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# Adapting to environmental and technological transformations through knowledge creation: insights from artisanal and small-scale gold mining in Tanzania

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ABSTRACT

Artisanal and small-scale gold mining (ASGM) is a key economic sector in Tanzania and the global South. Its predominant extraction method, mercury amalgamation, is valued for low cost and minimal skill requirements but poses severe risks to human health and the environment. ASGM is undergoing two major transformations: depletion of easily accessible deposits and growing mechanization. Cyanide leaching has emerged as a prominent alternative to mercury, promoted as a less harmful option yet still associated with significant environmental and health risks.

This study situates mercury and cyanide in ASGM within the Geography of Sustainability Transitions (GeoST) to examine how changes in the natural environment like mineral exhaustion influence extraction processes and sustainability. We adopt knowledge creation processes as an analytical lens to explore how miners develop and apply knowledge to adapt to transforming environmental and technological contexts.

Using a mixed-methods approach combining qualitative interviews and a quantitative survey conducted in Tanzania, we find that more efficient and relatively less environmentally harmful practices require complex knowledge of the natural environment and technologies that go beyond the sensory-based, experiential learning typical of mercury amalgamation. This knowledge gap sustains mercury use and exacerbates inequalities between miners with and without technical expertise. Our findings highlight the importance of linking knowledge creation with environmental conditions to support transitions away from highly unsustainable practices like mercury in ASGM.

## 1. Introduction

Artisanal and small-scale gold mining (ASGM) has traditionally been understood as the labor-intensive, low-capital activity that employs basic tools and machinery to extract gold from surface and near-surface deposits [1,2]. While this sector provides substantial employment in rural areas with limited livelihood opportunities, it poses severe environmental threats, particularly through mercury use in gold extraction [1]. Although this is a cost-effective extraction method requiring minimal expertise, mercury is a heavy metal and potent neurotoxin that endangers both human health and ecosystems [3]. The extensive use of mercury in ASGM accounts for approximately 37.7 % of global mercury emissions, prompting international regulatory efforts such as the 2013 Minamata Convention [3,4].

Over the past two decades, ASGM in Tanzania has undergone two critical transformations: the gradual exhaustion of accessible high-grade surface deposits and the emergence of new extraction technologies. The most significant of these technologies is cyanide leaching, increasingly adopted alongside mercury for its higher efficiency in gold extraction [5–10]. Under pressure to reduce mercury use, cyanide has been promoted by some organizations, scholars, and the Tanzanian government as a less harmful alternative to mercury, even though it also poses serious risks to human health and the environment [5–9,11–13]. Nevertheless, as it degrades more rapidly in the environment, cyanide is often framed as the “lesser evil” when properly managed and regulated [8,11,14,15].

Despite the availability and promotion of cyanide as a safer alternative, mercury remains central to ASGM, raising questions about

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whether miners are willing or able to adopt cyanide-based methods [5,6,12]. Most research on cyanide leaching emphasizes access to capital, organizational limitations, and government constraints as the primary barriers to phasing out mercury, while considerably less attention has been paid to the role of knowledge in enabling or resisting this transition [8,10,16]. Moreover, the risks associated with cyanide largely depend on how it is applied, which is shaped by the knowledge miners develop about both the natural environment (including ore properties) and the technology itself [6,8,9,17]. Efficient and responsible use requires technical expertise that many artisanal and small-scale miners lack [12]. This study addresses these critical gaps by examining how miners' knowledge shapes the adoption and use of both mercury and cyanide.

We explore this by situating the ASGM case within the Multi-Level-Perspective (MLP), a central framework in Sustainability Transitions (ST) research [18–20]. At its core, the MLP emphasizes socio-technical systems, understood as the interrelations between socio-economic and technological elements in society. ST scholarship investigates whether and how transformations in such systems foster transitions toward sustainable development. Yet, socio-technical change does not inherently promote sustainability. On the contrary, transitions may also reinforce unsustainable trajectories [21], resulting in what have been described as "unsustainable transitions" [22].

While the field of ST effectively addresses social and environmental challenges, its predominant socio-technical approach often underplays the role of the natural environment and geographical features in shaping transitions [23–27]. Scholars have highlighted this gap, calling for a more systematic integration of human-nature interactions into research on ST, and particularly within the sub-field of Geography of Sustainability Transitions (GeoST) [23,24,28].

Elements of the natural environment, such as resource endowments, can influence economic growth and innovation, a relationship that can be analyzed through knowledge dynamics, especially in natural resource-based industries [23,29]. Knowledge plays a pivotal role in determining whether these sectors generate positive economic externalities and contribute to broader technological development and economic diversification [23,29–32]. This article contributes to ST research by examining the natural environment, human-nature interactions, and knowledge creation. We argue that understanding how individuals create, acquire, and apply knowledge about the natural environment is essential, as this knowledge critically shapes technological and economic change and, consequently, sustainable development trajectories.

Investigating this gap through global South cases is particularly relevant, given that natural resource-based industries underpin many of these economies [25–26]. In such contexts, the natural environment is central, especially in rural areas dependent on resource extraction, including fishing, agriculture, forestry, and mining. Artisanal and small-scale gold mining in Tanzania therefore provides a critical case study for examining these dynamics [23,25,26,33].

This article addresses the outlined research gaps in ASGM and ST by exploring the following research questions:

1. What knowledge creation processes do miners engage in to extract gold, and why are they critical for sustainability transitions?
2. How do changes in the natural environment influence sustainability transitions in ASGM?

The article is structured as follows: In this article, Section 2 reviews key concepts related to knowledge creation in ST within the African context. Section 3 outlines the research methodology. Section 4 contextualizes the ASGM case study, examining the evolution of mining knowledge, practices, and regulations. Section 5 presents the empirical findings and connects them to the theoretical framework introduced in Section 2. Section 6 discusses the policy and research implications, while Section 7 concludes the study.

## 2. Knowledge creation processes for sustainability transitions in Africa

### 2.1. Sustainability transitions and the natural environment

The ST field studies how and whether currently unsustainable socio-technical systems can transition toward more sustainable modes of production and consumption. It examines how transitions unfold and explores the complex interactions among technologies, institutions, governance, and social and cultural practices that may promote or hinder change across multiple levels [18–21,23–27]. ST frameworks can be applied in various ways; in this study, we specifically use them to evaluate whether socio-technical transitions advance sustainable development or have limited or even negative impacts on sustainability, and why [21–22].

Within ST, the Multi-Level Perspective (MLP) has become a prominent framework for analyzing these interactions [18–20]. The MLP identifies three levels: niches, where emerging innovations develop; regimes, encompassing dominant technologies, policies, and cultural norms sustaining the prevailing societal order; and landscapes, representing the broader socio-political and economic context embedding niches and regimes [18].

While MLP research has extensively examined niches and regimes, the landscape level has received less attention. Traditionally, within the MLP, landscapes have been framed as the global political processes and market forces shaping transitions [19–20]. However, some scholars have introduced geographical interpretations, conceptualizing landscapes as the physical environment, the spatial context in which social relations unfold, or both [24,34]. Both perspectives help explain why regions with similar political, cultural, or technological conditions may follow divergent transition trajectories [31]. The emerging subfield of the Geography of Sustainability Transitions (GeoST) investigates such spatial variations, emphasizing the role of geography in shaping transitions [19,23,27,33,34]. While GeoST research has primarily focused on urban contexts, increasing attention on rural areas and the natural environment is needed, particularly in developing countries [24–26,35,36].

The natural environment consists of ecological and physical elements, including the climate, living beings, and morphological elements such as rivers or mineral deposits. While these originated independently of human influence, human actions significantly shape natural systems, making the natural environment and human activity inseparable, especially in our age of Anthropocene [24,37–40]. Nevertheless, when ST research considers the natural environment, it is often regarded as a passive element affected by human activity [24–26].

The natural environment is not only composed of physical matter with intrinsic chemical and geological properties, but is also socially constructed [40–41]. For instance, the physical properties of gold, e.g., malleability, durability, and density, exist independently of human activity. Yet, its value is shaped by social and economic systems that assign it symbolic meaning as a sign of wealth or investment asset. Similarly, while natural resources exist independently, their value emerges only when they are integrated into symbolic and socio-technical systems of production and consumption [37,42,43].

This also applies to mineral deposits: their value is dynamic, changing over time also due to technological advancements that lower extraction costs and make previously inaccessible resources recoverable [38]. Gold deeply buried within quartz veins for example, holds no economic value until humans develop the knowledge and technologies enabling its extraction from the natural environment [30,31,36]. This emphasizes how resource extraction operates within complex socio-technical-natural systems, where the natural environment, technological innovations, and human knowledge interact [24].

The prevalence of ASGM in the global South cannot be explained solely by financial constraints. Factors such as the presence and material characteristics of gold deposits, the availability of extraction technologies (e.g., mercury and cyanide), and miners' knowledge about these methods are equally crucial [44]. Understanding how natural resources become economically valuable requires acquiring knowledge about three key aspects: *what* (the material properties of the resource), *where* (its geographic location), and *how* (the technologies used for extraction). Ultimately, ST and GeoST would benefit from a stronger focus on the materiality of the natural environment and knowledge creation processes. This perspective can reveal previously overlooked drivers and barriers of transitions, offering a more comprehensive understanding of sustainability transformations in resource-dependent sectors.

### 2.2. Knowledge creation processes

Knowledge creation is an inherently relational process, arising from interactions between individuals, groups, and their physical or material environments [45]. Consequently, knowledge creation *processes* involve the continuous cognitive exchanges [46–47] that drive innovation and adaptation over time [42,28]. While all economic activities rely on knowledge creation, different sectors require distinct knowledge bases: analytical, synthetic, and symbolic [49].

Analytical knowledge, grounded in science, technology, and innovation (STI), seeks to understand the natural environment through research, systematic experimentation, and objective, repeatable methods [50]. Producing analytical knowledge is often costly and time-consuming, particularly for disadvantaged rural communities in the global South [51]. In these contexts, more informal and adaptable forms of knowledge, such as synthetic and symbolic knowledge, can be more accessible to local communities.

Synthetic knowledge, instead, emerges from direct interaction with the material environment and technologies, addressing specific challenges through practical and inductive processes [49]. It is commonly acquired through learning-by-doing, using, and interacting (DUI) [50]. Individuals may gain this knowledge by actively participating within work environments and benefiting from face-to-face interactions, co-presence, and even sensory experiences such as sight, odor, touch, sound, and taste [14,49,52].

Finally, symbolic knowledge, is deeply embedded in cultural traditions and passed down through generations [49,53]. Through shared practices, individuals create communities of practice and collective identities, shaping nature and resource extraction as socially constructed concepts [42,54]. The value and meaning of natural resources can change over time, transforming from negligible to highly valuable due to new knowledge, technological advances, or market shifts [38]. As communities adapt to changing landscapes and markets, symbolic knowledge can acquire both social and economic value and even become a valuable commodity [42,47,55,56].

Both synthetic and symbolic knowledge bases contribute to frugal innovations, which focus on minimizing costs through simplified design and development processes [57]. These innovations rely on the rapid, cost-effective production and dissemination of knowledge, addressing the urgent needs of economically constrained individuals and communities. In ASGM, such makeshift innovations have played a crucial role in developing low-cost technologies that require minimal formal knowledge. However, it remains ambiguous whether these innovations can lead to environmentally sustainable outcomes [23,57].

In knowledge creation processes individuals share and reinterpret existing information within new contexts.Yet, this requires adapting preexisting knowledge, which can be challenging due to its tacit and context-dependent nature [51,58]. While analytical knowledge is explicit, formal, and codifiable, synthetic and symbolic knowledge is largely tacit, embodied in individuals and specific environments, making it harder to articulate and apply to other contexts [48,49]. Consequently, this knowledge relies on informal sharingand face-to-face interactions [49].

Such context-dependent knowledge, also referred to as *sticky knowledge*, presents additional sharing challenges [23,51]. Unlike generic knowledge and general-purpose technologies, which are more universally applicable and cost-efficient [51,58], sticky knowledge is deeply tied to local environmental and social conditions. Although generic innovations offer economic advantages because they can more easily reach economies of scale, they can yield suboptimal results, particularly with regards to productivity and environmental sustainability [23]. Consequently, in regions with distinct geographical or geological characteristics, such as rural areas in the global South, localized knowledge can be crucial for effective adaptation and sustainability [23,55]

In ASGM, knowledge is often tacit,playing a crucial role in identifying deposits and extraction techniques. Mercury amalgamation remains prevalent as a general-purpose technology due to its low cost and minimal technical requirements, despite its severe health and environmental risks. In contrast, more environmentally sustainable methods, such as gravitational methods using borax smelting, require specific idiosyncratic knowledge and environmental conditions, limiting their adoption across different regions [12,14]. Moreover, technologies can become deeply embedded as behavioural and cultural routines, as with mercury in many ASGM communities, further entrenching its continued use. These examples highlight that achieving a transition toward sustainability may not only involve acquiring new knowledge, but also unlearning deeply embedded detrimental practices [59].

Overall, examining knowledge creation processes can reveal how individuals and communities engage with the natural environment, and whether these interactions result in sustainable outcomes. One useful way to differentiate these processes is by considering whether knowledge is acquired through direct engagement with the environment or through interaction with other individuals [29,30]. Knowledge acquired through direct engagement with the environment, in turn, can be broken down into knowledge of *what* material is extracted, *where* they are located, and *how* they are extracted (Fig. 1).

Studying these processes requires a qualitative and field-intensive research approach. Methods such as participant observation and semi-structured interviews are fundamental for capturing tacit knowledge that might otherwise remain undocumented. Additionally, integrating qualitative with quantitative methods enhances the scope and reliability of findings while addressing methodological limitations.

## 3. Material and methods

The research commenced with the university's ethics committee approving the study and the acquisition of a research permit from the Tanzania Commission for Science and Technology (COSTECH). We prioritized adherence to the European Union's General Data Protection Regulation (GDPR) guidelines on research integrity, ensuring transparency and reciprocity with informants while guaranteeing the anonymity of their data.

Fieldwork in Tanzania spanned five months between 2022 and 2024, covering the cities of Dodoma and Dar es Salaam and three mining regions: Geita (Geita district), Shinyanga (Kahama district), and Mbeya (Chunya district) (see Fig. 2).

The first month (August 2022) was exploratory, aimed at identifying key stakeholders and refining research questions. The remaining four months (July–September 2023 and May–June 2024) were dedicated to data collection. Using a mixed-methods approach, we gathered qualitative data through semi-structured interviews, focus group discussions, and participant observation in all locations, and quantitative data through surveys in the Kahama district. Although the quantitative data was limited to this geographical area, it provided contextual background and revealed patterns and associations between variables. The qualitative data, in turn, offered deeper insights into participants' experiences and deeper perspectives and inter-site differences. This integration allowed for methodological triangulation, enabling examination of the research problem from multiple perspectives and reducing the

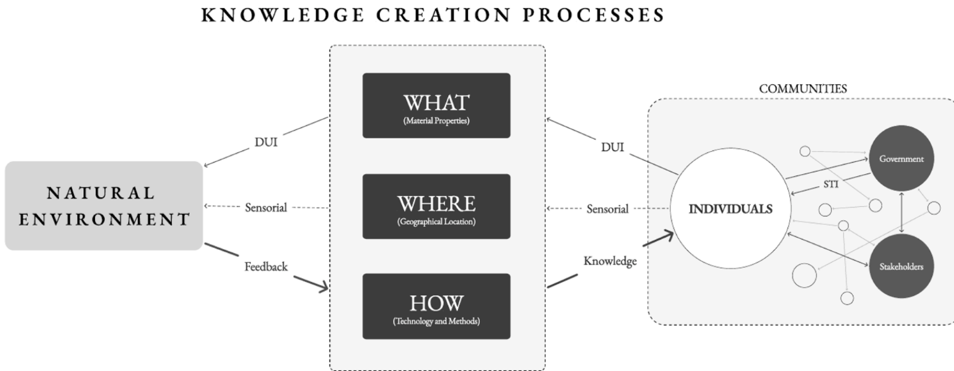


**Fig. 1.** Knowledge creation processes.
We frame knowledge creation from the perspective of a rural community. It highlights how individuals and communities can gather information about the properties of the natural environment through direct engagement and resource extraction, using sensorial and DUI learning modes. In contrast, STI knowledge is often acquired in isolation from rural communities, being received indirectly from external sources.

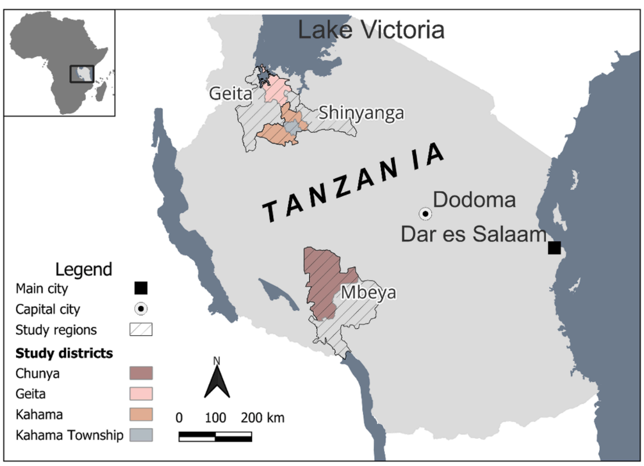


**Fig. 2.** Data collection areas.
Chunya, Geita, and Kahama districts within Tanzania. The survey was handed out in the Kahama district, including both Kahama and Kahama Township. Created with HDX data [60] through QGIS.

limitations of any single method [61]. The research design combined inductive and explanatory elements, enabling us to explore themes that emerged in one method through the lens of the other [62]. Following this design, we present our qualitative and quantitative findings together in the empirical section to support a narrative approach, while indicating the source of the data in the footnotes. We also include direct quotes from the semi-structured interviews with informants.

Among the various methods employed, semi-structured interviews constitute the primary source of data for this research. Specifically, we conducted a total of 119 semi-structured interviews. Respondents included miners involved in various stages of production, brokers, miners' family members, representatives from mining associations, NGOs, and the State Mining Corporation (STAMICO). These also include life-history interviews with long-term miners, which offer insights into the evolution of mining technology and the progressive depletion of superficial deposits. Interviews in Dodoma and Dar es Salaam involved public officials from the National Environment Management Council (NEMC), Ministry of Minerals, Ministry of Health, Government Chemist Laboratory Authority (GCLA), and the Geological Survey of Tanzania (GST).

Interview questions were tailored to each respondent. For miners, they addressed their practices, where and how they learned them, how they apply and share this knowledge in their work, and the challenges they encounter. Additional questions examined the perceptions and interpretations of miners regarding mineral deposits, technologies, and chemical effectiveness and toxicity, as well as their experiences and relationships with other miners, institutions, government officials, and miners' associations. Interviews with mining experts focused on technical aspects of technologies and mineral deposits, as well as the opportunities and challenges faced by ASGM miners in extracting them. Finally, discussions with government officials addressed difficulties in providing access to mining information, capital, training facilities, and demonstration centers.

Participant observation was carried out in mining and processing areas, mineral markets, and supply shops. This involved informal interactions documented in field notes, which were subsequently compiled daily into a detailed diary.

We carried out a preliminary analysis of the qualitative data on the field with respondents and research assistants, allowing their interpretations to contribute as additional data. We comprehensively analyzed the qualitative data through thematic analysis, identifying three primary themes: learning and knowledge acquisition, local knowledge, and mining and knowledge of the natural environment. These themes were further divided into sub-themes. For example, learning and knowledge acquisition included sub-themes such as teaching, DUI knowledge, STI knowledge, schooling, and large-scale mining (LSM). Local knowledge was subdivided into traditional beliefs, toxicity, safety, limits, and adaptation. Mining and knowledge of the natural environment encompassed sub-themes related to gold extraction, including sampling, alluvial processes, the presence of secondary minerals such as sulfide minerals and copper in gold deposits, mineral exhaustion, changes in gold deposits, processing, and excavation. These themes informed the structure of the empirical section.

In addition, we conducted a quantitative survey in the Kahama district of the Shinyanga region in 2023, comprising of 36 questions answered by 116 respondents. The survey combined closed- and open-ended questions covering demographic and socio-economic background (e.g., age, residence, education, work experience, roles in mining), mining practices and technologies (e.g., training sources, whether respondents have taught others, mercury and cyanide use, ore processing, gold sales), and perceptions, behaviors, and aspirations (e.g., environmental attitudes, access to capital, challenges, organizational representation, future plans).

We employed purposive sampling to include small-scale miners at various stages of production, categorizing them into 27 entrepreneurs and 89 workers. This method also enabled us to include a higher proportion of entrepreneurs in the sample than we would expect in the whole population. Entrepreneurs included license holders, pit or machinery owners, and miners who invested in machinery or other assets. Workers instead are laborers compensated through wages or a share of the output.

**Table 1**
Summary of gold deposit characteristics and knowledge bases required.

| | Surface deposits | Deeply buried underground deposits |
|---|---|---|
| **WHAT** Material properties of the ore | Readily available, oxidized ores; larger gold particles and nuggets; higher-grade, free-milling ores found in soft and hard rock. | Mostly smaller gold particles; complex and refractory ores; lower-grade ores found in hard rock. |
| **WHERE** Deposit location | Placer deposits (alluvial, eluvial). Normally up to 2 m below surface. | Underground and reef mining. Normally not exceeding 100 m below surface. |
| **HOW** Extraction methods | Labor-intensive, chisels and hammers, gravitational methods, mercury amalgamation. | Mining shafts, open pits; more mechanized methods; decreasing mercury effectiveness, requiring ore characterization and cyanide leaching. |
| **Knowledge required** | Surface environment (rivers, outcrops). | Ore characterization and exploration. |
| **Knowledge base required** | Sensorial, DUI methods, trial-and-error. | DUI and sensorial less effective; STI provides a significant advantage. |

This summary has been developed based on the literature reviewed in this chapter. It provides a broad classification that highlights general characteristics, which may vary across different geological settings. Instead of a clear-cut distinction, the changes in deposits (and related technologies) evolve along a spectrum as gold is extracted from greater depths. As mining activities move towards greater depths, knowledge complexity of extraction increases.

For the quantitative analysis, we derived binary dummy variables from survey responses (e.g., perceptions of mercury and cyanide as harmful) and constructed a four-category nominal variable classifying miners according to their reported use of mercury and/or cyanide (mercury only, cyanide only, both, neither). To examine socio-demographic and knowledge-related differences between entrepreneurs and workers (Table 1), we calculated row percentages and tested for statistical significance using Fisher's exact test, which is appropriate for small samples and categorical variables. In analyses of chemical use and perceptions (Table 2), the four-category usage variable was reported descriptively, while statistical testing was restricted to the aggregated binary dummy contrasts (mercury users vs. non-users; cyanide users vs. non-users) using Fisher's exact test. All analyses were performed in STATA.

## 4. Background: transforming knowledge, practices, and regulation in ASGM

This section contextualizes the case study by bringing a combination of empirical material and literature. Based on the fieldwork, the first sub-section briefly outlines current practices in ASGM in Tanzania. Secondly, we explore the literature to address how ASGM practices have evolved from pre-colonial to contemporary practices. The final section addresses regulations, policy, and practices related to cyanide. This is essential, as understanding the evolution of knowledge in relation to the natural mining environment requires first grasping the characteristics of the latter. Overall, by understanding how practices and technologies evolved through history and across different contexts, we emphasize how miners have created and reproduced knowledge about gold extraction.

### *4.1. Current practices in Tanzania's ASGM*

ASGM activities in Tanzania are similar to those found in many global South countries [1,2,6,11,12,63,64]. In Tanzania, these follows different modes of extraction including both placer and underground mining. The primary method of placer mining used by ASGM miners in Tanzania is alluvial mining, where natural erosion liberates gold from ore, subsequently transporting it by water into riverbeds. Throughout the fieldwork, we observed the steps pursued by miners to extract gold from these deposits.[1] First, they prospect for gold by manually sampling soft rock found in riverbeds or their surroundings. The ore is concentrated using artisanal sluice boxes and occasionally water pumps. The concentrate is then panned, with some miners incorporating mercury into the process. The resulting mercury-gold amalgam is burnt to obtain gold, while in mercury-free practices the gold is collected directly. Active alluvial mining in Tanzania is limited geographically and seasonally. Instead, most miners engage in underground mining, digging vertical accesses (hereafter shafts) that typically do not exceed 100 m in depth. This process employs artisanal tools like chisels and hammers, as well as compressors, and explosives in more advanced operations. The ore is crushed, either manually, using jaw crushers, ball mills or a combination of them, then concentrated through sluicing, and finally processed with mercury. This method generates gold while producing substantial tailings, often reprocessed using cyanide leaching technology. Alternatively, some miners skip the mercury phase and after the crushing and washing phases the ore is extracted directly through cyanide. These stages are consistent with previous research from Tanzania [9] and other countries [65,66], which include visual comparisons of mercury- and cyanide-based processing, their integration, and their potential environmental and human health impacts.

### *4.2. Evolving mining knowledge and technology in Tanzania and the global South*

Gold has been identified as an extremely precious resource across the world by countless cultures who had no previous contact with each other [67]. Similarly, gold mining practices have been conducted simultaneously and independently across different contexts for thousands of years, including in Sub-Saharan Africa [63,64,67–73]. The historical availability of easily accessible gold in surface deposits, including alluvial and eluvial types, facilitated extraction and processing through artisanal methods reliant on DUI and sensorial learning in pre-colonial Africa, Asia, and Latin America [63,64,70–73]. High-grade gold could easily be identified through its bright color and could be found in surface and near-surface deposits, typically within 1–2 m [71–73]. Gold found on the Earth's surface has often undergone weathering, meaning the gold is liberated from other minerals and can easily be extracted without the aid of agents like mercury or cyanide. Consequently, gold extraction could rely on direct observation and understanding of the environment. Miners studied the landscape, tracing rivers, identifying vegetation, and recognizing specific rock types [70].

The availability of free gold reduced the necessity for mining underground deposits, explaining why it was uncommon in pre-colonial contexts and challenging in contemporary ASGM [70–76]. Ores in deeply buried deposits are less exposed to weathering and oxidation, and often contain higher concentrations of refractory ores, which include sulfide minerals; and complex ores containing other metals such as copper or silver [12]. These minerals form complex chemical bonds with gold, increasing costs and knowledge required to extract gold [70, 71]. Extensive mining traditions can prove a significant advantage in these conditions compared to extraction of surface deposits, as the knowledge required for extraction is significantly higher [44]. Such deposits are normally valued only by LSM operations capable of overcoming these challenges through knowledge intensive activities and

[1] Data: participant observation and interviews, 2022-2024

**Table 2**
Differences between entrepreneurs and workers, assessed through percentages abd p-values from Fisher's Exact test.

| Categories | Selected variables | Entrepreneurs (27) | Workers (89) | Total | p-value |
|---|---|---|---|---|---|
| 1. Age | $18 \leq$ age $\leq 25$ | 3.70 % | 21.35 % | 17.24 % | 0.040 |
| | $25 <$ age $\leq 40$ | 59.26 % | 55.06 % | 56.03 % | – |
| | $40 <$ age | 37.04 % | 23.60 % | 26.72 % | – |
| 2. Education | Completed secondary school | 44.44 % | 12.50 % | 20 % | 0.001 |
| 3. Experience | I have worked in ASGM for $\leq$ 2 years | 7.41 % | 31.46 % | 25.86 % | 0.012 |
| | 3 years $\leq$ experience $\leq$ 9 years | 37.04 % | 50.56 % | 47.41 % | – |
| | Experience $\geq$ 10 years | 55.56 % | 17.98 % | 26.72 % | 0.000 |
| | Total | | | | 0.000 |
| 4. Teaching | I have taught someone how to do mining activities. | 85.19 % | 51.69 % | 59.48 % | 0.002 |
| | I have learnt how to do mining activities alone* | 22.22 % | 46.07 % | 40.52 % | 0.043 |
| | I have not received training from state or private initiatives. | 73.08 % | 98.88 % | 93.04 % | 0.000 |
| 5. Perception | Cyanide can be harmful to people and the environment** | 77.78 % | 25.84 % | 37.93 % | 0.000 |
| | Mercury can be harmful to people and the environment** | 77.78 % | 38.20 % | 47.41 % | 0.000 |

* Trial and error learning. Other answers included I have learned from friends, family, co-workers, school.
** Other responses included "Cyanide/mercury is not harmful to people and the environment" and "I don't know". Source: Authors' elaboration on the Kahama Survey.

This table illustrates differences between the entrepreneurs (27 individuals) and workers (89 individuals) in our sample across selected variables related to education, experience, training, knowledge sharing, and environmental awareness. The percentage indicates the respondents in each group who respondent positively to the statement (e.g., 3.70% of entrepreneurs are aged $18 \leq$ age $\leq 25$). Statistically significant relationships are indicated through the two-sided p-value in the last column. The p-values indicate the statistical significance of inequalities. Notably, a statistically significant relationship suggests that compared to entrepreneurs, workers are more likely to be younger (1), less educated (2), and have less experience in mining (3). Furthermore, entrepreneurs are statistically significantly more likely to having taught and learnt mining activities from others, including formal training from the government or other entities (4). Awareness of the dangers of mercury and cyanide also varies. A statistically significant greater proportion of entrepreneurs recognize the harmful effects of cyanide (77.78% vs. 25.84 %, $p = 0.000$) and mercury (77.78 % vs. 38.20 %, $p = 0.000$) compared to workers.

advanced technology [44]. Nevertheless, LSM operations often extract deposits initially identified by ASGM miners, underscoring the relevance of the knowledge they acquire [44].

Pre-colonial miners are believed to have first engaged with underground mining by targeting high-grade auriferous quartz veins, with outcrops visible from the surface [63,64,67,69,77]. In these cases, ore processing is required and primarily relied on gravity methods and water, made viable by the high-grade nature of the gold. Only high-grade ores, typically at least 60 *g* per ton in Southern Africa, and mostly soft rock deposits were considered valuable and exploitable [71, 74]. In some African regions, there is continuity between these artisanal methods and contemporary ASGM activities. For instance, the Shona miners in Zimbabwe continue to use shallow bowls for gravity-based methods [71].

While there is continuity between traditional mining practices and ASGM today, these have largely been influenced by colonization [63,64, 77]. European powers established mining firms across Latin America, Sub-Saharan Africa, and Asia, introducing mercury among other technologies between the 16th and 19th centuries [76,78]. Mercury enabled colonial firms to industrialize gold mining by extracting gold from lower-grade ores [67,79]. Yet, this technology gained prominence by indigenous populations only since the 1970s, when the end of the Bretton Woods system led to a surge in the price of gold [1,14,77,78,80]. These conditions created opportunities for livelihood creation in conditions of poverty, which still characterize ASGM today [70,81–83].

The combination of scientific knowledge, acquired from colonial firms, and traditional DUI and sensorial knowledge, opened opportunities for ASGM miners to extract gold from lower-grade ores in deeply-buried deposits. This has been further motivated by the depletion of more accessible surface and high-grade gold deposits [17,19]. The depletion of these more accessible gold deposits has rendered mercury indispensable in low-technology and low-knowledge contexts, as finer gold cannot be effectively captured through basic concentration methods [14,67,74,79,82]. The mercury amalgamation method facilitates gold extraction across various settings, serving as a generalized technology that in most oxidized deposits does not necessitate extensive knowledge of the ore.

Nevertheless, while mercury can extract up to 80 % of gold from surface oxidized ores, it is largely ineffective for refractory and complex ores [81]. In Tanzania's Lake Zone, particularly the Nyarugusu area, there has been a substantial decline in ASGM activity since the 1990s due to the exhaustion of surface gold deposits [76]. In this context, knowledge of mercury and the surface environment, particularly acquired through direct observation, has become less relevant [44]. Consequently, ASGM miners often struggle to identify potential deposits as they persist in adopting trial and error and sensorial knowledge bases in the absence of STI knowledge [6,75].

### 4.3. Cyanide: knowledge and regulation in Tanzania

Compared to mercury, cyanide leaching is more efficient, extracting 60–90 % of gold from ore [11,14]. While it is primarily suited to free-milling ores, it can also be applied to refractory and complex ores, albeit with lower efficiency [11,12]. Nevertheless, cyanide leaching can also represent a threat to humans and the environment, especially as under certain conditions it may produce the highly toxic hydrogen cyanide gas [11]. Many countries have strongly regulated the use of cyanide in mining, as the unsafe application of this technology can lead to environmental disasters [6,11,14,19,23]. A main challenge with cyanide leaching in ASGM relates to how technology is applied. Several unsafe cyanide practices have been observed, including the application of cyanide on mercury-contaminated tailings, which can promote the creation of one of mercury's most toxic chemical compounds: methylmercury [8,9,11,17]. This underscores the need for technical and science and technology knowledge to operate this technology effectively and safely. DUI and sensorial learning are less effective, demonstrating the increasing importance of more technical STI and context-specific sticky knowledge. Therefore, the use of cyanide by miners with insufficient expertise and equipment is often discouraged [6,12]. The following table summarizes different gold deposits characteristics, and what knowledge and technologies are required to extract them efficiently (Table 3).

Despite safety challenges, when regulated and controlled, cyanide is considered a lesser evil compared to mercury and has been identified by organizations and governments, including Tanzania's, as a solution to reduce mercury use [8,11,14,15]. Moreover, contrary to mercury, which can persist for centuries in the environment, hydrogen cyanide gas breaks down rapidly [6,11,14]. This makes *how* cyanide leaching is applied and the knowledge about this essential in determining whether it can be considered as a less harmful alternative to mercury or not [6,8,

**Table 3**
Mercury and cyanide users and perceived harm.

| Miner group | Miners n ( %) | Perceived mercury harmful n ( %) | Perceived cyanide harmful n ( %) | Fisher's exact (users vs perception) |
|---|---|---|---|---|
| Mercury only | 32 (27.8 %) | 20 (62.5 %) | 13 (40.6 %) | |
| Cyanide only | 10 (8.7 %) | 7 (70.0 %) | 9 (90.0 %) | |
| Both chemicals | 6 (5.2 %) | 5 (83.3 %) | 6 (100.0 %) | |
| Neither chemical | 67 (58.3 %) | 22 (32.8 %) | 15 (22.7 %) | |
| Total Mercury users | 38 (33.0 %) | 25 (65.8 %) | – | $p = 0.006$ |
| Total Cyanide users | 16 (13.9 %) | – | 15 (93.8 %) | $p = 0.000$ |

Source: Authors' elaboration on the Kahama Survey data.
This table presents the relationship between miners' use of chemicals for gold extraction and their perception of harm to humans and the environment. Miners are divided into four categories: 1) those who have used only mercury, 2) those who have used only cyanide, 3) those with experience using both chemicals, and 4) those who have used neither. These groups were compared with miners' perceptions of harm from mercury and cyanide, based on the survey question: "Do you think mercury/cyanide can be harmful to people and the environment?" which resulted in two binary variables were created: 1 = Yes, 0 = No/Neither. For statistical analysis, all mercury users and all cyanide users were combined into separate groups in the table's second section, and Fisher's exact test was applied to examine the association between chemical use and perceived harm. Aggregation was necessary due to the small sample sizes in the original four categories, which limited the statistical power of comparisons at that level.
The results show that miners with direct experience using a chemical are statistically significantly more likely to perceive it as harmful. For mercury, the association between usage and perceived harm is statistically significant ($p = 0.006$), indicating there is less than a 1 % probability that this association occurred by chance. For cyanide, the relationship is even stronger ($p = 0.000$). One survey was excluded due to incomplete responses.

9,72]. Consequently, regulation and enhancing knowledge acquisition are two crucial aspects in the adoption of cyanide practices.

In Tanzania, different government agencies regulate the use of cyanide, including the National Environment Management Council (NEMC) and the Occupational Safety and Health Authority (OSHA), which regulate environmental protection and safety and health issues respectively. Under these regulations, small-scale miners are not required to deposit cyanide leached tailings in tailing storage facilities, which are instead required for middle-scale operations [6,9,15].

With regards to knowledge acquisition, the main agency responsible for supporting ASGM by providing knowledge, equipment, and infrastructure is the State Mining Corporation (STAMICO). The latter conducts training for miners on safe alternatives to mercury, including cyanide leaching. One of the main projects developed by STAMICO is developing demonstration centers with cyanide leaching, mostly in regard to carbon-in-pulp technology [8,84]. However, these have limited impacts to small-scale miners, especially as they mostly use the more accessible VAT leaching technology [6,8,84]. Overall, the combination of loose regulations, enforcement, and limited knowledge acquisition, create space for miners to act informally and incurring in fewer costs. However, this also results in inefficient and sometimes unsafe cyanide leaching practices [6,9,11,84].

## 5. Empirical section: knowledge creation processes in ASGM

This section explores knowledge creation processes in Tanzanian ASGM by integrating qualitative evidence from interviews, focus groups, and participant observation with quantitative survey data in a narrative style.

### 5.1. Sensorial learning

Our qualitative data reveals miners continuously gather sensory knowledge, particularly through sight, as well as sound, touch, and odor.[2] These practices are embedded in specific geographical and geological contexts, especially when working with surface or near-surface deposits. In gold prospecting, visual observation is crucial for identifying alluvial deposits or quartz reef outcrops containing gold. Such reefs are common in the Lupa Goldfields, where some experienced miners use geobotanical prospecting to identify them. This is explained by Godfrey, a miner with over 20 years' experience in ASGM:

> *"From the bush, you can learn that termites cannot live without water. If you see three mounds in a straight line, there could be an underground water stream below. And even trees! If there are big trees all on the same line, their roots are getting more water than others. This is important because the gold vein is associated with water. Once you spot these patterns, sometimes you can even see the vein outcrop on the surface. Then, you crush the rock and test it."*

Similarly, another miner explains the process of identifying alluvial gold:

> *"First, you look where the water is running. The water carries sand containing gold, so you can just try and do sampling by panning there. If you find gold, you start working in that spot."*

Once potential extraction sites are identified, miners engage in a process referred to as the *local test*.[3] They pick a handful of ore, crush it, and pan it until bright golden particles emerge (Fig. 3). This test is essential, as it is used to establish the price of the ore for buyers or whether it is worth processing. Symbolic knowledge sometimes aids miners in explaining complex mining characteristics or processes. For instance, the Swahili term *mlenda*, which refers to an okra based slimy liquid soup, is metaphorically applied to describe such small, liquid-like gold particles within the ore, resembling the texture of mlenda.[4] Nevertheless, miners often struggle to articulate their processes, reflecting a high degree of tacit knowledge. Their understanding is shaped by direct engagement with the ore, the environment, and mining technologies, underscoring the importance of sensory engagement in non-verbal knowledge transmission.

Sensorial cues can also assist miners in assessing the toxicity of chemicals used in ASGM. Our interviews indicate that miners working with cyanide recognize both its presence and its dangers. The peculiar odor of cyanide is one cue, but more salient are its immediate effects, such as visible burn marks following skin contact with the chemical. When asked about their perception on cyanide, one cyanide operator recounted the impact they witnessed on wildlife:

> *"Oh yes, cyanide is very toxic. Once, I saw a bird, and other people saw cows drinking from the* [vat leaching] *tanks. They drank the water mixed with cyanide and died shortly after!"*

This is further corroborated by our quantitative data, which indicate that miners working with cyanide are more likely to recognize its dangers. This applies especially to entrepreneurs, as this sub-group directly engages with cyanide more frequently than most workers (see Table 1, Point 4; and Table 2).

Unlike cyanide, mercury has no odor, taste, or immediate physical symptoms. Its hazards are further obscured because both the vapor released during burning of mercury-gold amalgam and methylmercury are invisible, making them difficult for miners to detect (see Table 1, Point 5). During fieldwork, we repeatedly observed uncertainties concerning mercury's toxicity. For example, in an alluvial mining area in

[2] Data: Semi-structured interviews with miners and participant observation.
[3] Data: Participant observation and interviews with miners.
[4] Data: Interviews with miners.

**Fig. 3.** The gold in mlenda form resulting from the local test. Picture taken during the 2022 fieldwork in a processing area in the Kahama district.

Chunya, an experienced miner noticed another miner rinsing mercury remnants into the river after amalgamation and remarked:

> *"See? Again, they just washed the mercury into the river. It's not good, don't you see the kids playing in the river? Also, people use this water for domestic purposes.* [...] *But in the end, it is dangerous only if you have stomach ulcers. If you are healthy, even if you swallow it, it will go away when you go to the toilet."*

Another experienced miner, who was present, commented:

> *"I just heard that mercury is bad... but I've never seen any effect. Anyway, I drink milk, so if these effects are real, the milk will dilute the chemicals."*

Nevertheless, our quantitative data indicate that miners working directly with mercury or cyanide are statistically significantly more likely to perceive them as harmful to humans and the environment (Table 1).

Overall, these findings suggest that while many miners recognize potential risks associated with mercury, the underlying processes remain uncertain. This highlights that miners' awareness and understanding are also shaped by knowledge creation processes beyond direct sensory experience.

This also illustrates that although sensory methods are essential in some cases, they are insufficient in others. Interviews reveal that the absence of visible or tangible effects creates uncertainty, often filled by beliefs in magic, speculation, and hearsay. In the Lake Victoria Goldfields, for example, gold reef outcrops and alluvial deposits are rare, rendering surface observations largely ineffective. The peculiar geology of the Lupa Goldfields poses an additional challenge, as quartz veins expand and contract irregularly. Miners without analytical knowledge, such as geological data, often attribute these changes to magical influences. One miner described this belief:

> *"We found the vein so rich in gold and I was thinking 'I will not get less than 2 kg of gold!' But then the vein disappeared, and we only got 60 g Someone had bewitched my vein! They shifted it from my shaft to theirs* [...] *You have to go to the traditional healer to protect your vein, or someone will shift it to their own shaft. In short, you cannot get gold without protection from Mganga* [traditional healer]*."*

A further example was illustrated by Godfrey. He explained that most miners disregard geobotanical methods, and being a successful miner often brings speculations about how this wealth is obtained. In his words during the interview:

> *"I've discovered many gold deposits using these geobotanical methods, and I was the first to use ball mills in this area. It's hard work, but you also have to be smart. Yet miners don't understand this, and they say I am using magic and that I sacrificed my father to get rich.* [...] *When they don't understand something, they always think it's magic!"*

### 5.2. Learning through experience: DUI and trial-and-error practices

To overcome challenges with sensorial learning, miners often rely on DUI and trial-and-error practices. A notable example of this approach is in prospecting. Miners admit to frequently engaging in blind digging due to the higher costs and greater difficulty of acquiring geological knowledge through mineral exploration, compared to the relatively lower cost of labor.[5] Most entrepreneurs interviewed have stated to acquire licenses, dig shafts, and sample ore, without any preliminary geological data. Such entrepreneurs consider trial-and-error practices a more viable alternative to acquiring knowledge through other means. One entrepreneur described this practice in an interview:

> *"For us as small miners, we just go anywhere and dig. If you don't find anything, then the next day you shift to another place. There is no measurement to help you know if it's a good area to start digging. The big issue is, how deep should you go? Sometimes you find a place with gold, but the big challenge is that you don't get enough, and it lasts only for a short time.* [...] *This business is very risky because you have to dig a lot to find gold, and digging is a lot of money. If, in the end, there is not enough gold, you can get a big loss!"*

Miners also predominantly affirm engaging in trial-and-error methods in ore processing.[6] For example, miners frequently amalgamate ores with mercury, even when this approach is unproductive. This practice is explained by a miner:

> *"We do the local test and you can see how fine the gold is. And if you see maybe the particle size is too small, mercury is not very good, only cyanide works. But we must still try with mercury, you never know what you get."*

Cyanide leaching has similarly evolved through trial-and-error learning. Some miners reprocess the same ores multiple times, having observed gold recovery during subsequent rounds.[7] This observation and related uncertainty lead them to stockpile and process tailings multiple times. Similarly, miners have observed that increasing sodium cyanide in the leaching solution for ores with high parts per million (ppm) of gold or sulfide minerals improves gold recovery rates. Unlike with mercury processing, miners closely monitor the costs, recognizing that increasing chemical inputs can lead to significant financial losses.

Overall, stockpiling tailings has become central to trial-and-error practices, as miners acknowledge the latent value of these materials. While these methods do not provide precise data on ore composition or

[5] Data: interviews with entrepreneurs.

[6] Data: interviews with miners.

[7] Data: interviews with entrepreneurs and chemists.

detailed prospecting insights, the relatively positive outcomes have generated sufficient knowledge and economic returns motivating miners to pursue these practices despite their detrimental environmental impact.

### 5.3. Acquiring science and technology-based knowledge (STI)

While knowledge and technologies possessed by miners in ASGM have traditionally been frugal, miners are increasingly acquiring scientific geological information from larger companies and through ore characterization tests.[8] A limited number of informants reported acquiring geological information informally from private medium and LSM companies or government agencies. For example, one entrepreneur stated:

> *"There used to be a large-scale mining company doing exploration here on our land. They found gold, but now we are the ones mining here.* […] *You can get information from them, even if the companies are foreign. When they drill and explore, they drill with some Tanzanians, so there are ways to get information from those Tanzanians."*

In contrast, basic ore characterization tests are proliferating, offered by laboratories and elution plants at prices as low as TZS 30,000 (~USD 11) per sample. These tests primarily measure gold ppm and are increasingly used to assess the concentrations of copper, zinc, silver, and sulfides in the ore. While some miners admitted focusing only on gold ppm; others recognize the influence of other minerals on extraction processes, leading to increasing demand to include these minerals within tests.[9] An entrepreneur in Chunya illustrates this shift:

> *"Currently, we just analyze gold and copper because they charge thirty thousand only. Last time, I tried multi-element analysis, but they charge 150k per test, and it's not worth it. But… how can the chemist prepare the reagents if they don't know what material they have?"*

In the Lake Zone, miners report that tests for sulfide mineral content, now included in the more affordable analyses, have become essential for acquiring knowledge to assess operational profitability. This is expressed by an entrepreneur, while pointing at stacks of black tailings:

> *"You see those? They are rich in sulfur, and we cannot process them, so we keep them, hoping that one day we will find a solution. It requires too many chemicals: if the test shows more than three thousand sulfur ppm, there is no profit. Sometimes we got test results showing sulfur levels of seven thousand ppm!"*

These statements also draw attention to the critical role of chemists in cyanide leaching practices. Chemists are employed to manage ore sampling and especially the leaching process, which are essential for both gold recovery and minimizing the toxicity of sodium cyanide. As expressed by an entrepreneur:

> *"Every place is different. Here we have sulfur but not copper; in another area, there is copper but no sulfur. So, at each site, you need to find a good chemist who can separate these minerals. If you find a chemist who is not skilled enough, he will fail to separate all the gold from these other metals."*

In interviews with five chemists, only one had formal education for the role, while the others were trained informally, primarily learning through trial and error and from other miners or chemists. For example, Baraka, a plant operator aspiring to become a chemist in Chunya, has worked for two years under a chemist at a vat leaching plant and explains the primary challenge:

> *"If gold ppm is high, you must increase cyanide ppm. I can measure and adjust accordingly. Yet, as you dig deeper, conditions change; they say there is copper or sulfur. The 'fake chemist' may fail to handle these challenges. Me too, I still don't really know what to do with those minerals in the tailings.* […] *There are many chemists without certificates because plant owners often do not trust someone just because they graduated from university. So, when you're an operator like me, when you get experience, the owner will entrust you to be the chemist."*

This quote highlights how knowledge to address gold ppm and cyanide ppm is learned through a combination of trial-and-error practices and application of STI knowledge. In contrast, managing higher concentrations of copper or sulfides necessitates knowledge of additional chemicals and involves multiple variables, complicating trial-and-error approaches. Hence, some chemists keep and even share self-written notebooks summarizing the chemicals and procedures required. This denotes that despite the high costs of acquiring scientific knowledge, it is more easily codified and formally shared. While this illustrates the increasing importance of analytical knowledge in ASGM, its application often resembles synthetic knowledge.

The last quote also suggests some entrepreneurs raised the concern that informal chemists struggle to extract gold from complex and refractory ores. Yet, informal chemists are often regarded as more trustworthy, affordable, and accessible than their formally trained counterparts. As a consequence, most entrepreneurs prefer hiring informal chemists showcasing how being trusted as a worker often outweighs formal education. This aligns with previous research on the sector's emphasis on trust [8] and the gap between youth skills and employer requirements [85].

### 5.4. Communities of practice: acquiring and sharing information

Given the complexities in creating knowledge firsthand, acquiring information from others can be invaluable to miners. Moreover, limited tools imply acquiring knowledge such as geological data is unfeasible. Miners' associations play a critical role in this process, acting as intermediaries between government agencies (who also obtain knowledge from LSM and ASGM).[10] Consequently, networking and experience within LSM, associations, or government agencies offer miners significant advantages in sustaining ASGM activities.

Miners share information with each other, particularly with respect to practical skills. Many of our interview respondents reported learning mining activities on-site, either by following instructions from employers and co-workers or by observing others at work.[11] This is supported by our survey data, where respondents were asked, *"Who taught you mining activities? Indicate the main source"* (Table 4). The results indicated that *"learning alone"* accounted for the largest single share of answers at 40 %. However, when we aggregate the responses where miners indicated learning from others, we find that 59 % of respondents identified another person as their main source of knowledge. These findings are further validated by the question, *"Have you taught others about mining activities?"* to which 59 % of respondents answered affirmatively. Additionally, 93 % of respondents reported not receiving any training from government institutions. Notably, only one respondent, a cyanide leaching chemist, reported receiving formal mining education through a college.

Learning is crucial both for workers and entrepreneurs. For workers like Thomas, in-situ learning about mineral composition and the related chemicals allowed him to advance from a plant operator to a chemist. For others, acquiring sufficient knowledge facilitated their transition

[8] Data: interviews with miners and STAMICO.

[9] Data: interviews with entrepreneurs and elution plant managers.

[10] Data: interviews with miners, government agencies, and miners' associations.

[11] Data: interviews with miners and participant observation.

**Table 4**
Learning sources for workers and entrepreneurs.

| | Who taught you mining activities? (Main source) | | | | | | |
|---|---|---|---|---|---|---|---|
| | School | Alone | Family member | Friend | Employer/ co-worker | Total people | Total |
| Workers | 1 | **41** | 12 | 34 | 1 | **47** | 89 |
| Entrepreneurs | 0 | **6** | 9 | 10 | 2 | **21** | 27 |
| Total | 1 | **47** | 21 | 44 | 3 | **68** | 116 |
| Total (%) | 0.86 | **40.52** | 18.10 | 37.93 | 2.59 | **58.62** | 100.00 |

First three rows have frequencies and last row has row percentages of the total sample for each learning source. Two answers which received no answers are "From State or private initiatives" and "Other". The "Total people" is the cumulative answer of "Family member", "Friend", "Employer/co-worker". Source: Authors' elaboration on the Kahama Survey.

from workers to small-scale entrepreneurs.[12] As a result, the identity of an entrepreneur in ASGM is shaped by their knowledge and ability to learn and adapt to changing mining environments. Without this knowledge, aspiring miners may struggle to integrate into the communities of practice of ASGM. In turn, communities of practice motivate miners to learn, compete, adapt, and share knowledge. These identities are also intertwined with commodification processes, given that the primary goal of extraction is income generation through the sale of gold on global markets. Considering that no equal commodification processes rewarding safe practices is in place, acquiring knowledge is seldom directed towards this objective, resulting in poor environmental practices.

### 5.5. Creating and acquiring knowledge as adaptation practices

Advancements in technology and human-induced environmental changes require individuals and communities to continuously adapt. While many miners interviewed persist in using mercury amalgamation due to the resistance of established practices, more successful miners have continuously acquired knowledge about environmental changes and technological advancements.[13] For instance, a successful long-term miner from the Kahama district, with over four decades of experience, reflects on the evolution of ASGM from alluvial to mechanized practices:

> "*I started Mining in 1982, when there weren't many doing mining, most people didn't know about mining. Back then, we were just hammering the rocks; we didn't have all these machines. It was easier to find gold compared to now, you could just pick big gold nuggets and all you needed was washing in the rivers.* […] *We were satisfied with these small nuggets with no costs. We didn't have sampling and we just dumped the tailings in the river. We didn't know how much gold we were throwing away* […] *Mercury was already there, but it wasn't used so much like today. But now, the only gold you can find is dust form, and to remove it from the sand you need an agent, like mercury, or cyanide.* […] *One day a man came from Zimbabwe and started collecting the tailings we dumped. They took them to these plants they started building, and they were making big money. So, I thought if I learn about this technology, it will give me money.* […] *I think today there is more gold, but it is in form of dust, and you must put good capital so as to get the gold.*"

Similarly, an entrepreneur in Chunya stressed the importance of learning about new chemicals to adapt to the high copper content in their ore:

> "*At my PML* [primary mining license]*, we have a big issue with copper. If you have 10 ppm of gold and high copper ppm, and you use cyanide, lime, and caustic you will end up extracting… maybe only 60 %* [of gold]. *Nowadays, we are getting new reagents from Mwanza to deal with copper, like ammonium sulfide, sodium nitrate, hydrogen peroxide, and lead nitrate. When we mix these chemicals with cyanide, lime, and caustic, you can get up to 80 %.*"

These examples illustrate how acquiring knowledge can reshape the perceived value of resources. The ability miners have to acquire knowledge and reproduce it in different contexts represents a key adaptive practice to changing environments, technologies, and markets.

### 5.6. Knowledge inequalities

A further key finding from our quantitative analysis is the statistically significant difference between workers and entrepreneurs across several variables.[14] Table 4 shows entrepreneurs are significantly more likely to have completed secondary education and to have worked in the mining sector for a longer duration compared to workers. Similarly, entrepreneurs are more likely to have received training on mining activities from state agencies or other individuals, such as co-workers and friends. In contrast, workers are more likely to have learned mining activities independently, revealing a disparity in social capital between the two groups.

These findings reflect task-based inequalities: workers typically engage in simpler, repetitive tasks requiring limited and specific knowledge (e.g., manually crushing rocks, amalgamating with mercury, or operating ball mills). Entrepreneurs, by contrast, must possess a broader understanding of the entire process, including managing cyanide leaching operations and administrative tasks like obtaining mining licenses. These disparities highlight how ASGM provides opportunities to individuals with a wide range of socio-economic backgrounds and skill levels. However, these inequalities are also associated with the challenges workers face in transitioning from low-wage labor. This is corroborated by our interviews with entrepreneurs, where most acquired their roles through family connections or by bringing capital from other businesses rather than by progressing from within ASGM.

While understanding the natural environment and resource extraction is critical for entrepreneurs, it is less important for workers. Our qualitative data indicates that the most successful entrepreneurs actively seek to enhance their knowledge of ores and technologies to address mining challenges.[15] Adapting through knowledge creation provides a significant advantage to entrepreneurs, while it may have a smaller impact for capital-restricted workers.

## 6. Discussion

This study examined how changes in the natural environment influence ST in ASGM and how miners create and apply knowledge about extraction. Environmental changes, such as the depletion of surface deposits, emerging technologies, and rising gold prices, push miners to explore deeper, more complex to extract deposits. This shift necessitates new knowledge about deposit characteristics, locations, and extraction methods.

Our findings highlight the central role of knowledge and knowledge creation in enabling ASGM miners to adapt to environmental and

[12] ibid.
[13] Data: Interviews with miners and participant observation.
[14] Data: Table 1.
[15] Data: interviews with miners.

technological transformations and to transition away from mercury use. Mercury functions as a general-purpose technology, requiring minimal context-specific knowledge and supporting day-to-day livelihoods. In contrast, mining complex deposits efficiently through cyanide leaching demands specialized knowledge, as traditional sensory and trial-and-error methods are insufficient.

Economic gains, falling ore grades, and the exhaustion of more accessible surface gold deposits provide incentives to overcome knowledge barriers and acquire the skills necessary for cyanide leaching. At the same time, uncertainty about extraction outcomes and the high knowledge requirements sustain mercury use, even among miners who can afford cyanide-based methods. Cultural practices, limited regulatory enforcement, and economic accessibility further shape these choices, illustrating how current practices emerge from the interplay of multiple incentives.

In addition, although cyanide is arguably less harmful when properly managed, its safe and effective use requires skilled labor, mechanization, capital, and strong regulatory oversight. A fully safe and regulated ASGM based on cyanide extraction would demand significant restructuring of ASGM, introducing high-skill labor and stronger organizational hierarchies, which could exacerbate existing inequalities. The sector's shift toward knowledge-intensive practices threatens demand for low-skilled labor, historically a cornerstone of rural livelihoods in the global South.

In this evolving landscape, miners with greater access to knowledge and social networks—typically wealthier entrepreneurs—can leverage regulatory frameworks to capture higher profits from complex ore deposits. In contrast, workers and resource-limited entrepreneurs remain tied to low-skill subsistence employment and extraction through mercury.

These dynamics underscore the difficulty of achieving multiple Sustainable Development Goals simultaneously: fostering innovation and industrialization (SDG 9) while reducing poverty and promoting inclusive growth (SDGs 1 and 10). Consequently, under these conditions, the attempts to promote cyanide as an alternative to mercury cannot be considered a transition towards sustainable development. Cyanide does not currently significantly disincentivize mercury use; rather, it introduces additional chemical risks while reinforcing emerging inequalities.

Policy interventions must balance these objectives and leverage on these incentives, fostering sustainable development while mitigating hazardous practices in ASGM. Expanding access to geo-environmental knowledge and ore characterization tests could further nudge miners adopt less detrimental extraction methods tailored to local conditions. Leveraging knowledge creation processes and social learning of communities could improve knowledge dissemination. Policies should also facilitate co-existence between ASGM and larger operations, enabling ASGM miners to extract ore and sell it to regulated operators with specialized knowledge. This would provide both low-skilled employment in ASGM while supporting the growth of a more knowledge-intense, highly-skilled sector. However, this approach requires careful implementation to avoid reinforcing inequalities. Additionally, raising awareness about the risks of mercury remains crucial. Technologies that provide sensory warnings in proximity with mercury contaminated areas could be an innovative approach to risk reduction.

Beyond ASGM, this study contributes to ST research, and particularly to the Geography of Sustainability Transitions (GeoSt). We argue that systematically integrating the natural environment into this field—for example, by explicitly incorporating it into the concept of landscape within the MLP framework—offers a meaningful strategy to advance these objectives. Understanding the role of geography in transitions requires analyzing how knowledge about the natural environment and extraction technologies is created, shared, and applied, particularly in the global South, where natural resource-based industries play a central role.

Future research should further explore the materiality and agency of the natural environment in shaping transitions. A posthumanist or new materialist perspective could address the socio-technical bias in ST research, overcoming the challenges arising from opposing positivist and relational approaches. This would enhance the applicability of empirical case studies for policy development.

## 7. Conclusion

This study explored knowledge creation processes as adaptation to environmental and technological transformations in ASGM in Tanzania. Historically, ASGM has relied on low-capital and low-technology extraction methods, using sensory experience and trial-and-error learning. However, resource depletion of high-grade surface deposits and the increasing availability of more efficient technologies like cyanide leaching requires adaptation through learning.

Our findings show that miners adapt to environmental and technological shifts in ASGM through knowledge creation processes. Some acquire ore information through characterization tests, hire skilled professionals, and learn from government agencies or LSM operations. Miners who combine sensory learning with more advanced synthetic and analytical knowledge develop more effective extraction strategies and practices. Nevertheless, mercury use persists due to the uncertainties surrounding knowledge requirements of these technologies.

By focusing on knowledge creation processes, this study highlights systemic barriers to phasing out mercury in ASGM. While knowledge can catalyze sustainability transformations, its increasing cost and accessibility challenges can also create new inequalities. Ultimately, knowledge mediates the relationship between the natural environment, technologies, and communities, making it a critical factor in ST.

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## Statements and declarations

**Compliance with Ethical Standards**: This research has received approval from the University of Turku's ethics committee, as well as a research permit issued by the Tanzania Commission for Science and Technology (COSTECH).

**Informed consent**: informed consent was obtained from all participants involved in this study.

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

## CRediT authorship contribution statement

**Oliver D. Tomassi:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Funding acquisition. **Abel A. Kinyondo:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **Jussi S. Jauhiainen:** Writing – review & editing, Visualization, Validation, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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