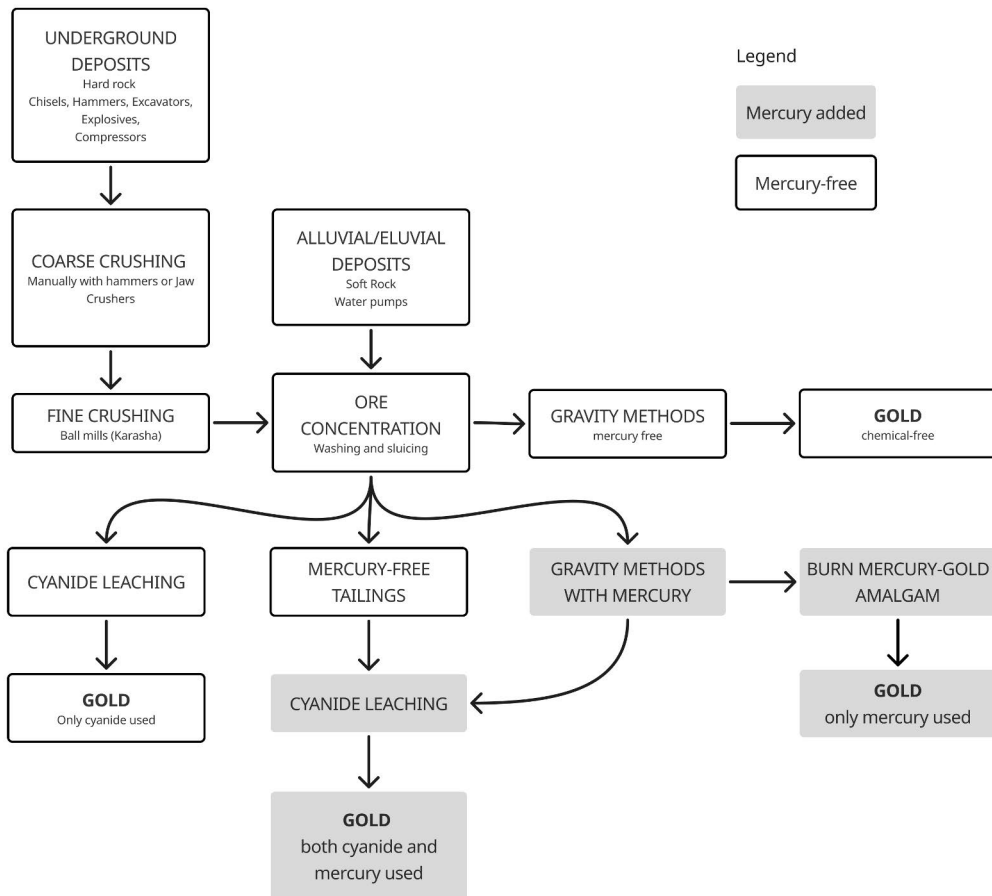
Despite both methods concentrating gold within the ore, significant quantities, especially finer particles, remain in the tailings. This includes tailings left after mercury-based processing. Often considered waste in the past by ASGM, tailings have gained value with the advent of cyanide leaching technology, which allows for the extraction of residual gold. While cyanide leaching was developed in the 19th century for LSM, it only became prominent in Tanzania's ASGM sector in the 2000s (Merket, 2019; Verbrugge and Geenen, 2020). This delay is largely attributed to the higher capital investment and technical knowledge required, in contrast to mercury or gravity-based methods. Cyanide leaching can extract 60–90% of the gold from ore, including lower-grade and finer particles (Drace et al., 2016; Hiji and Maganga, 2015; Veiga et al., 2014). The technology also enables the processing of larger ore volumes, making it significantly more efficient than mercury amalgamation. At the same time, scale is essential, as these operations are profitable only with several tonnes of ore.

The expansion of cyanide leaching in the 2000s has been supported by increased capital flows and a broader trend towards mechanization, particularly the introduction of ball mills (Hilson & Monhemius, 2006; Kabunga & Geenen, 2022; Manzila et al., 2022; Merket, 2019; Verbrugge et al., 2021).

Cyanide leaching operations vary widely in capital intensity, environmental impact, and applied technology. In Tanzanian ASGM, the two predominant techniques are VAT leaching and Carbon-in-Pulp (CIP). VAT leaching involves filling multiple tanks—typically two meters in diameter—with ore and tailings. These are percolated with a solution comprising water and chemicals such as sodium cyanide, lime, caustic soda, ammonium sulfide, sodium nitrate, hydrogen peroxide, and lead nitrate. Gold is then adsorbed by activated carbon and later extracted

through electrolysis in elution plants, where it is smelted into bullion that is typically sold at government-established mineral markets.

CIP technology follows a similar chemical process but requires more sophisticated and costly equipment, and can process larger ore volumes. As a result, CIP is typically associated with medium-scale mining rather than ASGM (Drace et al., 2016; Veiga et al., 2014). Consequently, CIP plants are few in number and often operated by government-linked entities (e.g., STAMICO), whereas VAT leaching plants are far more common (Kinyondo & Huggins, 2020, 2021).



**Figure 4.** Extraction processes in ASGM in Tanzania. Stages involving mercury addition and subsequent stages where mercury remains (e.g., use of mercury-containing tailings, burning of gold-mercury amalgam) are highlighted in grey. In this figure, the cyanide leaching process is presented as encompassing the subsequent elution stage. Author's elaboration.

## 4.2 Mercury and cyanide: sustainability and regulations

Both mercury amalgamation and cyanide leaching present significant health and environmental hazards (**Table 6**). In Tanzania, ASGM is estimated to use roughly 35 tonnes of mercury annually, compared to global ASGM emissions accounting to approximately 2000 tonnes per year (Keane et al., 2023; UNEP, 2019).

Studies suggest that between 25–33% of miners in Tanzania suffer from moderate chronic exposure to metallic mercury vapor, which can lead to neurological damage and birth defects (UNEP, 2019; URT, 2020a). In absolute terms, this could affect approximately 260,000 miners if a conservative estimate of 800,000 ASGM workers in Tanzania is assumed (URT, 2020a). These figures are alarming and indicate that mercury-based gold extraction contributes to a humanitarian and environmental crisis, rather than merely posing occupational hazards (URT, 2020a).

**Table 6.** Indicative comparison between mercury and cyanide in ASGM

Dimension	Mercury	Cyanide
<b>Capital requirements</b>	Tens of USD	Thousands of USD
<b>Scale of operation</b>	Artisanal and small-scale, easily adapted to individual or informal groups	Requires larger volumes of ore and is better suited to semi-industrial operations
<b>Time from extraction to revenue</b>	Hours, allowing rapid monetization	Weeks, due to longer leaching cycles and material preparation
<b>Machinery and technological requirements</b>	Minimal: artisanal tools and rudimentary equipment	Higher: excavators, ball mills, leaching tanks, and other industrial machinery necessary to process sufficient ore
<b>Human health impacts</b>	Long-term effects; chronic exposure leads to neurological and developmental harm	Acute toxicity; exposure can cause immediate or near-immediate death
<b>Environmental impacts</b>	Severe and long-lasting; mercury persists for centuries and bioaccumulates globally	Cyanide degrades more rapidly in the environment; however, spills can cause short-term but catastrophic ecological damage

Internationally, the 2013 Minamata Convention represents the strongest initiative aimed at broadly reducing, and where possible eliminating, mercury use. The convention identifies four worst practices that are particularly detrimental and

require urgent elimination (UNEP, 2018, 2023). In Tanzania, three of these practices are widespread: open burning, open burning in residential areas, and conducting cyanide leaching on mercury-contaminated tailings (UNEP, 2019; URT, 2020a). The mercury–gold amalgam burning stage is especially harmful because it releases toxic mercury vapor into the air, posing immediate inhalation risks for nearby miners and allowing the contaminant to travel across regions via atmospheric and precipitation processes (Jönsson et al., 2013; Malone et al., 2023; Oakley, 2023; UNEP, 2018).

Large amounts of tailings are produced annually from mercury amalgamation—estimated at 1 to 1.9 million tonnes in Tanzania alone. These tailings contain 64% of the total mercury originally applied, while the remaining 36% is released into the air due to evaporation or during burning to separate gold from mercury (URT, 2020a). Mercury concentrations in the tailings have been reported to range from 0.2 to 232 mg/kg, up to several thousand times higher than levels in natural soils, posing significant risks to humans, wildlife, and the environment (URT, 2020a). When mercury-contaminated tailings are subjected to cyanide leaching, the process favors the formation of methylmercury, a compound more toxic than elemental mercury due to its greater bioavailability to humans and ecosystems. This risk is further heightened in cyanide leaching operations lacking adequate tailings storage facilities, as methylmercury may evaporate, contaminate soil, and potentially infiltrate drinking water sources (Oakley, 2023; UNEP, 2018; URT, 2020a).

The final practice identified as requiring urgent elimination is whole ore amalgamation, whereby mercury is added to the entire excavated ore rather than first concentrating it through gravity methods. However, this practice has not been observed in Tanzania (Keane et al., 2023; URT, 2020a).

The Minamata Convention urges signatory countries to implement their own National Action Plans (NAP) to achieve these goals. Tanzania implemented its NAP for the period 2020–2025 with the aim of reducing mercury emissions by 30% (URT, 2020a), and more recently the Vice President’s office announced a new goal of phasing out mercury by 2030 (Mwendapole, 2024). The NAP builds on several strategies undertaken since 2009 to reduce mercury use, most significantly including the Sustainable Management of Mineral Resources Project (SMMRP) between 2009 and 2018, led by the World Bank. The project aimed to improve socio-economic, environmental, and governmental conditions surrounding mining in Tanzania, with a strong emphasis on reducing mercury use (Kinyondo & Huggins, 2021; URT, 2020a; World Bank, 2019).

These policies have translated, together with several smaller initiatives, in strategies promoting a range of alternatives to mercury, including gravity-based methods using borax, separation with magnets, and support for the retort to trap mercury vapor (Jönsson et al., 2013; Davies, 2014; Esdaile & Chalker, 2018; Geenen & Bikubanya, 2024; Veiga & Fadina, 2020). Although these alternatives are

environmentally sound, adoption by miners has remained limited due to concerns about lower gold recovery rates as well as social and practical constraints. While the Minamata Convention does not explicitly identify cyanide leaching as an alternative to mercury in ASGM, both Tanzania's NAP and the SMMRP have provided financial and technical support for its development and expansion (URT, 2020a; World Bank, 2019). By drawing from the empirical material from the articles, the following chapter (section 5.3) examines in greater detail the key strategies emerging from the SMMRP and NAP, highlighting the outcomes of these government-led policies and illustrating how they aim to foster alternative innovation pathways in ASGM that reduce reliance on mercury.

Despite its relative efficiency, the use of cyanide leaching in mining remains controversial due to significant challenges to health and the environment, even when it is not applied in combination with the mercury amalgamation method. Sodium cyanide is a highly toxic substance that poses serious risks to human health and wildlife by potentially reacting to produce deadly hydrogen cyanide gas. Although hydrogen cyanide degrades readily through chemical and biological processes—a significant advantage compared with mercury, which can persist in the environment for centuries (Manzila et al., 2022)—cyanide may form more environmentally harmful substances by bonding with other elements, including mercury itself (Drace et al., 2016). Inadequate waste and tailings management further exacerbate environmental challenges; for example, the improper disposal of cyanide-contaminated tailings by LSM companies into water bodies repeatedly harms ecosystems (Drace et al., 2016). Such challenges have led some countries to ban cyanide leaching for gold mining (Bocse, 2021; Hilson & Monhemius, 2006).

A UNEP-led report advises against the adoption of this technology by artisanal miners, recommending its application only in more advanced small-scale operations (Stapper et al., 2021). In Tanzania, it has been reported that most workers are unfamiliar with safe practices (Manzila et al., 2022; Nyanza et al., 2017). Moreover, while CIP holders are required to have tailings storage facilities, VAT leaching in ASGM does not impose the same requirement. Although CIP plants use higher concentrations of sodium cyanide, the chemicals employed in both processes are similar. A further concern regarding the sustainability of this technology relates to employment; the potential of ASGM to create jobs may be threatened by the more mechanized and efficient technology that extracts more gold with less labor (Malone et al., 2023; Stapper et al., 2021; URT, 2020a).

Broadly, despite potential risks, cyanide leaching is considered a lesser evil compared with mercury in ASGM due to improved possibilities for the safe disposal of tailings (Manzila et al., 2022; Drace et al., 2016; Veiga et al., 2014). Moreover, the absence of an equivalent convention targeting cyanide strengthens the urgency of eliminating mercury practices over cyanide alternatives.

One organizational structure in ASGM that could promote mercury abatement and prevent significant employment losses is the co-existence model. This is an organizational structure where artisanal miners work in collaboration with conventional medium- or large-scale companies, with a clear division of labor: artisanal miners extract the ore while companies process it (Veiga & Fadina, 2020). This can be structured in several ways. In one case, miners can own the land or mining licenses and sell unprocessed ore to companies who utilize cyanide leaching (Aubynn, 2009; Bansah et al., 2018; Malone et al., 2023; Rodríguez-Novoa & Holley, 2023; Veiga & Fadina, 2020). For example, in Peru and Colombia, some ASGM miners extract and grind ore using simple tools before selling it for cyanide processing by larger mining companies (Veiga & Fadina, 2020). Alternatively, mining companies may own land or mining concessions. This is illustrated by cases in Venezuela and Nicaragua, where ASGM cooperatives organize by gathering ore and processing it at small cyanide plants under concession from mining companies while receiving technical assistance (*ibid.*). These efforts require transparent sampling of the ore, for example by an independent institution or company to ensure trust and feasibility. Overall co-existence organizational structures offer two main benefits. First, by selling unprocessed ore, miners avoid mercury amalgamation and the associated environmental contamination. Second, by not handling chemical processing directly, artisanal miners reduce the risks linked to mismanagement of cyanide leaching (Stapper et al., 2021; Veiga & Fadina, 2020). However, the universal adoption of the co-existence model remains uncertain and controversial, as successful implementation requires significant transformations in capital, logistics, organization, culture trust, and even changing hierarchies and inequalities—factors that cannot be taken for granted (Malone et al., 2023; Veiga & Fadina, 2020).

Finally, the intrinsic characteristics of cyanide technology also facilitate objectives beyond environmental sustainability, including increased transparency, formalization, revenue capture, and domestic value addition (Huggins & Kinyondo, 2019; Kinyondo & Huggins, 2019; Pedersen, 2025; Pedersen et al., 2022). Formalization aims to integrate ASGM into existing legal frameworks, while resource nationalism seeks to strengthen state control over natural resources and enhance rent capture (Kinyondo & Huggins, 2019). For example, Pedersen (2025) demonstrates how the elution process centralizes and controls gold recovery, while producing more refined bullion and thereby generating greater domestic value addition than mercury amalgamation. Importantly, the state has supported the rapid expansion of elution facilities through an evolving regulatory framework that issues smelting and refining licenses to qualified operators (URT, 2010, 2019b). In this sense, regulatory reforms do not merely accommodate technological change for environmental objectives; they actively shape and promote the uptake of cyanide

leaching by embedding gold production within broader national strategies of formalization, revenue capture, and domestic value addition (Kinyondo & Byaro, 2024; Pedersen et al., 2022; Geenen & Bikubanya).

# 5 Empirical Analysis and Discussion

This chapter presents the empirical material that forms the basis of the doctoral thesis, combining qualitative and quantitative data within a narrative approach. It first introduces cyanide and mechanization as emerging niche-innovations and examines their integration into incumbent mercury-based extraction practices (Article I). The chapter then outlines policy strategies designed to reduce mercury use by supporting cyanide leaching, while also identifying the key factors that hinder this transition (Article II). It subsequently explores the knowledge creation processes involved in the mercury–cyanide transition (Article III). Finally, the chapter discusses how the empirical findings reveal inequalities that arise across these processes and within the three articles.

## 5.1 Mechanizing ASGM

Although ASGM has traditionally been a low-technology sector, a recent surge in mechanization marks a substantial transformation and a notable innovation within the industry. In Tanzania this shift is visible in the spread of ball mills, jaw crushers, and excavators, which have materially increased sector productivity. Cyanide leaching has emerged as a niche-innovation and has become a dominant technology since. Such mechanization has both enabled and necessitated larger investments in operations.

Entrepreneurs have adopted these technologies to scale up production and increase returns. They cite faster processing, higher profits, and reduced reliance on workers—which some describe in the interviews as untrustworthy—as key benefits. At the same time, mechanization creates clear costs and tensions. Entrepreneurs report high capital outlays for machinery relative to the low wages paid to workers, while the latter report declining employment opportunities. This resonates with the Kahama survey, where 51% of the sample miners identified finding work as a principal challenge. The impacts of mechanization extend beyond immediate employment statistics and operational expenses. These technologies—and cyanide leaching in particular—can be applied to restructure hierarchies and organizational relations, thereby placing additional pressure on low-paid workers.

## 5.2 Organizational practices (Article I)

Emerging technologies and mechanization are reshaping organizational practices (OPs) within ASGM. The evidence indicates that mechanization, with cyanide leaching as an important technological niche, is reconfiguring production organization incrementally by building on existing structures and hierarchies rather than wholly displacing them.

Mechanization tends to substitute for manual labor following similar extraction steps: excavators replace diggers and enable open-pit excavation instead of shafts; ball mills and jaw crushers supplant manual rock crushing and increase efficiency. Cyanide leaching is potentially more disruptive in technological and sustainability terms, since it can replace mercury amalgamation. In practice, however, cyanide is not simply a substitute for mercury, making how the technology is applied and integrated within extraction chains critical in determining its impact on sustainability.

I categorized the extraction practices I observed in the field into five OPs. The first is *outsourcing*, which emerged prominently in the narratives of miners and other stakeholders I interviewed across the country. Initially, a few entrepreneurs recognized the potential of recovering additional gold from tailings already processed with mercury by applying cyanide leaching, a method that was still uncommon at the time. This allowed them to acquire discarded tailings at little or no cost and reprocess them with cyanide. As the use of cyanide spread, however, tailings ceased to be treated as mere waste and instead became a negotiated commodity. While this practice still exists, it is less common than OPs which have evolved from it.

One of these is what I term *concessions*. Here, license or pit holders invite miners to extract ore from lease areas under various agreements. Entrepreneurs commonly supply basic extraction tools, including mercury in exchange for the resulting tailings and sometimes a share of gold recovered. Referred to by miners as the “local way,” this arrangement enables individuals without capital to mine while providing entrepreneurs and claim holders with payment and risk mitigation. This expression highlights the high informality involved in these practices, as they often involve payments in shares and flexible terms.

The third OP is *pooling*. In this arrangement miners control the whole extraction chain. The ore is extracted and processed using mercury amalgamation, with careful accumulation of tailings. When miners secure sufficient capital and ore tonnage, they bring these tailings for cyanide processing or operate their own cyanide plant. Because cyanide treatment requires substantial feedstock and a minimum grade to be profitable, pooling heavily depends on miners aggregating material and capital.

A variant I label *pooling mercury-free* follows the same aggregation logic but omits the mercury phase as miners process material directly with cyanide. This

variant typically requires higher capital and therefore tends to be adopted by operations that can forgo the quick cash that mercury amalgamation provides. Notably, capital for mercury-free pooling often derives from revenue earned in mercury-based activities; in other words, operations which are technically mercury-free are frequently financed through proceeds of mercury use, underscoring mercury's continued centrality. While this OP resonates with the co-existence model, in pooling mercury-free miners have control over the whole extraction process.

The final OP is *insourcing*, which also employs cyanide directly but differs in scale, frequency, and organization. Insourced operations process material more frequently (e.g., every two weeks), shortening the production-to-revenue interval. They rely on larger internal capital or access to loans, are more formally structured (with regular wages and less reliance on informal payment arrangements) and typically deploy greater mechanization—more excavators and improved processing equipment—enabling higher output and faster throughput.

The OP categorization is not rigid: organizations frequently blend practices and they transfer capital between them, as shown in the pooling mercury-free case. Nevertheless, taken together, these OPs point to a trajectory shaped by capital and mechanization: as access to capital expands, organizations are increasingly able to bypass the mercury phase. The classification highlights a spectrum in which the need for local arrangements diminishes as insecurity declines and capital increases. Earlier OPs reduce immediate risk, since mercury amalgamation methods generate quick revenue and remuneration for labor. Informal arrangements further diffuse risk across multiple shareholders, rather than centralizing responsibility in a single entrepreneur. They also allow production to occur before wages or shares are distributed—an obstacle less significant for more formalized mining groups with greater access to capital.

Cyanide adoption builds on existing practices and, crucially, on the capital flows that mercury amalgamation generates. This pattern demonstrates that the niche has advanced through incremental rather than radical innovation: cyanide leaching allows wealthier entrepreneurs to leverage existing infrastructure, knowledge, machinery, and tailings to capture additional value.

The dynamic interplay between the emerging niche (cyanide leaching) and the incumbent regime (mercury amalgamation) produces continual reconfiguration of organizational practices; these OPs are the crystallizations of those interactions at particular moments. Pressures to reduce mercury use are limited, and miners are incentivized by economic gains and typically prioritize income and security over environmental considerations. Thus, cyanide technologies are adopted primarily to maximize economic returns and reduce risk rather than to improve sustainability. These motives markedly shape the form and stabilization of OPs, and consequently,

the incremental integration of cyanide can prolong the persistence of unsustainable practices such as mercury use, leading to one of the worst environmental practices in ASGM identified by UNEP (2019). As the outsourcing, concessions, and pooling OPs present this worst practice, they cannot be considered environmentally sustainable (**Table 7**). The only OPs which avoid the use of mercury entirely, are pooling mercury-free and insourcing. The latter however, presents fewer employment opportunities due to the high mechanization rate, threatening to displace workers within the sector. Consequently, the pooling mercury-free is the only OP which avoids the use of mercury and retains similar employment numbers. However, this OP is uncommon in Tanzania, as it requires more capital, organizational capacity, and trust than other OPs using mercury. In addition to pooling mercury-free and insourcing, Table 7 shows how the co-existence model also provides a mercury-free approach. Yet, the latter requires significantly higher mechanization levels, trust, and capital, which make it unfeasible to upscale. The next section thoroughly discusses the characteristics, opportunities, limits, and challenges of this model and its impact on sustainable development.

**Table 7.** Key characteristics and sustainability of organizational practices and the co-existence model.

	<b>Pre-cyanide ASGM</b>	<b>Outsourcing</b>	<b>Concessions</b>	<b>Pooling</b>	<b>Pooling mercury-free</b>	<b>Insourcing</b>	<b>Co-existence</b>
<b>Mechanization level and output</b>	Low	Medium	Medium	Medium	Medium	High	High
<b>Processing</b>	Mercury	Mercury and Cyanide	Mercury and Cyanide	Mercury and Cyanide	Cyanide	Cyanide	Cyanide
<b>Frequency of cyanide leaching</b>	-	-	-	2 to 6 months	4-8 weeks	1-4 weeks	1-2 weeks
<b>Capital required</b>	Low	Low	Low	Medium	High	High	High
<b>Trust required</b>	Low	Medium	Low	Medium	Medium	Medium	High
<b>Expected environmental sustainability</b>	Low	Very low	Very low	Very low	Medium	Medium	Medium
<b>Employment (socio-economic sustainability)</b>	Medium	Medium	Medium	Medium	Medium	Lower	High

Overall, these findings underscore the importance of ensuring cultural, organizational, and economic viability to support broader local adoption of pooling mercury free. Further research is needed to examine how this OP could be scaled more widely.

More broadly, the empirical evidence suggests that the ability to leverage incumbent infrastructures, knowledge, and technologies within emerging niche-innovations provides a significant advantage for actors promoting such niches. This supports the argument that niche–regime compatibility can be a decisive factor in advancing a particular niche-innovation over more radical yet less compatible alternatives (Andersen et al., 2021; Loorbach et al., 2017; Ingram et al., 2015). Moreover, the findings highlight that although new technologies can enable transformations of existing hierarchies and disruptions of unsustainable systems, they can also generate new forms of unsustainable lock-in (Arhin & Behuria, 2025; Chlebna & Suitner, 2025; Gaillard et al., 2025; Grillitsch & Sotarauta, 2025; Klitkou et al., 2015; Sotarauta & Grillitsch, 2023a).

Given these findings, targeting OPs configurations can be a valid strategy in yielding more sustainable development. These findings call for a need to support pooling-mercury free strategies, and in the next section, I examine how pressures to promote mercury-free arrangements are emerging and what forces resist these changes.

### 5.3 Pushing and resisting mercury-free gold extraction (Article II)

Some forms of mercury free processing, including pooling-mercury free and co-existence models, offer a desirable pathway to ending mercury use. The government has sought to advance this goal by promoting cyanide leaching as a substitute for mercury, sometimes through projects resembling co-existence models (URT, 2020a). This section examines five elements that emerged from the data—including interviews with government officials and critical document analysis—and considers the resistance, frictions, and challenges they encounter on the ground.

#### 5.3.1 Transforming the regime: promoting mercury-free ASGM through policy

Article II examines government strategies that promote cyanide leaching technology as an alternative to mercury-based amalgamation in Tanzania. These strategies align closely with the National Action Plan (NAP), which reflects the Minamata Convention on Mercury. However, this policy direction builds on earlier initiatives, particularly the World Bank–funded Sustainable Management of Mineral Resources

Project (SMMRP), which prioritized objectives such as resource nationalism, formalization, domestic mineral value addition, and the introduction of best practices through the up-scaling of extraction into medium-scale mining (Kinyondo & Huggins, 2019; URT, 2020a; World Bank, 2019).

In practice, this approach has involved support for mechanized equipment, with CIP technology at its core, operated by the State mining corporation (STAMICO), in an effort to abandon less effective methods such as mercury amalgamation (Kinyondo & Huggins, 2019). The NAP recognizes that, although demonstration centers were initially developed to advance broader strategic objectives, support for these technologies also aligns with environmental goals, including mercury abatement, as well as socio-economic objectives such as poverty reduction (URT, 2020a:21).

As a result, demonstration centers reflect the influence of multiple policy agendas and respond to diverse and sometimes competing objectives. They operate under both internal and external pressures, illustrating the central role of the state in balancing environmental protection, developmental priorities, and economic interests. Environmental concerns were not the original priority of these models; nevertheless, their organizational design closely resembles co-existence models identified in other contexts (Aubynn, 2009; Veiga & Fadina, 2020). In these arrangements, the centers provide processing technology that enables miners to extract large volumes of ore for a fee (Kinyondo & Huggins, 2019).

In Article II, I identify five key strategies that support such co-existence arrangements and the broader expansion of cyanide technology in relation to mercury use:

1) Training and technology adoption. Both the NAP and SMMRP highlight training miners to adopt alternative technologies, with cyanide leaching presented as the main alternative to mercury. This training is delivered through demonstration centers and related initiatives across the country.

2) Demonstration centers. These centers go beyond training and include fully equipped CIP plants, five of which have been established nationally. They enable small-scale miners to process ore or tailings for a fee, offering a mercury-free alternative. The centers also aim to build technical expertise and attract investment in similar private plants.

3) Access to finance. The government has supported miners with grants and loans to facilitate technological upgrading and production scaling. For instance, in 2015 the SMMRP offered loans of up to US\$100,000, while the 2020 NAP allocated 7 billion TZS Shillings (approximately US\$3 million) to licensed small-scale miners.

4) Regulation of inputs. The government has worked to facilitate access to cyanide while regulating mercury supply. In 2022, it introduced a price cap of

600,000 TZS Shillings per 50 kg barrel of sodium cyanide in response to shortages. Regulations introduced in the early 2020s also aimed to control mercury sales, requiring buyers to hold registered licenses.

5) Support for collective organization. The government has promoted the formation of “making groups” (URT, 2020a:21) to enable miners to pool resources, achieve economies of scale, and afford technologies such as cyanide leaching. Miners’ associations, especially the Federation of Miners Association of Tanzania (FEMATA), play a central role in this strategy. Although established in 1987, FEMATA has gained increasing importance in recent years as a state-supported federation.

Taken together, these strategies reflect a consistent emphasis on up-scaling production and expanding cyanide leaching.

### 5.3.2 Barriers to co-existence models and transitions to mercury-free practices

The state’s efforts to promote a transition away from mercury through policy translate into upscaling production, providing investment, and transforming behavior through incentives and regulation. However, these objectives encounter substantial resistance, which I summarize in Article II as four barriers: mistrust, access to capital, inconsistency of time and scale (including risk aversion), and fragmentation of production.

The most common OPs explored in Article I, have evolved to overcome some of these barriers. For example, as previously shown in **Table 7**, OPs tend to minimize reliance on trust between miners in ASGM, whereas co-existence models require higher levels of trust.

Both quantitative and qualitative data show that a lack of trust is a key barrier in implementing co-existence models that depend on non-transparent transactions. In the Kahama survey, miners’ associations, which are key stakeholders in these transactions, are unknown to most miners. Most miners feel unrepresented by their agendas, partly because they are influenced by the state (e.g., the promotion of mercury abatement through the establishment of CIP plants). The qualitative data shows mistrust also emerges within mining businesses. Entrepreneurs report difficulties in trusting workers due to fears of theft or absenteeism, while workers express dissatisfaction with compensation and limited confidence in their employers. Similar tensions exist between groups and businesses, particularly in the buying and selling of tailings. Narratives of deception are widespread, with miners sometimes manipulating samples by concentrating high-gold-content material where buyers are likely to test. Pervasive mistrust obstructs the collaboration required for environmentally sustainable ASGM practices. Co-existence models, depend on

transactions involving unprocessed ore or mercury-free tailings, which contain uncertain amounts of gold and therefore require high levels of trust. In contrast, mercury-based extraction, even if imprecise, provides miners with rapid indications of gold presence in ore or tailings. These dynamics illustrate how mercury functions as a form of security for miners and mitigates the risks associated with non-transparent transactions.

The second barrier is limited access to capital, a longstanding challenge in ASGM that has become increasingly critical as mechanization and more complex extraction processes expand. Whereas earlier forms of ASGM, as well as other sectors in Africa, could often rely on informal microcapital, the larger sums now required exceed the capacity of such arrangements. Formal financial institutions remain inaccessible because they demand collateral and feasibility studies, such as geological assessments, that miners typically lack. Moreover, miners struggle to demonstrate and articulate extraction feasibility and their local knowledge. As a result, they often rely on brokers, whose loans come with exorbitant interest rates and unfavorable conditions. Even government grant schemes, introduced as an alternative, were reported by officials and miners to have been misappropriated, resulting in the premature termination of the scheme. The persistent lack of capital thus remains a critical obstacle to scaling production and investing in machinery required for cyanide leaching.

A third barrier arises from behavioral challenges stemming from insecurity in accessing capital, which I term the ‘inconsistency of time and scale.’ Time plays a central role in ASGM technology and revenue models. Mercury-based methods allow miners to process small quantities of ore profitably within hours, providing immediate returns. By contrast, cyanide leaching requires large quantities of ore and substantial upfront investment, creating long delays before revenue is generated. This investment-revenue gap, often lasting several months, discourages adoption of mercury-free methods, particularly when access to capital is restricted. This uncertainty motivates miners to accumulate large amounts of tailings after the mercury amalgamation process to reach economies of scale (**Figure 5**).

While careful planning and management could significantly contribute to mitigate risk, the cultural and psychological orientation of ASGM communities favors immediate, tangible rewards over uncertain, long-term gains. This “time-discounting” behavior reinforces reliance on mercury, even among miners who could occasionally afford cyanide leaching, as the future is perceived as distant and insecure in a low-trust, unpredictable sector.

The fourth barrier arises from organizational practices that fragment production through sharing arrangements, making mercury the only accessible extraction technology at this scale. Under these agreements, and for taxation purposes, extracted ore is often divided among shareholders. Businesses that control mining

areas typically distribute ore shares as payment to workers and shareholders, while taxes are sometimes collected in ore form, which is considered more traceable than cash transactions. These practices distribute both revenues and risks but also disperse production. In many cases, the pit owner receives 40–50% of the ore, with the remainder allocated to workers, license owner, and other shareholders. A common arrangement also involves individuals purchasing 25 kg sacks of ore from the companies extracting the ore, which can only be processed profitably with mercury. Such fragmentation substantially reduces opportunities for up scaling operations and for collective investment in alternative processing technologies.



**Figure 5.** Gold extraction through cyanide. Accumulated mine tailings surrounding the VAT leaching tanks in a gold plant in Kahama District, 2023. Author's photo.

Taken together, these factors present significant obstacles to the development of a mercury-free ASGM sector based solely on cyanide models. Large-scale processing facilities, such as VAT cyanide leaching plants or CIP, remain largely inaccessible to most miners and organizations. Even when miners are able to accumulate sufficient ore, the barriers outlined in this section suggest that processing in these facilities typically occurs only after mercury amalgamation. In the case of CIP, its higher efficiency enables miners to bring tailings processed both through

mercury and VAT leaching. This stands in sharp contrast with the initial objectives motivating the establishment of these plants in the first place. The financial and infrastructural inaccessibility of these plants also imply that only few entrepreneurs were aware about the CIP plants' existence.

These social and behavioral challenges associated with scaling up production illustrate how conditions of uncertainty—combined with limited capital and low levels of trust—can foster seemingly irrational, time-discounting behavior that undermines economically and especially environmentally optimal outcomes (Agneman et al., 2023; Assan & Kumar, 2009; de Bruijn & Antonides, 2022; Morton, 2024; Mullainathan & Shafir, 2013; Ostrom, 1990).

Moreover, the findings underscore the ambiguous roles played by institutions such as the state and miners' associations, whose conflicting interests give rise to ambivalent and sometimes contradictory strategies (Diamond, 1997; Igoe, 2003, 2024; Odeh, 2012; Omede & Bakare, 2014). In this sense, the results suggest that the uptake of cyanide leaching—and the supporting industries that further refine gold, such as elution plants—serves not only environmental objectives but also broader resource-nationalist strategies, enabling greater state control over gold production and domestic value addition, rather than solely focusing on reducing mercury use.

These tensions—shaped further by external pressures, including the Minamata Convention and the influence of foreign capital—have shaped policy directions and implementation strategies, producing uneven outcomes and inconsistent support for different groups (Johnstone & Newell, 2018; Swilling et al., 2016).

Overall, the results reinforce scholarship on socio-technical regimes in African contexts, and the global South more broadly, which highlights how power relations, institutional dynamics, and interactions among regime actors are central to understanding both technological and societal change as well as resistance to more environmentally sustainable pathways (Ghosh & Mguni, 2026; Ghosh et al., 2021; Johnstone & Newell, 2018; Ramos-Mejía et al., 2018; Swilling et al., 2016).

## 5.4 The landscape and the natural environment (Article III)

In examining the mercury–cyanide transition within the ST and MLP frameworks, Articles I and II addressed the roles of the niche and the regime, respectively. I now turn to the final analytical level—the landscape—drawing on the concepts associated with it as outlined in the analytical framework. The landscape represents a further dimension of the mercury–cyanide transition. The landscape introduces an additional dimension to the mercury–cyanide transition. Within ASGM, elements such as the gold and mercury markets and global political processes, including the Minamata

Convention, form part of this level. Article III focuses on a different set of landscape dynamics, namely the natural and material environment.

The analysis of this article has been devoted to the significance of the material environment and miners' relationship with it. While miners are socially embedded, they are also situated within the non-human environment, where varying natural characteristics demand different extraction methods. These interactions intersect with the use of technology and human labor.

Within this context, understanding how miners create knowledge is essential, as it is the means through which they interpret the natural environment, available technologies, and, ultimately, affects their behavior and extraction practices. It is therefore important to examine miners' knowledge of resource extraction: the material properties of the environment, the location of deposits, and the technologies through which extraction can occur.

By weaving empirical data together with existing literature and frameworks on knowledge creation, these processes can be organized into four categories: sensory learning, trial and error, the acquisition of STI-based knowledge, and social learning. Within the context of technological change and declining ore grades, miners draw on these forms of learning to adapt, maintain competitiveness, and pursue profitable extraction.

#### 5.4.1 Learning through the senses

Sensory knowledge—particularly sight, sound, touch, and smell—is central to locating and extracting gold, especially surface and near-surface deposits. Through visual observation, miners identify alluvial deposits by studying river flows and vegetation patterns. In some cases, quartz reefs appear as outcrops that can be followed during excavation. This was particularly evident in the data collected in the Lupa Goldfields area in Chunya.

Visual observation is also crucial in a second stage, when ore samples are tested. Miners commonly conduct a “local test,” crushing and panning ore to evaluate whether the gold content justifies extraction costs. These practices are supported by cultural-symbolic knowledge. For example, miners use specific vocabularies to describe different gold characteristics. When particles appear sticky after a local test, they are referred to as *mlenda*, the Swahili term for an okra-based soup. Such symbolic knowledge facilitates communication about mining conditions and articulates tacit, practice-based expertise learned through experience rather than formal education.

Sensory cues also inform miners about chemical toxicity. Chemists and miners working directly with cyanide recognize its effects through burn marks on the skin or by observing wildlife deaths near VAT leaching plants. However, sensory

knowledge faces clear limitations. Surface deposits are diminishing, reducing the reliability of such methods. Moreover, some technologies, such as mercury, present dangers that cannot be detected sensorially. Mercury is odorless, its vapor invisible, and its health effects long-term, making connections between cause and effect extremely difficult to establish sensorially.

In uncertain situations, and in the absence of direct evidence, miners sometimes turn to cultural beliefs or magic to explain geological inconsistencies and unexpected environmental changes beyond the reach of sensory interpretation.

#### 5.4.2 Learning through trial and error

Trial and error, or DUI knowledge methods, partly compensate for the limitations of sensory learning. In the absence of visible outcrops, miners engage in blind prospecting, digging pits without geological assessments. Although costly and environmentally damaging, this practice can yield results when pits are located in proximity of areas where gold has been previously extracted. Compared to geological surveys, which are prohibitively expensive at this scale, trial and error remains a more feasible option.

Similar practices are found in ore processing. Miners frequently use mercury, even when they acknowledge its limited effectiveness, as this can nevertheless yield gold recovery. Cyanide processing follows a comparable logic. Faced with uncertainty, miners often reprocess the same ore and tailings multiple times, as they observe continued gold recovery in subsequent rounds due to limited effectiveness of previous rounds.

Overall, the evidence indicates that miners prioritize labor-intensive experimentation over formal geological or chemical analysis, applying trial-and-error methods in both prospecting and processing. While these practices are often imprecise and environmentally harmful, they have generated sufficient economic returns to sustain their continued use. The reliance on labor rather than scientific testing reflects the relatively low cost of labor compared with formal geological or chemical analysis.

#### 5.4.3 Acquiring science- and technology-based knowledge

In recent years, traditional sensory- and trial-and-error-based knowledge has increasingly been combined with scientific and analytical approaches, particularly in relation to ore properties. New technologies have enabled miners to integrate traditional approaches with emerging innovations, such as affordable ore characterization tests that provide detailed information on geochemical properties. These tests allow miners to measure gold content and determine the presence and

quantity of secondary minerals. Mining operations are increasingly recognizing that a thorough understanding of mineral characterization is essential, as it directly informs the selection of chemicals for cyanide leaching and influences both the feasibility and profitability of extraction.

A second factor is the growing importance of science- and technology-based knowledge acquired from external sources. For example, some ASGM businesses have gained expertise from previous LSM companies operating in the area or from government agencies such as STAMICO, which conducts geological testing nationwide.

The presence of formally educated workers, particularly chemists, has also increased at mining sites. These workers are reported to overcome extraction challenges—such as managing secondary minerals—by applying complex chemical procedures that are difficult to identify through trial-and-error alone.

Nevertheless, trial-and-error practices persist, even in cyanide leaching, since most chemists are informally trained within the workplace. Employers often prioritize hiring workers from trusted networks rather than formally trained, unknown chemists, reflecting the pervasive low levels of trust in the sector. As a result, informally trained yet trusted workers remain a cornerstone of operations despite their limited formal expertise.

#### 5.4.4 Social learning, communities of practice, and adaptation

Knowledge creation processes do not operate independently or outside social contexts. Information acquired through any of these processes is shared within communities, adding further layer of complexity and possibilities for knowledge acquisition in environments where mineral information is limited. This is particularly important given the high costs and challenges of acquiring such knowledge independently through STI or DUI knowledge creation processes.

Survey data support this pattern: 59% of miners reported learning from peers at the workplace, 40% learned independently, and only 1% received formal education in mineral extraction. These findings highlight the critical role of social capital and networks in ASGM. Miners benefit not only from peer learning but also from informal networks extending to public institutions and LSM companies, which often provide a strategic advantage.

Collective learning is therefore essential for both economic success and identity formation. In dynamic environmental and technological landscapes, entrepreneurs thrive only by acquiring the knowledge necessary for profitable gold extraction. Engagement in knowledge acquisition and sharing situates miners within communities of practice, where learning becomes part of their professional identity.

Knowledge creation processes also serve as mechanisms for adaptation to technologies and changing environments, enabling miners to remain competitive. While mercury has historically been a central technology, facilitating rapid extraction, the ability to acquire specific extraction knowledge allows businesses to sustain their position in the sector. Miners with more developed knowledge creation practices can adapt strategies to extract different deposits more effectively, in contrast to those who rely solely on mercury amalgamation for perceived security.

Overall, successful miners integrate multiple knowledge bases. Scientific knowledge provides advantages in exploration and precise extraction, while informal and experiential knowledge supports day-to-day operations. It is the combination of these knowledge types that enables miners to adapt to technological and environmental change and maintain competitiveness within the ASGM sector.

This empirical analysis indicates that examining knowledge creation processes can provide a more nuanced understanding of human-nature interactions, and more broadly role of the natural environment within transition processes (Andersen & Wicken, 2021; Arhin & Behuria, 2025; Ostrom, 1990). In this context, integrating the natural environment more systematically into GeoST and to conceptualize it as part of the landscape within the MLP framework has been a vital strategy, as these elements are often influential yet frequently overlooked (Andersson et al., 2024; Andersen et al., 2021; El Bilali, 2019; Hansen & Coenen, 2015; Vermunt et al., 2020). Such integration is essential because it highlights how material properties can either facilitate or hinder technological adoption and transitions towards sustainable development (Binz et al., 2020, 2025; Hansen & Coenen, 2015; Munro, 2019).

## 5.5 Inequalities

Across the three articles, I identify multiple dimensions of inequality associated with the mercury–cyanide transition, including unequal access to resources and knowledge, and unequal distribution in agency. These patterns call into question whether a shift to cyanide leaching can be considered a “just” transition. In the quantitative survey I use the workers–entrepreneurs variable to capture these differences. This variable reveals sharp disparities: entrepreneurs are older, more educated, and report more years of experience in ASGM than workers. Entrepreneurs also report greater access to mining training, easier access to capital for mining purposes, and feel more represented by miners’ associations (Table 2 Article II; Table 2 Article III). Together, these findings point to distributional inequalities in social capital (the capacity to obtain economic or informational support from peers, family, and institutions), access to capital, and ownership of means of production. The concerns reported by miners reflect these divides: entrepreneurs tend to focus

on securing capital for operations, whereas workers emphasize late and poor payments and occupational hazards (Table 2, Article II).

### 5.5.1 Agency and inequality

I have examined agency to explore which actors hold greater power in shifting production practices and in adopting alternatives to mercury amalgamation, such as less environmentally harmful technologies like cyanide leaching. Wealthier entrepreneurs possess both the capital and technical expertise necessary to determine how production is organized, whether through insourcing or the pooling OPs. Their agency stems not only from their capacity to adapt to changing environmental conditions and technological innovations, but also from their control over key means of production—land, licenses, and machinery—which positions them to make such decisions in the first place. In contrast, many workers have limited agency to avoid mercury use or to influence production methods. They must operate within conditions set by employers and are primarily concerned with securing daily livelihoods, a situation closely linked to constrained financial resources. This disparity reflects broader inequalities in influencing decision-making processes (i.e., procedural inequalities) (Lee & Byrne, 2019; Sovacool et al., 2021). Overall, these dynamics indicate that agency is unevenly distributed: some actors possess far greater capacity to steer production away from mercury use than others.

The empirical evidence aligns with previous literature showing that actors endowed with greater resources, power, and knowledge possess enhanced agency to shape transition outcomes (Grillitsch & Sotarauta, 2025; Sotarauta & Grillitsch, 2023b, 2023a; Verbrugge and Geenen, 2020). At the same time, examining production through the lens of organizational practices offers an important contribution to understanding how individuals operating with similar technologies may nonetheless generate divergent transition outcomes and regional development trajectories (Gaillard et al., 2025; Grillitsch & Sotarauta, 2025; Nkuba et al., 2022; Veiga et al., 2014; Verbrugge & Geenen, 2020).

### 5.5.2 Knowledge inequalities

Both quantitative and qualitative data indicate pronounced differences in the mining knowledge creation processes. Entrepreneurs are more likely than workers to have taught peers and to have been taught; workers are more likely to have learned mining tasks independently. Workers' duties are often repetitive and offer limited opportunities for skill development (for example, manually breaking rock, transporting ore, or digging). Interviews corroborate that entrepreneurs' networks and communities of practice enable access to knowledge from LSM or government

agencies and facilitate access to mining claims. Entrepreneurs are also more likely than workers to recognize mercury and cyanide as potential threats to human health and the environment, reflecting their greater engagement with these knowledge networks.

### 5.5.3 Resulting dimensions of inequality

Weaving the empirical evidence through the just transitions framework (distributional, procedural, recognition, and cosmopolitan inequalities) shows how inequalities are intertwined with the adoption of these technologies and reproduce the conditions for the persistence of mercury amalgamation.

The distributional inequalities in capital and knowledge position wealthier entrepreneurs to acquire tailings, enabling them to yield profits from the work of less affluent miners who remain dependent on the less efficient method of mercury amalgamation to sustain their livelihoods, and have no use for tailings. This inequality is a key finding, as it helps explain both the persistence of mercury and cyanide processing within ASGM value chains and the reinforcement of broader inequalities within the sector.

These dynamics also show how distributional inequalities translate into procedural inequalities greater wealth and social capital not only facilitate capital accumulation cycles, but they also give actors greater leverage in decision-making—for example through miners' associations or political networks—and to shape policy or its implementation. Recognition inequalities follow, as financially constrained miners, and especially workers, remain underrepresented and unaccounted for in the sector. These dynamics are mutually reinforcing: procedural and recognition inequalities perpetuate further distributional disparities.

Finally, the economic and procedural dimensions intersect with health and environmental harms. Mercury and cyanide contamination disproportionately affect local populations and especially miners who ignore the dangers of these chemicals and have no alternative for their livelihoods. A further layer of cosmopolitan inequalities is represented by distant consumers of the commodities, who purchase refined products while chemicals threaten distant realities.

Engaging these findings with the broader Just Transitions literature reveals both points of convergence and areas where this case extends existing debates. While the empirical analysis supports the applicability of the Just Transitions framework beyond energy transitions and demonstrates its relevance for natural resource sectors such as ASGM (Lee & Byrne, 2019; McCauley et al., 2019; Sovacool et al., 2017, 2021), it also shows that analyzing justice dimensions through the lens of access, technology adoption, and knowledge creation is crucial for understanding how these processes unfold in practice. The results further highlight the value of adopting a

relational lens, where inequalities are interpreted not as static distributions but as outcomes of ongoing interactions between actors with uneven agency and resources. In this regard, the findings underscore how informality, poverty, and historically rooted power asymmetries shape the dynamics of technological change and reproduce multiple dimensions of inequality (Geenen & Bikubanya, 2024; Ramos-Mejía et al., 2018; Swilling et al., 2016; Ghosh & Mguni, 2026; Morales & Ramos-Mejía, 2023).

## 6 Conclusions

This chapter concludes the doctoral dissertation by answering the research questions and objectives set out in the introduction. It revisits the main findings, contributions, policy implications, and directions for future research, while also reflecting on the study's scope and limitations.

The first objective has been to understand the empirical dynamics of ST in ASGM and to identify the socio-technical and economic barriers that sustain mercury use. The analysis addressed questions including: *How is cyanide being integrated within ASGM extraction chains using mercury? How does the integration of cyanide in ASGM extraction practices affect sustainability? What knowledge creation processes do miners engage in to extract gold? What are the primary strategies identified and promoted to transition away from mercury use in ASGM in Tanzania? Why does mercury use persist despite the implementation of strategies intended to reduce its prevalence?*

Across the three articles, the evidence shows that mercury is deeply embedded in ASGM and that cyanide leaching has been integrated into existing production chains and practices rather than disrupting them. The two chemicals serve different needs of miners: mercury enables rapid, low-cost extraction through amalgamation, whereas cyanide requires higher capital and supports ambitions to scale-up production through larger investments. In practice, many miners use both technologies sequentially in single extraction process. Mercury is commonly applied for daily extraction, with tailings accumulated and later processed through cyanide leaching to recover additional gold. Only a small minority relies solely on cyanide leaching; most cyanide operations treat tailings already processed with mercury, underscoring the centrality of mercury despite the wider diffusion of cyanide. Consequently, integrating cyanide leaching into existing ASGM production chains fails to enhance environmental sustainability, as it does not significantly reduce mercury use while creating one of the sector's most harmful practices: cyanide leaching on mercury-contaminated tailings. These outcomes are more damaging than those associated with the use of either chemical alone.

Beyond technical considerations, the findings show the centrality of mercury in organizational practices and socio-economic relations among miners. Mercury

operates not only as an extraction agent but also as a basis for distributing output and payments, and as indicative evidence of high gold content in ore and tailings. It also enhances miners' perceived security. Mercury reduces the need for extensive trust, complex organizational and logistical arrangements, and high-interest loans, all of which are required to finance cyanide leaching operations without mercury. This arrangement enables miners to conduct operations in informality and with minimal upfront capital and allows payments for chemicals and labor to be deferred, even as ecological and human costs accumulate over time. Overall, these findings—and the organizational practices in which mercury remains central—are closely linked to a key challenge in ASGM: informality. The very social and economic relationships that sustain mercury use are embedded in informal practices, suggesting that the sector's persistent informality is closely connected to the continued reliance on mercury. The OPs can thus be understood as adaptive mechanisms through which actors manage insecurity in informal settings (Ramos-Mejía et al., 2018).

A further empirical observation is that the technical knowledge required for alternatives reinforces miners' reliance on mercury. Mercury amalgamation offers easy-to-learn methods, in contrast to cyanide leaching, which demands careful measurement of chemicals and knowledge of ore characteristics for enhanced profitability. Barriers to gold extraction with mercury are therefore substantially lower than for less environmentally harmful technologies; the necessary skills are limited and can be acquired quickly. Low capital requirements, limited knowledge needs, and rapid learning make mercury-based extraction an attractive livelihood option, particularly in rural areas with few alternatives.

Taken together, the evidence demonstrates that multiple, interacting factors bind mercury to ASGM. Mercury amalgamation aligns with the need for quick cash, low investment, and limited knowledge barriers, while shaping social and economic relations and mediating risk. By contrast, cyanide and other less harmful technologies carry high barriers related to capital, skills, and knowledge, and they primarily meet the needs of wealthier stakeholders. Rather than displacing existing relations, cyanide often enables further extraction, reinforces hierarchies, and creates new ones.

Overall, the findings indicate that current policy strategies and the regulatory framework in Tanzania have been effective in promoting cyanide as an extraction technology and in identifying some of the key challenges associated with the transition. However, these measures have not been sufficient to reduce mercury use, and extraction up-scaling remains concentrated among a small subset of actors. As a result, they do not offer viable pathways for most miners in the ASGM sector to transition away from mercury. Given these conditions, achieving the targets set out in 2020 of reducing mercury use by 30% by 2025 (URT, 2020a) and fully phasing it

out by 2030 (Mwendapole, 2024) will remain extremely difficult without significant technological, behavioral, and political change.

These challenges relate to the second objective I set out to explore in this doctoral thesis, which is to analyze how a more efficient and less environmentally harmful technology, cyanide leaching, affects social, economic, and environmental inequalities in ASGM. I set out to explore these through the research question: *How does the adoption of cyanide leaching reshape socio-economic and environmental inequalities within the ASGM sector?*

Endorsement of cyanide has facilitated the industrialization of the sector, transforming production processes and creating new winners and losers. This industrial uptake yields benefits such as greater traceability, increased economic complexity, and the development of knowledge and technical capacities that can spill over into other industries. These gains can contribute in addressing long-standing challenges in Africa related to limited control over, and limited technical knowledge about, resource extraction. By cultivating higher-skill employment, such industrialization can support the emergence of knowledge-intensive activities and wider structural transformation.

At the same time, the transition risks creating a skills mismatch, with a surplus of unskilled labor and a shortage of skilled workers. As the means of production become more exclusive, questions of inclusion and exclusion arise, particularly regarding access to benefits and the distribution of environmental and social burdens. Within ASGM, I have explored inequalities in the sector especially between entrepreneurs and workers. Differences in capital, access to finance, social capital, and education give entrepreneurs greater agency to influence political processes and capture the advantages associated with a more efficient but more exclusive technology.

These inequalities are compounded by a second challenge: the depletion of easily accessible surface deposits and declining ore grades. As a response, extraction moves to deeper non-oxidized and complex ores, industrial technologies, mechanized equipment, and in situ knowledge become essential for profitable operations. As mercury is less effective in these contexts, miners that rely solely on amalgamation and lack the means to acquire alternative technologies face increased pressure.

These findings emphasize the challenge of advancing multiple Sustainable Development Goals (SDGs) simultaneously. Supporting mechanization and cyanide leaching in ASGM can promote innovation and industrialization (SDG 9) and contribute to economic growth (SDG 1). However, the adoption of these technologies raises concerns about inclusive growth and poverty reduction, as cyanide can reproduce and deepen existing inequalities (SDG 10). Furthermore, because cyanide leaching does not significantly reduce the use of mercury, it remains prevalent. The release of both chemicals into the environment continues to pose

serious risks to environmental and ecosystem-focused SDGs, such as SDG 14, Life Below Water, as these substances substantially harm aquatic ecosystems. This tension between objectives underscores the difficulty of framing the shift from mercury to cyanide as a transition towards sustainable development.

The findings from the first two objectives of this thesis indicate the need for policy interventions not only to phase out mercury use within the set deadlines, but also to address emerging inequalities in the context of growing industrialization in ASGM. The co-existence model promoted in Tanzania presents important limitations in reducing mercury use and could be improved by addressing time inconsistency, limited trust, and constrained access to capital and knowledge. Given the complex interconnections of mercury with economic, behavioral, and technological factors, no single technical solution is likely to fully address these challenges.

One pragmatic measure is to develop a market for mercury-free tailings and to reduce frictions in their purchase. Practical steps include routine ore characterization tests, dissemination of guidance on interpreting results, improved sampling techniques, and better support for often overlooked stages such as sluicing and crushing. These would contribute towards greater transparency and reduce the trust needed in transactions. These measures should be complemented by incentives for purchasing mercury-free tailings through stricter regulation and enforcement and/or further economic incentives for those who leach mercury-free tailings with cyanide.

These challenges also require incentives for miners to accumulate mercury-free ore or tailings, or to process tailings through cyanide in the first place. At present, buyers are generally uninterested in small volumes of tailings. The resulting time gap creates uncertainty, which miners often address by processing ore with mercury to secure short-term capital. One important incentive would be to expand access to finance for cyanide leaching on the condition that mercury is not used. However, this must also address the key obstacle of miners' limited collateral and their difficulty in demonstrating extraction feasibility to potential funders. Building technical knowledge and developing feasibility assessments could help miners communicate viability more effectively and thereby attract investment.

Another option is to support vertical and horizontal integration across mining businesses through long-term purchasing contracts. Such contracts can provide predictable supply for buyers and guaranteed outlets for producers, especially where entrepreneurs with access to cyanide hold greater access to capital. However, these arrangements may reduce flexibility and bargaining power for producers and buyers alike and therefore must be implemented equitably and transparently.

Implementing these technical and organizational measures effectively depends on how they intersect with existing hierarchies within the sector. The empirical analysis shows that certain entrepreneurs hold greater agency—through their control

of cyanide processing facilities, access to capital, and ability to shape organizational practices. Consequently, they occupy strategically important positions within the ASGM value chain and represent key leverage points for policy interventions aimed at reducing mercury use and promoting more sustainable practices. Recognizing this helps narrow the focus of effective intervention in a fragmented and informal sector.

Beyond the sector, ASGM is embedded in broader labor market transformations in Tanzania and across Africa. If the surplus of unskilled labor grows, inequalities may widen and workers' wages may face downward pressure. Policies that expand education and develop alternative rural livelihoods are therefore necessary to absorb unskilled labor and to align with the longer-term agenda to formalize ASGM, which has advanced markedly in Tanzania in recent decades.

Finally, natural and global processes will shape mercury use in the coming decades. Exhaustion of surface deposits and supply and price dynamics for chemicals—especially mercury—are likely to be influential. Although mercury prices appear to be rising and there has been speculation about supply constraints following the Minamata Convention, the fieldwork data showed no indication of imminent supply disruption of mercury.

Nonetheless, diminishing accessible deposits may drive further industrialization: declining effectiveness or inaccessibility of mercury could reshape the socio-economic structures outlined above, potentially increasing reliance on cyanide and displacing unskilled labor. Future research should examine these trajectories and the governance measures needed to align industrialization with sustainable development in Africa.

The third objective has been to contribute—through the ASGM case—to the development of sustainability transition theories, with critical engagement with the MLP and Just Transitions frameworks in the global South. This objective has been guided by the following research question: *How does the ASGM case study in Tanzania contribute to sustainability transitions research in the global South?*

The thesis expands transitions scholarship in Africa and the global South by working across niche, regime, and landscape levels of the MLP, advancing a relational approach that foregrounds informality, local knowledge systems, institutional dynamics, and knowledge creation processes especially in relation to the natural environment. This approach moves beyond a purely technical perspective to capture the complex interplay of factors that underlie socio-economic and behavioral challenges associated with technology, which empirically translate into the persistence of mercury use.

The relational perspective helps explain the resilience of mercury by highlighting how resistance to change is embedded in relationships among individuals and the roles those relationships play. It also illuminates how niche-innovations emerge and interact with existing infrastructures (the “mercury regime”) to form organizational

practices that evolve into regimes. This perspective clarifies how integration of more sustainable practices and technologies in the value chains, can yield more environmentally detrimental and unsustainable outcomes on the ground. More broadly, the findings speak to a central feature of sustainability transitions in the global South: arrangements such as OPs that combine mercury and cyanide into more harmful hybrid practices emerge from actors' efforts to secure livelihoods under conditions of uncertainty and informality. In prioritizing short-term stability through social and organizational arrangements, long-term environmental considerations may be subordinated (Ramos-Mejía et al., 2018). A promising direction for future research would be to explore whether and how formalization—through regulatory and policy reforms in ASGM and related sectors—can enhance security and reduce reliance on environmentally unsustainable practices that are used to secure short-term stability but generate long-term environmental and human health harm. These insights are also critical for analyzing distributional, procedural, recognition, and cosmopolitan dimensions of inequality, as such contexts may compel vulnerable populations to draw urgently on common-pool resources in ways that support immediate survival while undermining long-term prospects for poverty alleviation and sustainable development.

A further contribution of this thesis concerns the integration of the natural environment into ST frameworks, and specifically GeoST. Incorporating the natural environment is essential for explaining why transitions occur in some places rather than others, especially in sectors directly dependent on natural resources. For the global South, where natural resources are central to many economies, a relational approach that examines how individuals and communities engage with the natural environment and with each other can reveal knowledge creation processes that inform understanding of material characteristics and how to interact with them (or even extract them). Researchers applying the MLP could, for example, expand the concept of landscape to include elements of the natural environment. Further development would benefit from posthumanist and new materialist perspectives that treat the natural environment as an active agent within transitions, addressing the overly socio-technical focus of much ST research. Such approaches are vital for understanding human–nature interactions and for informing more sustainable futures.

# Acknowledgements

Although this space is brief, it is perhaps one of the most meaningful parts of this thesis. A dissertation may carry a single name on its cover, but it is never truly the work of one person alone. This work has been shaped by many influences, both large and small, and is ultimately the result of many encounters. It is difficult to claim that a work, or the inspiration behind it, belongs solely to oneself; it is equally a product of the environments and the minds that have contributed to it. Without these encounters, this thesis would not exist in its present form or substance. More than that, I cannot imagine myself without them, as they have shaped not only this work but also the person I have become. This thesis is made up of countless parts and fragments, things I have learned and gathered through these very encounters. In many ways, this dissertation is built from them, not least because people and interactions with people form the very bones, the data, on which this research rests.

I would then like to begin with the very bones of this research. I am deeply indebted to the people I met in Tanzania, particularly within the artisanal and small-scale mining communities. Words cannot capture the generosity with which you welcomed me into your homes and workplaces, sharing your time, stories, insecurities, aspirations, and challenges. You have challenged the way I think and shared profoundly moving experiences. In opening your lives to me, you gave far more than insights for this thesis: you offered lessons for my own life, ways of living, and, in many cases, friendship. This work would not have been possible without you. I am especially grateful to the entrepreneurs, who shared the complexities of organizing operations and making sense of gold extraction, and to the workers, who entrusted me with their personal stories and daily struggles.

*Nina deni kubwa sana kwa watu watu niliokutana nao Tanzania hasa jamii za wachimbaji wadogo. Maneno hayatoshi kuelezea ukarimu wenu na namna mlivyonikaribisha majumbani kwenu, maeneo yenu ya kazi, pamojaa na kunipa muda wenu, hadithi zenu, matarajio yenu na changamoto pia. Mmebadilisha namna yangu ya kufikiria na mmenionesha uzoefu wenye mguso mkubwa. Kwa kufungua maisha yenu kwangu mmenipa zaidi ya maarifa kwa ajili ya tasnifu hii- mmenipa funzo kwaajili ya maisha yangu binafsi, namna ya kuishi na namna mbalimbali za urafiki. Kazi hii isingewezekana bila nyie. Ahsanteni sana nyote. Nitoe shukrani*

*zangu za kipekee kwa wajasiriamali wote walionishirikisha changamoto zao katika kupanga shughuli zote za uchimbaji wa dhahabu, na pia kwa vibarua walioniamini na kunipa hadithi zao binafsi na mapambano ya kilasiku.*

I also offer my sincere thanks to the government officials, NGO representatives, experts, and practitioners—both within Tanzania and beyond—who generously shared their time and expertise. Your willingness to engage in dialogue, challenge my assumptions, and provide critical insights has been fundamental to this research. Special thanks are due to the Ministry of Minerals, the National Environment Management Council (NEMC), the Mining Commission, the Government Chemist Laboratory Authority (GCLA), the State Mining Corporation (STAMICO), the Geological Survey of Tanzania (GST), and the Federation of Miners Associations (FEMATA) for their institutional support, expertise, and openness to dialogue.

My deepest gratitude goes to my thesis supervisors, whose guidance shaped both this work and my growth as a researcher. Professor Jussi Jauhiainen, as my primary supervisor, this journey would not have begun without your belief in my ability to complete it. You instilled in me both academic ambition and critical thinking. You took my passion for natural resource extraction and layered it with complexity through your enthusiasm for innovation, technology, and even AI: dimensions I had barely explored before. That intersection became one of the most generative spaces of my research. Every time I knocked on your office door with ideas, questions, doubts, or half-formed solutions, you welcomed me in for conversations that were not aimed at giving me answers but new ways of looking at things, hence I would unavoidably leave with more questions. Your direct and honest approach was invaluable; every discussion felt like laying another brick in the wall of my education as an academic. You like to say that every PhD journey is like getting a drivers' license. As a driving instructor, you knew when to let me drive and at times pulling the brakes or steering towards particular direction to help me gain academic independence.

I would also like to express my gratitude to my co-supervisors who brought different yet complementary perspectives to this work. Associate Professor Abel Kinyondo, your engagement as co-supervisor proved invaluable in grounding this research in Tanzanian realities. You helped me identify the most pertinent research questions and encouraged me to examine them through fresh lenses. Your deep expertise in the subject matter was particularly crucial during my fieldwork in Tanzania. I also appreciate your advice during data collection, for providing comments to my first article, and co-authored two others. Professor Jon Mugabe, I am deeply grateful for your co-supervision throughout this journey. Your thoughtful feedback and insights have profoundly shaped this thesis, and I especially look forward to our upcoming collaboration in Pretoria. Thank you for your warm welcome and support.

My sincere appreciation extends to the pre-examiners of this thesis, Professor Gavin Bridge and Professor Gavin Hilson. I am truly grateful for the time and expertise you devoted to reviewing my work, and for your valuable suggestions that both strengthened this thesis and pointed toward promising avenues for future research. I would also like to thank Professor Roy Maconachie for accepting to serve as my opponent. I greatly appreciate your willingness to engage with this work, and I am very much looking forward to meeting you in person and to our discussion during the defense in Turku.

Next, I would like to extend my deepest thanks to Fatma (Fetty) Andersson, Charles Shimba, Joyce Nkaina, and Vincent Shyonela, the best research assistants I could ever have hoped for in Tanzania. This work simply would not have been possible without you: the translations, survey collections, transcriptions. But more than that, you allowed me to see mining and Tanzania through your own eyes and lived experiences, which I believe have profoundly enriched both this research and my personal understanding of ASGM and the country. You showed me how to see the world through your perspective, making this not just a reflexive journey but also an incredibly fun and rewarding learning experience. You became much more than assistants — you were true companions and friends. Our journey together brought endless, dusty, bumpy *boda boda* rides, and eating *kitimoto* together at the end of long, exhausting fieldwork days were some of the greatest rewards I could have imagined. Thank you all four for taking this *mzungu* along for the ride and enduring all the attention that came with it. Fetty, thank you for your incredible sociability — your gift for conversation helped us make so many friends along the way in Kahama. I'll always cherish those moments of "making stories" while eating bone marrow in our informants' homes or enjoying *matunda* to cool off at day's end. Charles, thank you for being like a fun younger brother, for sharing your passion for Simba, and for those long rides across Tanzania from Kahama through Shinyanga to Dodoma. Joyce, thank you for the kindness you showed both me and our informants in Mwanza, Geita, and Nyarugusu. And Vincent — some of my very best memories were made with you in Chunya and Mbeya. I really appreciated your enthusiasm for learning about gold mining. Your curiosity and drive to understand new things constantly motivated me. It was always an adventure going off the beaten track and getting lost in the middle of nowhere with *boda boda* drivers who'd run out of gas!

In Tanzania, I would also like to express my gratitude to Elard Mawala and Jesper Bosse Jønsson for generously sharing your time and expertise. Your advice has proven invaluable throughout this research process. My sincere thanks also go to Anna Frohn Pedersen for sharing your firsthand knowledge and insights on ASGM in Geita and Tanzania, as well as your guidance on navigating the

bureaucratic hurdles that often arise during fieldwork. I would also like to thank Dr. Bernard Mnzava for introducing me to Tanzania and gypsum mining in 2022.

Amongst other things, this PhD journey required me to delve deeply into the technical aspects of mining, particularly the geology, chemistry, and engineering of gold extraction. For patiently explaining the complex behaviour of gold particles, the intricacies of gold geology, and the chemical reactions involved in cyanide extraction processes, I am especially grateful to Kirsten Dales, John Kalimenze, Antti Peronius, and Cyrus Njonde. I would also like to extend my sincere appreciation to all the Tanzanian geologists, mining engineers, and environmental engineers who generously shared their expertise. As experts who were also miners and key informants in ASGM, your insights into the technical, geological, and chemical dimensions of this research have been invaluable.

Beyond my time in Tanzania, I have spent most of these four years in Turku, where I spent most of my (often dark and cold) days writing this dissertation, analysing data, and preparing grant applications. It has been in these moments that the support of my colleagues at the University of Turku proved most valuable. I feel profoundly fortunate to have spent these years within our Geography Department. The support I have received has transformed what could have been a solitary process into something not only enjoyable, but intellectually stimulating. This department became far more than a workspace: it became a community where I shared significant portions of my life and personality. The conversations — including those during *aamukahvi* — have been a constant source of learning and inspiration. I am grateful to all my colleagues who have provided support throughout this journey. Special recognition goes to Sanna Mäki for her leadership as head of section in fostering this vibrant community. Kiitos kaikille!

Thank you to Professor Niina Käykö and Msilikale Msilanga for your insights and support with matters concerning Tanzania and especially for our time together in both Turku and Dar es Salaam. Lauri Hooli, your stories and experiences in Tanzania and across Africa have been truly inspiring and you've become not only someone I could easily trust but also look up to. I'm also grateful to Mikel Calle for being my elder Latin brother in the early PhD years, and Katri Gadd for the empathy and sincerity you bring to our office every day. Special thanks to Camilla Marucco Al-Mimar, Salla Eilola, and Tikli Loivaranta — your thoughtful listening and critical questions have made me think more deeply about my research and my positionality in Tanzania. My thanks extend to Johanna Yliskylä-Perulahti, Joni Mäkinen, Jukka Käyhkö, Juuso Suomi, Leena Laurila, Miriam Tedeschi, Nora Fagerholm, Petteri Alho, Päivi Oinas, and Risto Kalliola, for contributing to our department's vibrant community, and for the many meaningful moments we've shared along the way.

It would be difficult to imagine my PhD journey without Roosa Wingström and Mia Jaatsi. You were central not just in my academic settling in Finland, but in

shaping my entire life here. What I treasure most is how we created our own little society – both academic and delightfully not-so-academic. Together we built a space where we could exchange brilliant ideas, learn from each other's experiences and mistakes. Your continuous feedback on my articles and funding applications taught me more than I can express, and I genuinely wouldn't be here without you. As I am writing this moments after Roosa drove me to the hospital with a broken foot — just one of countless episodes where you've rescued me from trouble — I'm reminded of the extraordinary kindness you've shown me since my first days in Turku. You became the first person I could rely on in this department and country, setting the path for me to follow in your footsteps. You've been the ideal friend and colleague I needed: bringing boundless energy and always ready to help me out.

Mia, thank you for being my *viisas pöllö*, for meeting all my stories with such profound empathy and care. You have this remarkable ability to make even my biggest challenges seem small and manageable. Your wisdom and foresight, always being one step ahead, helped me navigate all the ups and downs this PhD journey brought. Felix Hallikainen, our group wouldn't be the same without you. Your arrival brought so much to our dynamic, and it's been wonderful having your support and sharing laughs since you joined the department. I still marvel at how both you and Roosa managed to ignite a passion for Bocelli and karaoke bars! To all three of you (plus Muppe!), thank you for being more than friends — truly my Finnish family. Thanks for putting up with my everyday grumpiness and for simply accepting me as I am.

One of the unexpected joys of my PhD journey has been our geography football team. Together we shared endless games and countless good times. To Amin Sadeqi, Carlos Gonzales-Inca, Frank Chimaimba, Hilary Mvungi, and Sadegh Kaboli: you helped me rediscover my love for a sport I once cherished, and even discover that extra lung capacity to chase down every last ball. Beyond football and being colleagues, you became true friends. Carlos, *gracias por tu amistad* — you've always been there to offer a helping hand (or a trailer) whenever I needed it. Amin, Frank, Hilary, and Sadegh, thank you for all the moments we've shared and for the laughter that made even the toughest days brighter. Hilary, I'm also particularly grateful for your Tanzanian insights and for helping translate this thesis' abstract into Swahili.

My gratitude extends to Justo Jonas for your invaluable contributions in Turku assisting with transcriptions, translating surveys and interview guides, and creating the maps for this thesis. To Agustín Garagorry, thank you not only for helping design my (admittedly imperfect) figures, but also *para tomar mate* and your ability to disagree with me on almost anything. And to Tytti Tengström, thank you for bringing joy to our workplace and for providing the crucial Finnish translation of my abstract — a final yet essential step in completing this thesis.

Of course, I must extend my heartfelt thanks to all my fellow doctoral researchers. Your support, and shared experiences have been my constant motivation throughout this journey. The growing community we've built together, with all our activities and mutual support both in and out of the department, has made these past four years not just productive but genuinely enjoyable. My particular gratitude goes to Adnan, Akseli, Arpa, Asfand, Bea, Emmy, Iiro, Joha, Jouko, Khairiya, Luma, Mariah, Meiju, Monica, Siiri, Tanya, Temitope, and Venla for all the shared moments that made this journey special. As part of this group, I've been especially fortunate to share this entire PhD journey with Aino Saarinen, Karoliina (yksi) Lintunen, and Linnea Blåfield. Your presence from my very first day in Finland has been invaluable. Thank you for your patient attempts to teach me Finnish, for being such wonderful friends through all the ups and downs, for answering my endless questions about Lapland, and for introducing me to Finnish cultural quirks like queuing for free buckets.

Beyond our geography department in Turku, I would like to share my gratitude to the Nordic Africa Institute, especially to Grasian Mkodzongi and Eleanor Fisher, for hosting me in Uppsala in 2025. This experience proved invaluable to my research journey.

I would also like to take time to thank my family and friends who have supported me throughout the process. *Ai miei genitori, Catherine e Marco, e a Natascia e a Emily, che si prendono cura della nostra famiglia e di me, nonostante la distanza. Ad Ayla e Gemma, che avete portato tanta gioia nella mia vita. Myriam, grazie non solo per tutte le nostre avventure, ma soprattutto perché mi sostieni quando sono stanco, insopportabile o con un piede rotto. Mi dai la forza per tenere in piedi tutta questa architettura. A Ferdinando, dopo una mangiata a casa tua la vita sembra in discesa (ovviamente, non in bici a stomaco pieno). A Codd\*\*\*occosu, passano gli anni ma voi restate sempre.*

In conclusion, I would like to acknowledge the funding sources that made this research possible. My sincere thanks go to the Ministry of Education and Culture of Finland for financing this research through the Finland-Africa Platform for Innovation (FAPI) SDG9; to the Doctoral Programme in Biology, Geography and Geology at the University of Turku; and to the Kyösti Haataja Foundation within the OP Research Foundation.

09.03.2025

*Oliver Tomassi*

# Declaration of generative Ai in the writing process

During the preparation of this thesis the researcher used Open AI's ChatGPT and Microsoft Copilot 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.

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ISBN 978-952-02-0617-8 (PRINT)  
ISBN 978-952-02-0618-5 (PDF)  
ISSN 0082-6979 (Print)  
ISSN 2343-3183 (Online)