

Environmental implications of Chemical based artisanal and small scale mining in post war Tigray, Northern Ethiopia

Hagos Gebreslassie Gebru

hagmeb@gmail.com

Adigrat University

Belay Manjur Gebru

Tigray Institute of Policy Studies

Zenebe Girmay Siyum

Mekelle University

Gebreslassie Teklay Weldengus

Adigrat University

Research Article

Keywords: Artisanal and small-scale mining, Toxic chemicals, Mercury and Cyanide, Systematic review, Devastating war, Tigray

Posted Date: April 10th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9166971/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Artisanal and small-scale mining (ASM) is one of the top off farm sources of livelihood, causing drastic environmental and health problems, which, however, has overlooked. This synthesis was aimed to assess the multidimensional crisis, particularly environmental consequences from the chemical based ASMs in the aftermath of the devastating war in Tigray. An investigation of audio-visual content released through media, systematic literature review, as well as field observations and discussions were used to generate quantitative and qualitative data. Collected data were analyzed using descriptive statistics, narrative, and content analysis methods. The findings revealed a dramatic increase in illegal, informal and indirect participation in ASMs. These have evolved into aggressive, land-destructive, and toxigenic operations involving the widespread use of internationally banned chemicals, particularly mercury (Hg) and cyanide (CN). This escalation is attributed to the collapse of previously functional systems for legalizing, formalizing, regulating, and monitoring ASMs. The use of these toxic substances poses significant environmental threats by disrupting hydrological processes, altering soil dynamics, and undermining agricultural productivity. Their infiltrations into human and animal bodies are potential to cause severe health risks. Addressing this complex and multifaceted challenge requires a research-informed, coordinated, and multi-sectoral approach that carefully balances economic and livelihood needs with the imperative to protect environmental integrity and public health.

1. Background and Justification

Artisanal and small-scale mineral mining (ASM) can be defined as mineral extraction conducted by individuals or small enterprises with minimal capital investment, rude tools, and limited technological inputs, typically resulting in low production. It is one of the non-agricultural livelihoods for an estimated 130–270 million people globally and contributes significantly to foreign exchange earnings, particularly in Africa, Latin America, and Asia [1, 2]. However, based on the factors, including poor governance, lack of alternative livelihoods and economic opportunities, limited infrastructures and knowledge, conflict and instability, and insecure land and resource tenure, the ASM types vary from formal to informal, legal to illegal, from chemical-based to non-chemical, traditional to modern and other class types. In particular, armed conflicts and geopolitical unrest at different levels can lead to unsustainable practices, fostering environmental violations and illegal mining operations [3, 4, 5].

Illegal ASMs cause complex, irreversible, and long-lasting environmental problems, often more severe than those resulting from other human-induced stressors, with insignificant economic revenues. Numerous biophysical impacts from illegal ASMs have been reported in different countries, including deforestation [6], hydrological disturbances [7, 8, 9], soil fertility loss and degradation [10, 11], and loss of biodiversity [12]. The environmental impacts of chemical-based ASMs are potential to cause direct physical alterations of land resources and ecosystem degradation; they also result from the harmful chemicals used in mining processes. Many chemical-based illegal ASMs worldwide use various toxic substances, including mercury (Hg), cyanides (CN), arsenic (As), sulfuric acid (H_2SO_4), and nitric acid (HNO_3), to facilitate the extraction of minerals from ores. Different studies [13, 14] have indicated that

ASM is the leading source of mercury and cyanide contamination. Artisanal and small-scale gold mining (ASGM) alone releases approximately 410 to 1,400 tons of mercury annually, accounting for 37% of global emissions [15]. The study by [16] has also reported that the mercury release from mineral mining exceeded 50%. Other commonly used chemicals, such as cyanides, arsenic, sulfuric acid, and nitric acid, also pose severe and long-lasting environmental and climate risks [11, 17]. Moreover, illegal ASMs, particularly those relying on hazardous chemicals, contribute to significant public health and social problems [18, 19].

Tigray, in northern Ethiopia, is among the world's regions with a long history of traditional mineral mining. This practice dates back to the ancient civilizations of the Axumite kingdom (100–940 AD) and the earlier Yeha Kingdom (10th – 5th century BC [20]. These ancient civilizations were known for their advanced mining techniques, which laid the foundation for the current mining technologies and shaped the region's socioeconomic and cultural structures. Over time, however, traditional mining practices in Tigray have been significantly influenced, and at times disrupted by the political systems of successive regimes in Ethiopia. The formal and informal participation of private individuals and entities in ASMs began widely following the suspension of Ethiopia's prohibition on private mining in 1991. Since then, reports indicate that thousands of people, particularly in gold mining, have been involved in ASMs [21, 22]. As a result, ASM has played a crucial role in providing livelihoods for many unemployed citizens and contributing to Ethiopia's foreign currency earnings. At the same time, however, ASM has the potential of degrading environment and affect water sources, soil quality, land stability, and vegetation [22, 21]. It has also had adverse effects on the underground layers of river systems [23]. Regardless of ASM's potential to cause serious environmental, social, and health problems in Tigray, various regulatory, formalization, and reclamation efforts have been consistently implemented to mitigate its environmental consequences, with notable progress reported.

However, in early November 2020, war was declared in Tigray, involving the Ethiopian National Defense Force (ENDF), formal and informal military factions from the Amhara region, the Eritrean Defense Force (EDF), and other groups [24, 25]. Numerous reports have confirmed that the war has led to breaking long-standing social institutions and the destruction, burning, and looting of livelihood sources [24, 26, 25]. Moreover, the war has caused extensive environmental destruction, abruptly halting decades of ecosystem restoration efforts and progress [26]. In the face of this crisis, priorities have shifted from environmental sustainability to survival-based economic activities [24, 27, 25]. In this volatile context, since the start of the war in Tigray, ASMs in the region have become increasingly complex and unregulated (20). The practice has expanded significantly, accompanied by a surge in the use of toxic chemicals, posing serious threats to public health and the environment.

However, there are some studies fragmented across time, space, and content, limiting their utility for comprehensive policy and intervention development. The studies on African ASMs have primarily concentrated on regulatory frameworks and economic dimensions [28, 29, and 30]. There are also some studies that examined the traditional inputs and tools used, environmental threats, and socio-economic affairs related to ASMs in Tigray before the war [21, 22]. These studies primarily concentrated on the

physical impacts and economic roles of the traditional ASGMs. However, most of times how armed conflicts compromise the environment and public health from uncontrolled mining operations and heightened usage of dangerous chemicals have been overlooked. The studies failed to capture the compounded risks from ASMs faced by vulnerable populations in post-conflict areas where compromised healthcare systems and food insecurity prevail. The purpose of this synthesis is therefore to investigate the conditions of ASMs, the use of toxic chemicals, and their implications for the environment and public health, possible reclamation strategies, and policy pathways in Tigray. Investigations of audio-visual content shared on public and social media platforms, systematic literature review, observations, and discussions were conducted to address the following research questions:

1. How has the war affected the ASM?
2. What toxic chemicals are being used in ASM?
3. What emerging challenges are posed by chemical-based ASMs?
4. What measures can be taken to promote environmentally safe and sustainable ASMs?

The findings of this study provide valuable evidence to inform sustainable and environmentally safe mining practices. The outcomes are relevant for practitioners, researchers, and policymakers working to enhance the economic contributions of ASMs while safeguarding ecological and human health. Furthermore, this synthesis contributes to the global body of ASM literature and aligns with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly those related to environmental protection, public health, and responsible resource management in conflict-affected regions.

2. Materials and methods

2.1 Study area description

Tigray, a regional state located in northern Ethiopia, spans latitudes 12° to 15° North and longitudes 36°30' to 41°30' East (Fig. 1). The region covers an approximate area of 80,000 square kilometers and is known for its rugged topography and mountainous terrain. These physical features significantly influence the region's geomorphology, water quality, ecological zones, soil types, and biodiversity. Elevation in Tigray varies drastically, ranging from about 500 meters above sea level (m.a.s.l.) in the northeast to nearly 4,000 m.a.s.l. in the southwest. In terms of agro-ecological classification, about 53% of the land falls under lowland (Kolla – below 1,500 m.a.s.l.), 39% is categorized as mid-highland (Weina-Dega – 1,500 to 2,300 m.a.s.l.), and 8% as upper highland (Dega – 2,300 to 3,000 m.a.s.l.). This variation in altitude and climate supports diverse ecosystems and influences land use and livelihood strategies across the region.

Tigray has an estimated population of 5.7 million, including about 2.1 million children and adolescents aged 5 to 17, and 1.8 million youth and young adults between 15 and 34 years old [31]. The region is endowed with a wide range of mineral resources, including gold, copper, silver, iron, zinc, lead, nickel, oil

shale, asbestos, silica sand, kaolin, graphite, gypsum, gemstones, marble, granite, slate, limestone, and dolomite [32]. Artisanal and small-scale mining (ASM) is a significant economic activity in Tigray, particularly concentrated in the northwestern, central, and eastern zones. These mining activities have historically supported local livelihoods but also pose environmental and health challenges that are increasingly important in the context of post-conflict recovery.

2.2. Methodology

Investigating issues related to active artisanal and small-scale mining (ASM) in Tigray, being at the mining sites is challenging due to security concerns. Therefore, this study employed a mixed-source synthesis approach, combining a structured review of scientific literature with qualitative analysis of publicly available media, social media content, and informal stakeholder discussions.

(a) Literature review approach

A systematic literature review was conducted to examine the environmental and public health implications of chemical-based artisanal and small-scale mining (ASMs), with a particular focus on hazardous substances such as mercury and cyanide. The search strategy involved the use of targeted search phrases, including "chemical-based ASMs," "mercury and cyanide in ASMs," "environmental and health implications of illegal chemical-based ASMs" "coping strategies of chemical-based ASMs," and "lessons and experiences of countries in managing chemical-based/illegal ASMs. These phrases were applied across three major scientific databases, Google Scholar, Web of Science, and ScienceDirect, to identify relevant studies. The review covered publications available up to September, 2025. A total of 48 peer-reviewed articles, technical reports, and international conference proceedings were considered based on their relevance, credibility, and contribution to the study's research objectives. Key inclusion criteria required the studies to focus on how the causes affect ASM, the use of chemicals in ASMs, associated environmental and health impacts, and the management or policy responses to these challenges.

(b) Public and/Social media message content analysis

To complement the scientific literature and capture real-time developments and public perceptions, a content analysis was conducted on a diverse range of publicly accessible audio-visual and textual materials. These sources included news, reports, and feature stories from media outlets such as Tigray Television, Addis Standard, and Reporter, as well as photos, videos, and user-generated commentaries shared on social media platforms like Facebook and YouTube. Additionally, artistic representations, such as songs, poems, and short films, depicting artisanal and small-scale mining (ASM) practices and their associated impacts in Tigray were also analyzed.

In general, eighty (80) contents released through the platforms were selected for this purpose. These contents were screened and selected based on the predefined criteria, including their relevance to the research themes, clarity of the information presented, and the credibility of the sources. The selected contents were then thematically categorized using an inductive coding approach. Thematic categories

identified during the analysis included the nature and rate of ASM participation, driving factors behind the growth of ASM, the use and handling of toxic chemicals, environmental degradation and related public health concerns, and the socio-economic conditions prevailing in mining-affected communities.

(c) Informal stakeholder discussion

To ground the findings in local perspectives, the research included informal discussions with ten individuals who had direct or indirect involvement in artisanal and small-scale mining (ASMs). These participants included former miners, local community members, and environmental officers. Insights gathered from these conversations were documented through detailed notes and thematically integrated into the broader analysis. This approach enriched the study by capturing lived experiences, local interpretations, and nuanced understandings that may not be fully reflected in formal sources.

2.3. Data analysis and synthesis

The data collected from multiple sources were analyzed using a combination of qualitative and quantitative techniques to ensure a comprehensive interpretation. Thematic content analysis was applied to both textual and visual materials through an iterative coding process, allowing for the identification of recurring patterns and key themes. Descriptive statistics were used where appropriate, particularly to summarize quantitative elements such as the frequency of chemical mentions, the number of media reports, and spatial references to artisanal and small-scale mining (ASM) sites.

By integrating insights from scientific literature, media narratives, social media content, and local stakeholder perspectives, the analysis offered a multidimensional understanding of the environmental and public health implications of chemical-based ASMs in Tigray. This mixed-methods approach enabled the study to capture both empirical evidence and contextual nuances surrounding ASM practices in the region, particularly in the post-war contexts.

3. Results and Discussion

3.1. ASM after the war in Tigray

Results from the current investigation have indicated that the complexity and participants in ASMs have increased significantly following the devastating war that occurred from November 2020 to November 2022. The results from the content analysis (Fig. 2) showed a diversified community sections are being involved intensively in ASMs.

As can be seen from Fig. 2, all of the contents considered in this research (100%), discussions and observations have indicated sharp increase in the number and diversity of communities participating in ASMs after the devastative war in Tigray. Various sections of the Tigray society, including children, elderly men, and women, politicians at different levels, members of the armed forces (including military commanders), and non-citizens, are participating in ASMs. According to the results of the discussions, the increase of participating communities and intensities is attributed to the devastative war. The

increased and diversified ASMs communities, especially under the involvement of military and civil officials is challenging for regulation and monitoring. Consequently, the number of individuals involved in ASM illegally and indirectly has risen sharply (Fig. 3).

Due to the fall of efforts to regulate, formalize, and act of checking environmental soundness which had been relatively well-maintained previously, the war has made the ASMs to deteriorate into illegal and informal, aggressive, and destructive types of mining activities (Table 1). The chain of participating in ASMs, starting from the licensing through mining operation to marketing, has also become significantly complicated. According to the reflections of the contents analyzed (100%) in Fig. 3, the communities who use ASMs as primary and secondary source of livelihood and wealth as well as the individuals who are involving illegally and indirectly in ASMs have increase significantly.

Table 1
socioeconomic causes and consequences of ASMs in Tigray after war

Socioeconomic causes and consequences of the ASMs	Reflection
Decreasing the act of legalization and formalization	80
Decreasing the act of regulating and monitoring	80
Increasing conflict b/n residents and ASMs	80
Complicated and illegal marketing	80
Risks of crop productivity failure	80
Using illegal ASMs for political consumption	80
Reduction of hard currency earnings for the country	50

To evaluate the socioeconomic causes and consequences of ASMs in Tigray, the act of legalization and formalization, act of regulating and monitoring, conflicts b/n residents and ASMs communities, illegal marketing, the risks of crop productivity failure, act of consuming illegal ASMs for political consumption and the hard currency earnings for the country were used as indicators. Accordingly, the contents analyzed have reflected (Table 1) a decreasing in act of legalization and formalization, regulating and monitoring, increasing conflict b/n residents and ASMs, complicated and illegal marketing, sever risks of crop productivity failure, high consumption illegal ASMs for political consumption, and failed to earn expected hard currency for the country. Likewise, although Ethiopia continues to earn substantial hard currency from the ASMs in Tigray, a considerable portion of it has lost to smugglers and brokers, ultimately harming the public and the ecology badly.

The power vacuum and the government’s inability to regulate, monitor, and formalize the ASMs (Table 1) have caused not only an increase in the number and diversity of the ASM’s communities but also made miners in Tigray use highly toxic and internationally banned chemicals. The results (Fig. 4) indicated that the current ASMs in Tigray are using many toxic chemicals, including Mercury (Hg) and Cyanides (CN).

Chemicals, including Arsenic (As) and Sulfuric acid (H₂SO₄), are also in use. There are also arguments claiming there is no chemical potential in amalgamating minerals, which is not used in Tigray's ASMs. The reports by [33] and [34] agreed that extensive use of Mercury and Cyanides in Tigray's mining operation. According to these reports, some of the areas where illegal mining with the application of these toxic chemicals takes place include Asgede, Tsimbla, La'ilay Adiyabo, Medebay, Zana, Sheraro, Tahtay Adiyabo, Tahtay Koraro, and Tselemti in the North Western Zone, as well as Abergele, Kola Tembien, Abiy Addi, La'ilay Maychew, Adet, Tahtay Maychew, Tanqua, and Maikinetal in the Central Zone. The aforementioned chemicals are the most toxic chemicals commonly used for amalgamating the minerals from ores elsewhere [11, 17, 13, 2, 14].

3.2. Environmental implications of the chemical-based ASMs

3.2.1. Physical effects of ASMs on land resources

The problems with the chemical-based ASMs in Tigray during this war-traumatized period are not limited to the pattern of participation and marketing, but also cause devastating and long-lasting damage to the environment. Almost all of the opinions and views of respondents in the discussions and observations revealed that the ASMs in Tigray are causing drastic damage to the basic land resources (water, soil, forest, and wildlife). The techniques and equipment they used are still (if not more rude) very traditional and arbitrary approaches, which failed to follow the multi-step process involving geological, geophysical, geochemical, and remote sensing techniques. Although any mining operation has to be preceded by exploration studies, including surveys, field studies, and drilling test boreholes and other exploratory excavations are important to identify potential locations and overall feasibility of the mineral ores deposit of a particular area [35, 36, 37], most mining activities in Tigray are extremely traditional. The knowledge of miners on nature and formations of types of geological material, associated structures, and forces responsible for the targeted mineral deposition is extremely limited. They simply use arbitrary approaches, rude and labor-intensive instruments, including shovels, picks, hammers, and plastic pans locally called Dola [22]. So, the mining operation in Tigray is mainly conducted by individual miners or small enterprises with limited capital investment and low production.

The environmental impacts from such mining activities are multidimensional. Before the war in Tigray erupted, there had been some studies that had identified the impacts of traditional gold mining on the land resources matrices of water, soil, land, and vegetation [10, 21, 22, 23]. These studies have shown that gold mining has been causing reasonable environmental impacts, including water availability and quality degradation, soil erosion and degradation, vegetation and tree dismantling, and agricultural land disturbance. The study by [22] on the numbers and patterns of participants in traditional gold mining in northwestern Tigray had shown severe damage to all land resource matrices. The study by [10] on the impacts of artisanal gold mining on soil and woody vegetation in Tigray has also evidenced severity. According to these studies, the sector had been causing severe soil erosion (sheet, rill, and gully) affecting the geomorphology of land forms and threatening the sustainable livelihoods of local

communities. The study has also presented drastic effects on the status, structure, and composition of massive areas of vegetation and woody species, discouraging sustainable land management in Tigray. The study by [23] has also evidenced the effects of traditional gold mining not only on the surface processes but also affects the hydrology, geophysics, chemistry, and their interacting processes in the subsurface, ground, and interface zones of these layers. Consequently, the accesses to water, energy supply, and other uses from rivers are continuously declining. The impact of ASM on ecosystem services extends from field to river basin scales through excessive sediment transportation, flooding, deterioration of water flows are some the downstream impacts from the sector [38, 39].

In Tigray, the ASMs communities are currently relying on harmful chemicals to extract gold from ore. Due to the breakdown of regulatory institutions during the recent armed conflicts [18], the artisanal and small-scale gold mining (ASGM) in Tigray has triggered severe ecological disruption. They use Mercury (Hg) and cyanide (CN) and other different types of chemicals to facilitate the mining activities. These chemicals, though effective and efficient in extracting gold [40, 41], they have severe ecosystem and health consequences. The negative effects from these chemicals on the environmental resources especially to the water in the river systems (hydrology, biodiversity and chemical contents), soils, and air quality are expected to be worst and complicated.

Mercury and Cyanide are potential in contaminating the hydrologic, ecologic and geochemical processes in the surface, subsurface and ground layers of the river systems. They undergo numerous biogeochemical reactions in water bodies, affecting the water quality, aquatic ecosystem, hydrologic processes, and sediment transport. They can be dissolved in water, precipitated as minerals, adsorbed to various solid materials, volatilized to the atmosphere, present as liquid elemental, or can be converted from inorganic to biologically available organic forms (methyl mercury) through microbial, photochemical, and dark abiotic reduction and oxidation reactions [42, 23, 43, 17]. Excess concentration of these different types of Mercury in fresh water could then constrain the survival of aquatic plants as well as the vertebrate and invertebrate aquatic animals, which are potentially important in regulating the hydrologic processes, water qualities, and sediment transportation.

The Mercury and Cyanide from the ASM's tails can be distributed to the soil profiles by water flow and then cause different soil quality problems, reducing land productivity. These chemicals affect directly and/or indirectly the biological, chemical, and physical properties of the soil profile. They inhibit the growth, activities, population, and structure of the soil microbial organisms [44, 45, 46]. According to the studies by [47] and [48], only 20–30 gram of mercury in a one kg of soil types is enough for significantly affecting the diversity, activities and genetic structure of the bacteria, fungi and actinomycetes which are the main components of the micro flora in the soil ecosystem. They can also negatively affect soil structure, leading to reduced water infiltration and aeration [49, 50]. Moreover, these chemicals affect the acidic, ion exchange capacity, nutrient availability properties and other chemical properties of soil. Apart from the above indirect effects, mercury and cyanide even at low concentration are potential to affect the germination rates, root development, metabolism, photosynthesis and respiration rates, as well as

nutrient uptake of plants [51] Thus, these all can significantly reduce crop yields and the overall productivity of agricultural land and then affect the food security of the agrarian communities.

The ecological footprint of artisanal and small-scale gold mining (ASGM) in Tigray's post-conflict environment reveals significant environmental health concerns. Mercury contamination from gold processing has created widespread pollution gradients in both terrestrial and aquatic matrices, with demonstrated trophic transfer in local ecosystems [1]. The environmental redox chemistry facilitates mercury methylation, producing bioavailable neurotoxins that concentrate in higher trophic levels, presenting dual threats to ecosystem integrity and public health [18]. Parallel concerns emerge from cyanide utilization, where inadequate processing techniques have led to acute contamination events in surface waters; with residual complexes demonstrating prolonged Eco-toxicological effects. The collapse of regulatory oversight following regional conflicts has intensified these impacts, creating permissive conditions for environmentally destructive mining practices [18].

The cascading ecological effects of ASGM in Tigray extend across multiple environmental compartments. Mining-induced landscape modifications, including vegetation removal and substrate disruption, have triggered measurable biodiversity loss and ecosystem service degradation [52]. Geomorphological alterations from unplanned mining operations have precipitated severe soil erosion patterns and modified watershed hydrology, with documented cases of irreversible habitat modification [53]. Ecological impacts extend beyond chemical contamination. Deforestation and soil erosion from mining activities have degraded habitats, reducing biodiversity and disrupting hydrological systems [52, 53]. Poor tailings management has further exacerbated heavy metal dispersion, contaminating groundwater and surface water [54, 55]. Spatially, mercury accumulates in alluvial sediments, creating long-term pollution reservoirs) while cyanide contamination is more localized but extends downstream [1]. Post-conflict assessments reveal pollutant levels exceeding safety thresholds, indicating irreversible damage in some areas [18].

3.3. Environmental Health Implication of Chemical-based ASMs

Apart from the above impairing effects to the ecosystem services, the chemical based illegal ASMs with the pervasive absence of tailings management infrastructure results diffuse toxic chemicals pollution which contaminates shallow and deep aquifers and surface water bodies, soil and air. It causes to increase the concentration of the toxic chemicals available in the daily consumptions of water, food and air into the level of causing severe health crisis. As stated in the above sections, mercury and cyanide are highly toxic substances poisoning surface waters (rivers and streams) that are vital for drinking, irrigation, and livestock water supply purposes [55, 56]. These chemicals are also easily leached into groundwater, contaminating the wells and other water supply systems [57, 58, 55]. Moreover, they contaminate soil, which is the medium through enter these toxic chemicals into crops and grasses and are then enriched and transferred to animals and humans through various food chains [46]. Not only

through these paths, mining using mercury also release harmful mercury into the air, which can be inhaled by the miners and the residents.

The entrance of these toxic chemicals into the human bodies of the miners and nearby residents through the paths discussed here and others can pose serious health risks. Mercury exposure can cause a range of neurological problems, including tremors, cognitive impairment, and developmental delays in children [59]. The mining communities and residents near mining sites suffer from respiratory problems, a range of chronic illnesses, including kidney damage, neurological disorders, and various forms of cancer. Prolonged exposures to these toxic chemicals weaken the immune system, making individuals more susceptible to infectious diseases. Especially children and pregnant women are significantly hampered by these chemicals. It can cause severe birth defects, developmental delays of the embryo, and reproductive health problems. Likewise, cyanide also poses a significant threat to both human and animal health. Cyanide exposure can lead to acute poisoning, causing symptoms like headaches, nausea, dizziness, and, in severe cases, death [61, 60].

The chemical-based illegal ASMs in Tigray have the potential to cause a severe health crisis for local communities, exacerbating existing vulnerabilities and undermining the region's long-term health and well-being. The damage of these toxic chemicals on the public will be devastating as the war has changed the access to clean water from bad to worse. The water, hygiene, and sanitation (WASH) services and infrastructures have already been deliberately destroyed and looted by the armed forces [62, 63, 64]. The sources of water for domestic purposes of many people (rural and semi-urban) have become unsafe sources, including the rivers, wells, ponds, and springs, etc. As a consequence, the prevalence of the public to different waterborne diseases (diarrhea, cholera, and others) becomes higher. Moreover, synergistic interactions between the toxic contaminants and malnutrition may heighten health vulnerabilities [65, 18].

3.4. Reclamation strategies and policy pathways

Chemical-based artisanal and small-scale mining (ASM) has deeply damaging and long-lasting consequences for both the environment and public health. The toxic chemicals released from these mining operations primarily mercury and cyanide contaminate the water, soil, and air, threatening ecosystems, food security, and the health of both humans and animals. While ASM plays a crucial economic role, its long-term sustainability depends on transitioning to chemical-free methods by strengthening environmental regulations and monitoring, implementing health surveillance in mining communities, and enhancing community education and capacity building. Several countries have successfully banned or regulated mercury and cyanide-based ASM through strong legal frameworks, effective enforcement, and international cooperation. Examples include the Philippines, Indonesia, Colombia, China, Ghana, and Tanzania, where the adoption of alternative, safer mining technologies has allowed continued economic benefits without causing environmental harm often supported by global agreements like the Mina Mata Convention [66, 67, 30]. On the other hand, countries such as Brazil, Peru, the Democratic Republic of the Congo (DRC), and Zimbabwe have faced significant challenges in

banning the chemical-based ASM due to weak enforcement mechanisms, economic dependence on informal mining, and the prevalence of illegal mining networks [68].

To address Tigray's mining crisis, there are multiple potential strategies. It is very important to note that implementing real-time, portable, and cost-effective remediation strategy. The development and deployment of low-cost, low-maintenance sensors for rapid detection of mercury and cyanide levels in water, soil, and air is valuable for timely interventions and sustainable management of ASM impacts. Phytoremediation using hyper accumulators (e.g., *Brassica juncea*), constructed wetlands for contaminant degradation, and engineered tailings containment can mitigate further contaminant dispersion [69, 70, 71, and 55]. Strengthening governance through participatory monitoring and policy reforms is critically important [30]. Innovative financing (e.g., environmental trust funds) and international partnerships are needed to support long-term rehabilitation [71, 72, and 73]. Therefore, Tigray's ASGM crisis requires coordinated environmental, health, and policy interventions. Evidence-based remediation, robust governance, and community engagement are essential to mitigate ecological and public health impacts.

4. Conclusion and recommendation

Artisanal and small-scale mining (ASM) in Tigray has intensified in the aftermath of the devastating war. Various section of society including children, the elderly, men, women, politicians at different levels, members of the armed forces (including military commanders), citizens and non-citizens are participating in ASM, either directly or indirectly, legally or illegally, and in groups or individually. Analyses show that the number of individuals involved illegally and indirectly in a chemical-based approach that poses significant risks to both the environment and health of lives have risen sharply. The use of toxic chemicals particularly Mercury and Cyanide poses severe environmental risks, disrupting hydrologic processes, soil dynamics, and agricultural productivity. Their infiltration into human and animal bodies leads to serious health issues, including neurological, respiratory, and reproductive problems, as well as weakened immune systems. Although the ASM in Tigray plays a crucial role in sustaining livelihoods and generating hard currency for Ethiopia, its sustainability and to minimize environmental and public health risks demands serious monitoring, formalization, and regulatory efforts. Addressing these impacts requires a comprehensive research based coordinated approach that balances economic and livelihood development with the well-being of environment and public health.

Declarations

Declaring funding

There was no fund granted to this research. But, researchers had been paid a salary from their respective affiliated institution.

Clinical trial number

Clinical trial number for this research was not required and applicable.

Field permission

Prior permissions for field observation were obtained from the relevant local authorities' and local landowners to undertake field observations.

Ethical approval and accordance

The study received ethical approval from the Adigrat University Ethics Committee ('AdU TR STR Oct 2025'). All research procedures were performed in accordance with the ethical guidelines and regulations of the University of Adigrat.

Consent to publish

Consent for publication was not applicable because we have not incorporated any individual person's data in any form.

Consent to Participate

Informed consent (verbal) was obtained from all participants prior to data collection after explaining the objectives of the study, assuring confidentiality, and confirming voluntary participation.

Author Contribution

Hagos Gebreslassie Gebru, Belay Manjur Gebru, Zenebe Girmay Siyum, Gebreslassie Teklay Weldengus The authors listed in the above have made participation in developing the manuscript entitled "Environmental implications of Chemical based artisanal and small scale mining in post war Tigray, Northern Ethiopia". The first author has initiated the idea, collected, and analysed data. Moreover he participated in the write up of the manuscript. The second author also has developed the research idea and reviewed. The third author has contributed in thorough reviewing and editing the manuscript. The last author has also contributed in editing the developed manuscript.

Data Availability

The data that support this result are published and unpublished literatures. But, there are some data that can be released up on request.

References

1. Louisa J, Justin M. The Mercury Problem in Artisanal and Small-Scale Gold Mining. *Chem – Eur J*. 2020;24/27:6905–16. <https://doi.org/10.1002/chem.201704840>.
2. Basu N, Renne EP, Long RN. An integrated assessment approach to address artisanal and small-scale gold mining in Ghana. *Int J Environ Res Public Health*. 2018;12(9):11683–98.
3. Quash Y, Kross A, Jaeger JA. (2024). Assessing the impact of gold mining on forest cover in the Surinamese Amazon from 1997 to 2019: A semi-automated satellite-based approach. *Ecological Informatics*, 80, p.102442.
4. Chirico PG, Malpeli KC. (2014). The role of conflict minerals, artisanal mining, and informal trading networks in African intrastate and regional conflicts. *Journal Article* Sep, 18(11), 27am.
5. Chase M. (2010). Conflict minerals and the democratic republic of congo. San Francisco (Business for Social Responsibility). Retrieved from: http://www.bsr.org/reports/BSR_Conflict_Minerals_and_the_DRC.pdf.
6. Andrew JS. Potential application of mediation to land use conflicts in small-scale mining. *J Clean Prod*. 2003;11(2):117–30.
7. Macdonald K, Lund M, Blanchette M. (2015). Impacts of artisanal small-scale gold mining on water quality of a tropical river (Surow River, Ghana). In 10th International Conference on Acid Rock Drainage & IMWA Annual Conference. 21–24.
8. Macháček J. Alluvial artisanal and small-scale mining in a River stream—rutsiro case study (Rwanda). *Forests*. 2020;11(7):762.
9. Darko HF, Karikari AY, Duah AA, Akurugu BA, Mante V, Teye FO. Effect of small-scale illegal mining on surface water and sediment quality in Ghana. *Int J River Basin Manage*. 2023;21(3):385–6.
10. Meaza H, Ali M, Tesfamariam Z, Abebe N. Impacts of artisanal gold mining systems on soil and woody vegetation in the semi-arid environment of northern Ethiopia. *Singap J Trop Geogr*. 2017;38(3):386–401.
11. Beda J, Ouattara J, Messou A, Coulibaly L. Impacts of artisanal and small-scale gold mining on soils in northern regions of Côte d'Ivoire: cases of Boundiali, Korhogo and Tengrela. *Int J Biol Chem Sci*. 2021;15(3):1234–48.
12. Sonter L, Ali S, Watson J. (2018). Mining and biodiversity: key issues and research needs in conservation science. *Proceedings of the Royal Society B*, 285(1892), 20181926.
13. Elwaleed A, Jeong H, Abdelbagi AH, Thi Quynh N, Nugraha WC, Agusa T, Ishibashi Y, Arizono K. Assessment of Mercury Contamination in Water and Soil from Informal Artisanal Gold Mining: Implications for Environmental and Human Health in Darmali Area. *Sudan Sustain*. 2024;16(10):3931.
14. Mantey J, Nyarko KB, Owusu-Nimo F, Awua KA, Bempah CK, Amankwah RK, Akatu WE, Appiah-Effah E. (2020). Mercury contamination of soil and water media from different illegal artisanal small-scale gold mining operations. *Heliyon* 2020, 6, 1–13.
15. Seccatore J, Veiga M, Origliasso C, Marin T, De Tomi G. An estimation of the artisanal small-scale production of gold in the world. *Sc total Env*. 2014;496:662–7.

16. Bishop, K., Shanley, J. B., Riscassi, A., de Wit, H. A., Eklöf, K., Meng, B., ... Zhu, W. (2020). Recent advances in understanding and measurement of mercury in the environment: Terrestrial Hg cycling. *Science of the Total Environment*, 721, 138647.
17. Liu R, Liu F, Jiao J, Xu Y, Dong Y, RM EW, Zhang X, Chen H. Potential Toxic impacts of Hg Migration in the Disjointed Hyporheic Zone in the Gold Mining Area Experiencing River Water Level Changes. *Water*. 2022;14(19):2950.
18. Hilson G, Hilson A, Maconachie R, McQuilken J, Goumandakoye H. Artisanal and small-scale mining (ASM) in sub-Saharan Africa: Re-conceptualizing formalization and 'illegal' activity. *Geoforum*. 2022;130:1–12. <https://doi.org/10.1016/j.geoforum.2022.01.001>.
19. Gibb H, O'Leary KG. Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: a comprehensive review. *Environ Health Perspect*. 2014;122(7):667–72.
20. Nyssen J, Kiros H. (2022). Map of Tigray's mineral resources (north Ethiopia) - Canadian and other international mining licenses. Zenodo. <https://doi.org/10.5281/zenodo.6525135>
21. Meaza H, Ali M, Hishe S, Tesfamariam Z. Small scale gold mining effects on the miners and local communities in semi-arid region of Ethiopia. *J Geography/Revija za Geografijo*. 2015;10(1):25–40.
22. Hagos G, Sisay W, Alem Z, Niguse G, Mekonen A. Participation on traditional gold mining and its impact on natural resources, the case of Asgede Tsimbla, Tigray, Northern Ethiopia. *J Earth Sci Geotech Eng*. 2016;6(1):89–97.
23. Weldeabzgi B, Alemayehu T, Estifanos S. Assessing the environmental impact of artisanal gold mining activities on the waters and sediments around meli, northwestern Tigray, Ethiopia. *Momona Ethiop J Sci*. 2021;13(2):281–99.
24. WPF. (2021). Starving Tigray how armed conflict and mass atrocities have destroyed an Ethiopian region's economy and food System and are threatening famine. <https://reliefweb.int/sites/reliefweb.int/files/resources/Starving-Tigray-report-final.pdf>
25. Manaye A, Afewerk A, Manjur B, Solomon N. The Effect of the war on smallholder agriculture in Tigray, Northern Ethiopia. *Cogent Food Agric*. 2023;9(1):2247696.
26. Nyssen J, Negash E, Van Schaeybroeck B, Haegeman K, Annys S. Crop cultivation at wartime—plight and resilience of Tigray's Agrarian Society (North Ethiopia). *De?F Peace Econ*. 2022;34(5):618–45. <https://doi.org/10.1080/10242694.2022.2066420>.
27. Negash E, Birhane E, Gebrekirstos A, Gebremedhin MA, Annys S, Rannestad MM, Nyssen J. Remote sensing reveals how armed conflict regressed woody vegetation cover and ecosystem restoration efforts in Tigray (Ethiopia). *Sci Remote Sens*. 2023;8:100108.
28. Berman N, Couttenier M, Rohner D, Thoenig M. This mine is mine! How minerals fuel conflicts in Africa. *Am Econ Rev*. 2017;107(6):1564–610.
29. Hilson G. The COVID-19 pandemic and small-scale mining: Reflections from the field. *Extractive Industries Soc*. 2020;7(3):861–4. <https://doi.org/10.1016/j.exis.2020.05.008>.

30. Hilson G, Maconachie R. Entrepreneurship and innovation in Africa's artisanal and small-scale mining sector. *Resour Policy*. 2020;65., Article 101565.
<https://doi.org/10.1016/j.resourpol.2019.101565>.
31. Gebru AL, Abay TK, Asmerom AT. Post-conflict challenges and aspirations of Tigray Youth. Ethiopia: A needs assessment and recovery roadmap; 2024.
32. Yihdego Y, Salem HS, Ayongaba B, Veljkovic Z. Mining sector challenges in developing countries, Tigray, Ethiopia and inspirational success stories from Australia. *Int J Min Mineral Eng*. 2018;9(4):321–67.
33. Chiristian Y. (2024). Mining in Tigray: A Resource Curse Amid Genocide. Accessed from <https://omnatigray.org/mining-in-tigray-a-resource-curse-amid-genocide>. On 2024.
34. Batsebeha S. (2025). Tigray's Gilded Trap: Unmasking illegal mining's toxic legacy – Addis Standard. accessed from <https://ethiopanorama.com>
35. Uwiduhaye JDA, Ngaruye JC, Saibi H. Defining potential mineral exploration targets from the interpretation of aeromagnetic data in western Rwanda. *Ore Geol Rev*. 2021;128:103927.
36. Zheng W, Liu B, McKinley JM, Cooper MR, Wang L. Geology and geochemistry-based metallogenic exploration model for the eastern Tethys Himalayan metallogenic belt, Tibet. *J Geochem Explor*. 2021;224:106743.
37. Wang D, Lin F, Shi M, Wang H, Yang X. Geological setting, tectonic evolution and spatio-temporal distributions of main mineral resources in South East Asia: A comprehensive review. *Solid Earth Sci*. 2023;8(1):34–48.
38. Ansa-Asare OD, Duah AA, Owusu BK, Amisigo B, Mainoo PA, Entsua-Mensah R. (2013). Impact of small-scale mining on the water resources of the Pra River basin. CSIR-WRI Technical report, Accra, Ghana, 27.
39. Abdelaal A, Sultan M, Abotalib AZ, Bedair M, Krishnamurthy RV, Elhebiry M. Emerging mercury and methylmercury contamination from new artisanal and small-scale gold mining along the Nile Valley, Egypt. *Environ Sci Pollut Res*. 2023;30(18):52514–34.
40. Göknelma M, Birich A, Stopic S, Friedrich B. A review on alternative gold recovery re-agents to cyanide. *J Mater Sci Chem Eng*. 2016;4(8):8–17.
41. Zhang Y, Cui M, Wang J, Liu X, Lyu X. A review of gold extraction using alternatives to cyanide: Focus on current status and future prospects of the novel eco-friendly synthetic gold lixivants. *Miner Eng*. 2022;176:107336.
42. Riaz A, Khan S, Muhammad S, Shah MT. Mercury contamination in water and sediments and the associated health risk: a case study of artisanal gold-mining. *Mine Water Environ* (Internet). 2019;38(4):847–54.
43. Espiritu EQ, Claveria RJR, Bernadas PJC. Assessment of surface water quality and mercury levels from Artisanal and small-scale gold mining (ASGM) along Acupan River, Benguet, Philippines. *Environ Geochem Health*. 2022;44(10):3655–76.

44. Xie X, Liao M, Ma A, Zhang H. Effects of contamination of single and combined cadmium and mercury on the soil microbial community structural diversity and functional diversity. *Chin J Geochem.* 2011;30(3):366–84.
45. Aždajić M, Yumvihoze E, Blais JM, Poulain AJ. The effect of legacy gold mining on methylmercury cycling and microbial community structure in northern freshwater lakes. *Environ Science: Processes Impacts.* 2021;23(8):1220–30.
46. Due J, Ren Y, Li J, Zhang S, Huang H, Liu J. The study on the effect of mercury pollution on soil microorganisms around mercury mining area. *Sci Rep.* 2023;13(1):21605.
47. Harris-Hellal J, Vallaeys T, Garnier-Zarli E, Bousserhine N. Effects of mercury on soil microbial communities in tropical soils of French Guyana. *Appl Soil Ecol.* 2009;41(1):59–68.
48. Frossard E, Aighewi BA, Aké Sévérin, Barjolle D, Baumann P, Bernet T, Dao D et al. The challenge of improving soil fertility in yam cropping systems of West Africa. *Frontiers in plant science* 8 (2017): 1953.
49. Hidayati N, Juhaeti T, Syarif F. Mercury and cyanide contaminations in gold mine environment and possible solution of cleaning up by using phytoextraction. *Hayati J Biosci.* 2009;16(3):88–94.
50. Suhadi S, Sueb S, Muliya BK, Ashoffi AM. A Pollution of mercury and cyanide soils and plants in surrounding in the Artisanal and Small-Scale Gold Mining (ASGM) at Sekotong District, West Lombok, West Nusa Tenggara. *Biol Environ Pollution.* 2021;1(1):30–8.
51. Azevedo R, Rodriguez E. (2012). Phytotoxicity of mercury in plants: a review. *Journal of Botany*, 2012(1), 848614.
52. Le Billon P. Diamond wars? Conflict diamonds and geographies of resource wars. *Ann Assoc Am Geogr.* 2008;98(2):345–82. <https://doi.org/10.1080/00045600701846538>.
53. Mach EJ, McBride LL, van Riper CJ. Environmental impacts of armed conflict in resource-rich regions. *Nat Sustain.* 2020;3(1):39–47. <https://doi.org/10.1038/s41893-019-0440-x>.
54. Veiga M, Baker R. Global mercury project. Protocols for Environmental and Health Assessment of Mercury Released by Artisanal and Small-scale Gold Miners. Vienna, Austria: United Nations Industrial Development Organization; 2004.
55. Pant R, Mathpal N, Chauhan R, Singh A, Gupta A. A Review of Mercury Contamination in Water and Its Impact on Public Health. *Mercury Toxicity Mitigation: Sustainable Nexus Approach*; 2024. pp. 93–115.
56. Aristide YKS, Ernest AK. Assessment of mercury, Herausgeber and cyanide (CN) pollution in surfacewaters, groundwaters and sediments around industrial mining sites in the department of Divo (Ivory Coast). *J Water Resour Prot.* 2021;13(2):75–91.
57. Maha MM, Matsuyama A, Arima T, Sainoki A. (2024). Assessment of Total Mercury Levels Emitted from ASGM into Soil and Groundwater in Chami Town, Mauritania. *Sustainability*, 16(18), pp.7992.
58. Aleku DL, Lazareva O, Pichler T. Mercury in groundwater–Source, transport and remediation. *Appl Geochem.* 2024;170:106060.

59. Esdaile LJ, Chalker JM. The mercury problem in artisanal and small-scale gold mining. *Chemistry–A Eur J*. 2018;24(27):6905–16.
60. Kwaansa-Ansah E, Amenorfe L, Armah E, Opoku F. Human health risk assessment of cyanide levels in water and tuber crops from Kenyasi, a mining community in the Brong Ahafo Region of Ghana. *Int J Food Contam*. 2017;4:1–11.
61. Knoblauch AM, Farnham A, Ouoba J, Zanetti J, Müller S, Jean-Richard V, Utzinger J, Wehrli B, Brugger F, Diagbouga S, Winkler MS. Potential health effects of cyanide use in artisanal and small-scale gold mining in Burkina Faso. *J Clean Prod*. 2020;252:119689.
62. Gesesew, H., Berhane, K., Siraj, E. S., Siraj, D., Gebregziabher, M., Gebre, Y. G.,... Tesfay, F. H. (2021). The impact of war on the health system of the Tigray region in Ethiopia: an assessment. *BMJ Global Health*, 6(11).
63. Shishaye HA, Gebremicael TG, Meresa H, Gebre FA, Kidanu S. (2023). Assessing the impact of war on the water supply infrastructure in Tigray, Ethiopia.
64. Asgedom AA, Redae GH, Gebretnsae H, Tequare MH, Hidru HD, Gebrekidan GB, Berhe AK, Ebrahim MM, Cherinet M, Gebretsadik GG, Woldearegay HG. 2025. Post-war status of water supply, sanitation, hygiene and related reported diseases in Tigray, Ethiopia: A community-based cross-sectional study. *International Journal of Hygiene and Environmental Health*, 263, p.114460.
65. Steckling N, Tobollik M, Plass D, Hornberg C, Ericson B, Fuller R, Bose-O'Reilly S. Global burden of disease of mercury used in artisanal small-scale gold mining. *Annals global health*. 2017;83(2):234–47.
66. Katz-Lavigne S, Mkodzongi G, Nyandoro M. Bandits' and machete gangs: The criminalization of artisanal and small-scale mining in the Democratic Republic of Congo and Zimbabwe. *Extractive Industries Soc*. 2024;19:101504.
67. Bansah KJ. From diurnal to nocturnal: Surviving in a chaotic artisanal and small-scale mining sector. *Resour Policy*. 2019;64:101475.
68. Hilson G. Abatement of mercury pollution in the small-scale gold mining industry: Restructuring the policy and research agendas. *Sci Total Environ*. 2006;362(1–3):1–14.
69. Schwartz F, Lee S, Darrah T. (2021). A review of the scope of artisanal and small-scale mining worldwide, poverty, and the associated health impacts. *GeoHealth*, 5(1), e2020GH000325.
70. Marrugo-Negrete J, Durango-Hernández J, Pinedo-Hernández J, Olivero-Verbel J, Díez S. Phytoremediation of mercury-contaminated soils by *Jatropha curcas*. *Chemosphere*. 2015;127:58–63.
71. Akcil A, Mudder T. Microbial destruction of cyanide wastes in gold mining: process review. *Biotechnol Lett*. 2003;25(6):445–50.
72. Asare D, Ansong M, Asante WA, Kyereh B. Impact of different illegal artisanal small-scale mining techniques on soil properties in a major mining landscape in Ghana. *Environ Challenges*. 2024;17:101008.

73. Biney, E., Biney, N., Dadzie, I., Harris, E., Quartey, G. A., Asare, Y. M., ... Forkuo,E. K. (2022). Impact of mining on vegetation cover: A case study of Prestea Huni-Valley municipality. Scientific African, 17, e01387.

Figures



Figure 1
Location of Tigray region in the northern Ethiopia

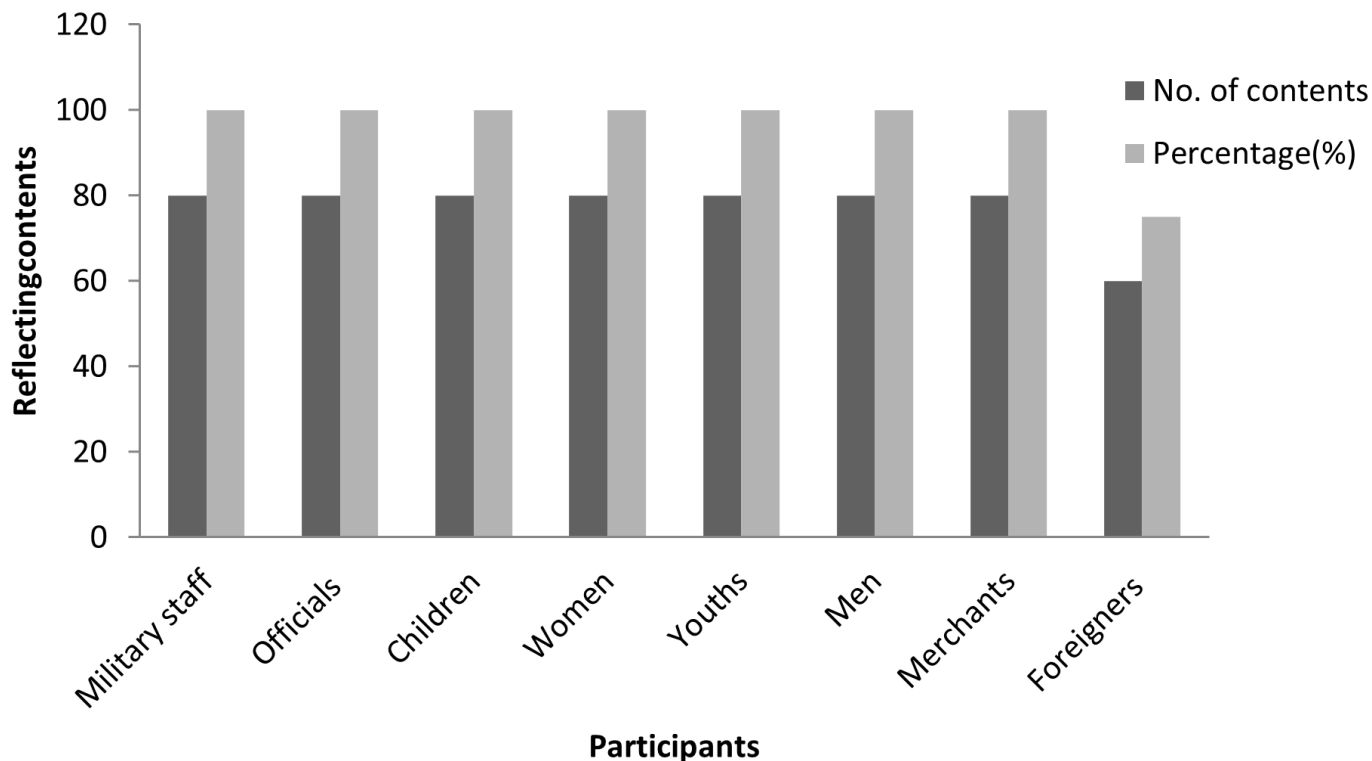


Figure 2

Community sections participating in the artisanal and small-scale mining (ASM) of Tigray

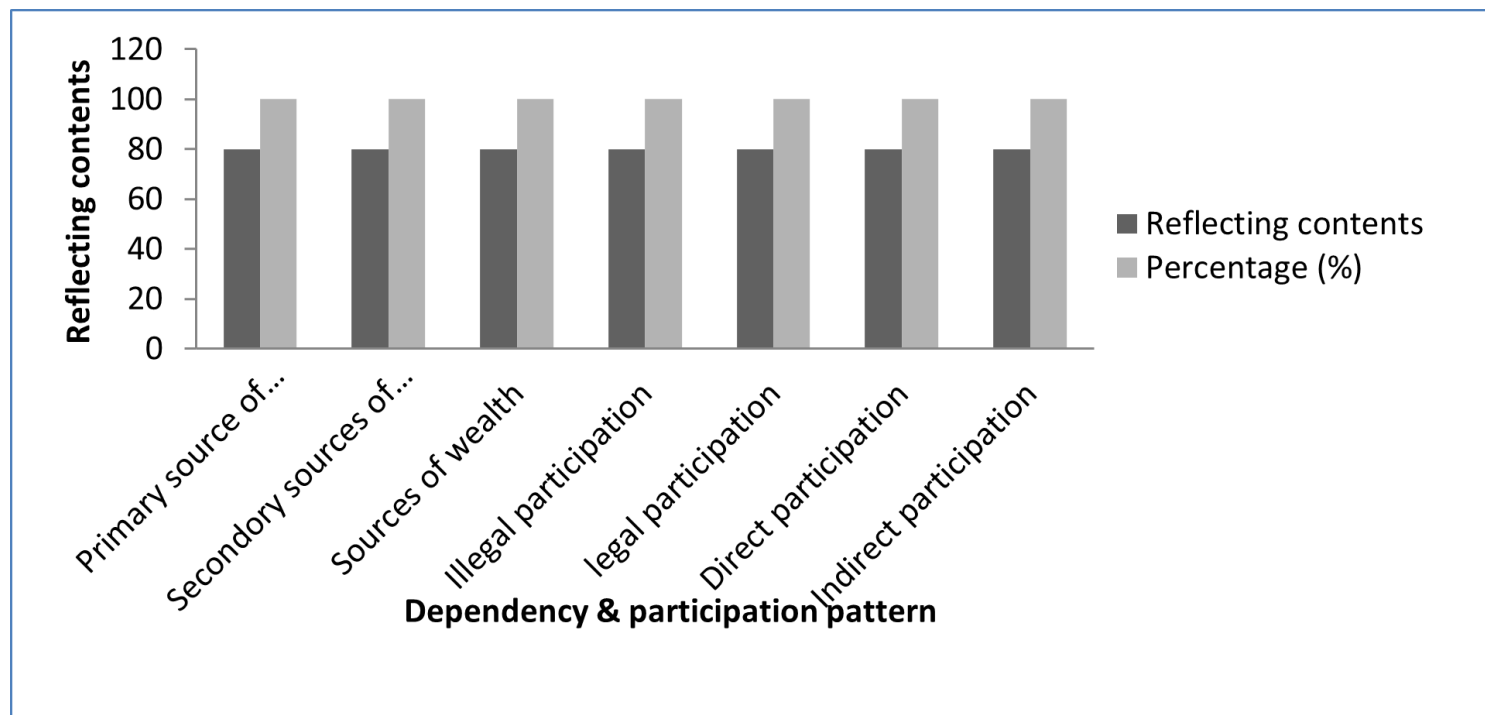


Figure 3

Dependency and participation pattern of ASMs communities in Tigray

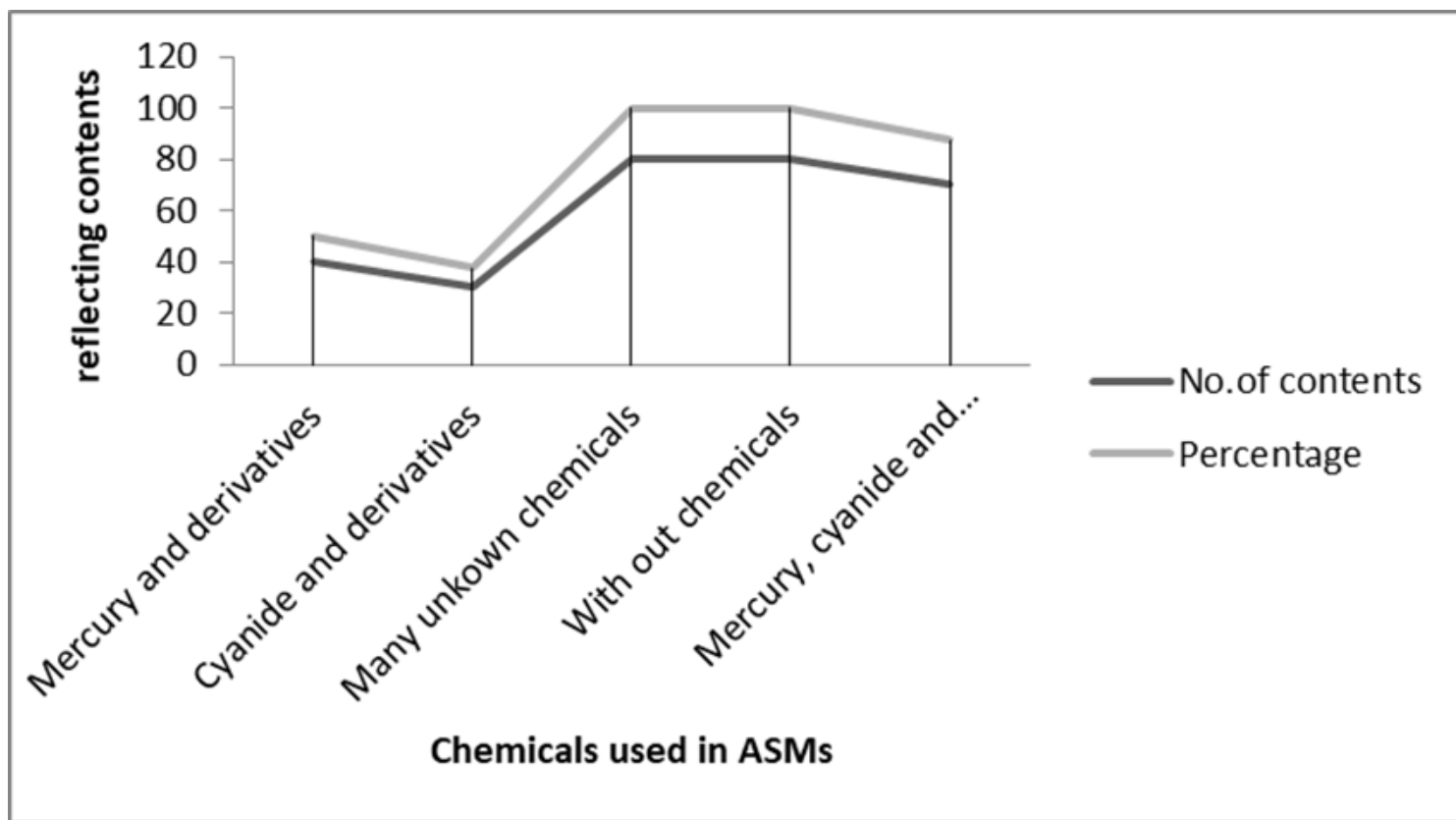


Figure 4

Chemical usages in the ASMs of Tigray

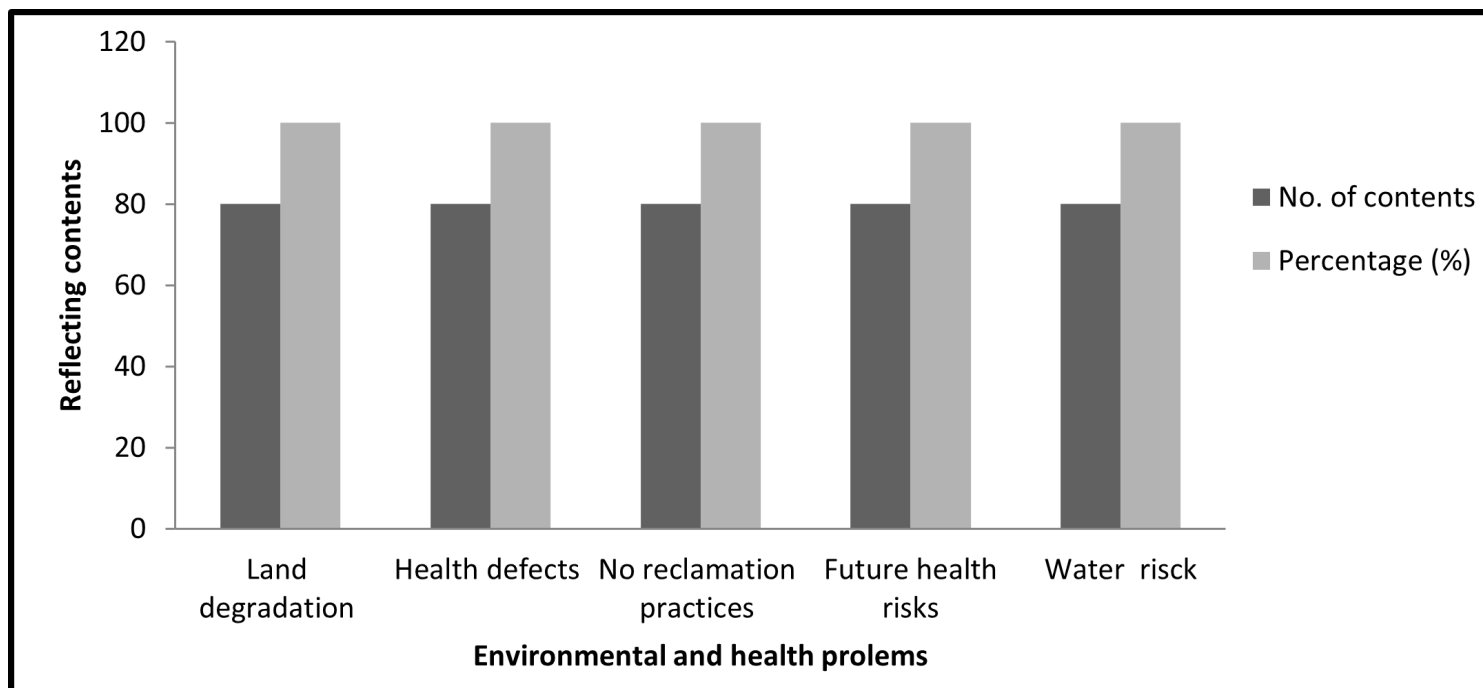


Figure 5

Environmental and health problems ASMs in Tigray

