

Assessing the Economic, Social, and Environmental Impacts of Informal Artisanal and Small-Scale Gold Operating Firms in Northwestern Tigray, Ethiopia

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Abstract: For countries endowed with mineral resources, particularly those with gold-bearing ores, gold serves as a vital economic driver, expanding infrastructure, creating jobs, generating higher tax revenues, attracting substantial foreign direct investment, and providing a hedge against economic uncertainty and currency devaluation. Luckily, following the Cessation Agreement signed between the Federal Government of Ethiopia and the Tigray People's Liberation Front (TPLF) in Pretoria (South Africa) on November 2, 2022, the demand for gold surged and international gold prices rose. As a result, several informal artisanal and small-scale miners (ASGM) as well as other unregulated gold mining operations restarted and began new gold ventures in the gold-endowed northwestern region of Tigray. Consequently, gold operations in Northwestern Tigray have become a blessing, generating profit for informal artisanal and small-scale gold miners (ASGM) while also draining the region's natural resources through possible adverse environmental impacts and endangering Northwestern Tigray's pristine environment. As of mid-April 2026, the Pretoria Peace Agreement between the Ethiopian Government and the Tigray People's Liberation Front is effectively nullified. Nonetheless, gold operations persist. They provide critical employment opportunities for several local people who were forced to abandon their animal husbandry and agricultural livelihoods. To address their severe joblessness, many migrant refugees and school-aged children, who dropped out of school, are drawn to the mining region. However, because ASGM is informal, unregulated, and often conducted without licenses or formal legalization, it largely uses the conventional "take-make-waste" approach. They contribute to geological alterations, vegetation loss, hazardous waste accumulation, and substantial climate change driven by greenhouse gas (GHG) emissions. The mercury and cyanide used to extract gold from ore have significantly exceeded the WHO and EPA safety limits for drinking water contamination and environmental pollution. Therefore, this study uses a mix of the pillars of sustainable development (socio-economic and environmental) and the cradle-to-cradle approach (which leverages material upcycling, uses renewable energy, and promotes diversified production) as a conceptual framework to assess the socio-economic and environmental impacts of gold mining operations in Northwestern Tigray. Methodologically, the study primarily drew on published works by academic and industry experts and used multiple electronic databases, including Google Scholar and Scopus. Recognizing that existing ASGMs are informal, the study suggests establishing formalized licensing requirements before ASGMs begin operations. Furthermore, the study calls for national government agencies, local government units, and the private sector to jointly develop, support, and manage regular regulatory assessment techniques that support the development of community-based

environmental monitoring programs. These programs will enhance equitable benefit-sharing mechanisms, minimize ecological footprints, and ensure that local communities and state governments share responsibility for establishing robust, incentive-based, formal approaches to integrating ASGM activities into the formal economy. To enhance environmental restoration and enable existing mining sites to thrive for productive future uses, the study also suggests transforming toxic waste into renewable resources and highlights that the remaining reengineered and reorganized toxic waste stored in tailings needs to be integrated into circular biological economy streams (such as nutrient-rich soil, organic biomass) and technical streams (such as recovered metals, green materials) for productive uses. To address the study's limitations, elaborate and strengthen the socio-economic and environmental effects of ASGM activities in Northwestern Tigray, and make their operational dynamics more transparent so as to facilitate sustainable development, a longitudinal empirical analysis of primary data collected across multiple time points is recommended.

Keywords: resource curse, footprints, gold mining activities, pristine environment, cradle-to-grave, stakeholder engagement, cradle-to-cradle system of sustainability, pull and push factors

Introduction

The wicked war that was committed on the people of Tigray from November 2020 to November 2022 by a quartet of genocidal forces—the Ethiopian Federal Armed Forces, the Amhara Special Forces, the Fano militias, and the Eritrean war forces—contributed to genocidal killings, bodily injuries, and mental health problems. These forces equated the Tigrayans to cancer. To solidify their genocidal intentions, the perpetrators used rape as a weapon and inserted iron rods that were designed to clean gun barrels into the wombs of women and girls to prevent the survivors from giving birth to future Tigrayan generations (Ibrahim, 2024).

After two years of horrific war, on November 2, 2022, the Ethiopian Federal Government and Tigray People's Liberation Front (TPLF) signed the Cessation of Hostilities Agreement, also known as the Pretoria Peace Agreement, to immediately and permanently halt all forms of violence and active hostilities between the federal government and the Tigrayan forces. However, after the Pretoria Peace Agreement failed to restore harmony and address the plight of internally displaced people returning to Tigray's disputed territories, the TPLF had no choice but to nullify the Pretoria Peace Agreement it signed with the Federal Government on April 19, 2026 (Wazema Memo, 2026).

Several artisanal and small-scale gold mining (ASGM) and several non-combatant military groups exceeded the regional government's capacity to manage them (Meaza, Ali, Tesfamariam, & Abebe, 2017; Meaza, 2025), so they are still actively engaged in gold mining operations in the northwestern part of Tigray located along the northern greenstone belt between 13°42' and 14°28' north latitude and 36°23' and 37°31' east longitude.

More specifically, to extract gold ore from streams, agricultural areas, and historical sites in the northwestern zone of Tigray (Girma & Endal, 2025), ASGM miners have employed geologists, engineers, and other professionals. In addition, a significant number of manual workers from the abandoned agricultural and animal husbandry areas, school dropouts, and poverty-driven workers from other regions of Tigray have been routinely hired.

Several Canadian and Chinese companies that had been licensed and accountable to the Federal Government of Ethiopia before the war were prevented by regional government authorities from resuming their prior mining operations during the post-war period (Staff Reporter, 2025). However, having cooperated with Ezana Mining Development, a subsidiary of the Endowment Fund for the Rehabilitation of Tigray (EFFORT), following the

force majeure event of the two-year war (Endale, 2024), these companies resumed operations in Northwestern Tigray as subsidiaries of East Africa Metals (EAM). To support this effort, local military personnel and ex-combatants guarded them, and they used mining machinery paid for by shadowy “foreign investors” Tibet Huay and Silk Road, which owned a 70 percent stake in the *Adiabo* projects. While East Africa Metal retained 30 percent ownership, it resumed gold mining operations using mining machinery paid for by shadowy “foreign investors” such as Tibet Huay and Silk Road Investment (Girma & Endal, 2025).

The large quantities of illicit gold that are extracted from the *Laelay Adyabo* (*Adinigisti*), *Asgede*, *Tsimbla*, *Rahwa*, *Mato Bula*, and *Da Tambuk* districts are smuggled from Shire—the epicenter for the collection and distribution of Tigray’s black-market gold—to Dubai, United Arab Emirates, which is considered a historically valued diplomatic partner of Ethiopia, along the following three major routes (Demissie & Soliman, 2024a; Girma & Endal, 2025).

First, smuggled gold ore is transported from Shire Inda Selassie, Tigray’s gold hub, across the Mereb River into Eritrea and Sudan before heading to Dubai. Secondly, gold ore is illegally transported from Shire to Dubai via the Mekelle-Addis Ababa route (Plaut, 2025), using large, camouflaged vehicles bearing the insignia of international organizations. Third, though less elaborate than the routes noted above, Ethiopia’s gold mining companies intermittently use routes through Somaliland, Kenya, and Uganda to transport gold to Dubai (Kassahun, 2025). According to Gebremedhin (2024) and Dawit (2025), artisanal and small-scale gold mining companies (ASMGs) operating in Northwestern Tigray smuggle more than \$2 billion in gold annually without paying taxes to regional and local governments. If local and regional governments had legally collected taxes on the smuggled gold, the VOA (2024) states that these funds would have been used to restore services that were discontinued or destroyed during the war and to revitalize the war-torn region of Northwest Tigray.

Given the ASMG’s outdated linear path for gold mining operations, which has contributed to the “resource curse” quagmire that has heavily burdened Northwestern Tigray, fundamental changes are needed. To examine the economic, social, and environmental impacts of gold mining in Tigray, this study proposes a theoretical framework that reviews a sustainable development model aligned with a cradle-to-cradle, or virtuous-circle system paradigm, that leverages upcycled materials and renewable energy and promotes diversified production.

Consequently, to investigate the impact of gold mining in Northwestern Tigray, this article is structured as follows. Section 2 reviews studies on sustainable development and the cradle-to-cradle approach, which are vital for analyzing the impacts and reconstruction of, gold-mining sites. Section 3 provides the conceptual framework and narrative map needed to organize and align the paper with its goals. Section 4 reviews the types of gold mining operations in Northwestern Tigray, including surface, underground, and alluvial mining. Drawing on credible secondary sources, Section 5 examines the economic, social, and environmental impacts of gold mining in Tigray. Section 6 summarizes the study, outlines its limitations, discusses policy implications, and proposes primary-based longitudinal studies to fully ascertain the economic, social, and environmental impacts of gold mining in Northwestern Tigray.

A Brief Review of the Literature on Sustainable Development and the Cradle-to-Cradle Approach

Tigray is blessed with golden ores. Before the outbreak of war, which occurred from November 2020 to November 2022, Tigray was among the largest suppliers of gold to the National Bank of Ethiopia. For instance, the Ministry of Mines notes that Tigray held the most gold-mining licenses in Ethiopia, with over 90 licenses

registered (see Girma & Endale, 2025; Demissie & Soliman, 2024b). Noting Northwestern Tigray's endowed gold opportunity, several artisanal and small-scale mining companies either resumed or began extracting gold ore from the surface or deep within Northwestern Tigray after the war.

More specifically, because economic opportunities were limited in Tigray, regional authorities allowed the formation of 25-person mining cooperative bands among ex-fighters of the Tigray Defense Forces (TDF) and allocated them plots of land. Currently, more than 100,000 traditional artisanal gold miners use manual or basic equipment to mine gold in Northwestern Tigray (Girma & Endale, 2025) and are endeavoring to help the region recover from the severe consequences of the genocidal war it experienced from November 2020 to April 2022.

Without regulatory oversight, illegal mining operations have also flourished in Tigray, seriously harming the environment and the region's mining communities (Seifu, 2025). More specifically, most gold miners in Northwestern Tigray have operated unregulated on the margins. The topsoil, which contains essential nutrients and seeds necessary for plant growth and development, has been substantially degraded. By altering the surrounding aquatic ecosystem, miners have significantly changed the land's topography and contributed substantially to topsoil erosion. The use of toxic chemicals, such as mercury and cyanide, in the refining of gold ore has significantly impacted both human health and the environment. Furthermore, miners who use dredging machines to deepen water channels have also overwhelmingly disturbed and destroyed the seabed ecosystem. They have recklessly left behind gold mining pits which fill with rainwater and become breeding grounds for mosquitoes that spread malaria throughout the communities.

In short, as will be demonstrated later, the activities of large- and small-scale mining companies in Northwestern Tigray, based on conventional linear methods, or cradle-to-grave approaches, have substantially contributed to population displacement, rising prices for necessities, and insecure living conditions. This has precipitated conflicts between owners and workers (Hardy, 2022; Ashton, 2022; Gebremedhin, 2024; Christian, 2024; Soesilo, Hawa, & Nuraeni, 2024).

Shifting away from the cradle-to-grave, or conventional linear production systems, which are dominated by economic efficiency targets (i.e., doing more with less by reducing materials, energy, and toxic substances), and associated with high energy use, waste generation, air pollution, land contamination, and limited diversity, this study attempts to use a mixed approach that combines the model of sustainable development developed by the United Nations and the nexus of cradle-to-cradle (C2C) designed by McDonough and Braungart (2012).

In other words, recognizing that economic growth overwhelmingly tends to consume its foundations and deplete natural resources on which the future of its economic and social development depends, the study attempts to use a mixed approach of the core agenda set by the United Nations Organization, Division for Sustainable Development, "Earth Summit" of 1992, and McDonough and Braungart's (2012)'s cradle-to-cradle model (C2C).

Briefly, sustainable development calls for phasing out unsustainable behavior and instead developing levers for sustainable, effective global action, operating on three foundational pillars. Economic viability fosters growth without depleting factors of production. Social equity ensures that all members of a society have access to resources, basic human rights, health care services, and equality. Environmental sustainability rests on preserving ecosystems and non-renewable resources, transitioning to renewable energy sources, and protecting vulnerable habitats from degradation (United Nations, 1992; Desta, 2018).

Designed by McDonough and Braungart (2012), the cradle-to-cradle model (C2C) is based on a circular flow of materials. It minimizes waste and creates positive environmental impacts by using reusable materials. By challenging the status quo of industrial production, in which products were designed for obsolescence, C2C

proposes a radical shift toward a circular economy in which materials and products can perpetually cycle through biological or technical loops (McDonough & Braungart, 2012). As stated below, the tenets of the cradle-to-cradle operating paradigm rest on: (A) waste as (food) resources, (B) using solar and other renewable energy to achieve eco-effective energy operations, and (C) embracing diversity to harmonize production and achieve eco-effectiveness.

A. Waste equals food: McDonough and Braungart (2012) argue that in the cradle-to-cradle mode of operations, waste of one system through the material reutilization process becomes nutrients for another. In other words, through the transcending process of birth, decay, and rebirth in either technical (designed for industrial recycling) or biological systems (designed to return to the soil and feed environmental processes), a closed-loop system allows nutrients to flow indefinitely, and the process significantly contributes to the health of a nation's ecosystem. Assuming that material flows are the most ecological, safe, and sustainable, instead of discarding products at the end of their cycle, Young, Dhanda, and Hollenhorst (2024) and Ankrah et al. (2018) strongly argue that engineers and designers could effectively redesign using a closed-loop flow system to return them to the loop for further production.

B. Utilize current solar energy: Based on the premise that living things thrive on the sun's energy, and, underlying that, trees and plants manufacture food from sunlight, McDonough and Braungart (2012) further expanded the cradle-to-cradle framework and suggested that effectively utilizing solar energy, wind, hydro, and other sources of renewable resources is fundamentally crucial for undertaking both biological and technical revitalization activities (McDonough & Braungart, 2012).

C. Celebrating diversity: Natural systems thrive on diversity and are the cornerstone of the cradle-to-cradle paradigm. Going beyond conventional methods of designing innovations, McDonough and Braungart (2012) persuasively avoid one-size-fits-all solutions; instead, they design products and systems that account for local cultures, environments, and economies. The framework of diversity encompasses biological, cultural, and conceptual aspects essential to developing resilient, robust, and adaptable solutions. More specifically, McDonough and Braungart (2012) suggest that the core principles of diversity include: (1) biological (plants, animals, and other variety of life on earth are appropriate to specific local contexts and needs); (2) socio-cultural (the appreciation of cultures, beliefs, and value); and (3) conceptual diversity (a variety of ideas, perspectives, and innovative solutions to problems are essential for the promotion of social fairness and designing a company's operations). The framework posits that diversity is fundamentally essential to promoting local ecosystems and fostering innovation. Therefore, McDonough and Braungart (2012) convincingly argue that designing a product using biological or technical nutrients based on the community will not only respect diversity but ultimately reduce its ecological footprint.

As a guide to the economic, social, and environmental pillars of sustainability, the Gold Industry Group's (2023) model strongly recommends answering the following three key questions as a vital practical roadmap for implementing cradle-to-cradle gold production: (1) Can the application of renewable materials be used to regenerate gold production? (2) If so, can the production processes of gold mining be made efficient and utilize minimal resources? (3) Rather than focusing solely on creating financial value, could gold mining ventures be made to adopt the cradle-to-cradle approach to create economic, social, and ecological value simultaneously?

A Conceptual Framework

The conceptual framework used in this study, presented in Table 1 below, integrates the three dimensions of sustainable development proposed by the United Nations with the three nexus-valuable assets of the cradle-

to-cradle model, outlined by McDonough and Braungart (2012). More specifically, it presents an integrated, hybrid operational definition of the sustainability variable model, intertwined with the holistic cradle-to-cradle framework used to assess the economic, social, and environmental impacts of artisanal gold mining operations in Northwestern Tigray (see, for example, Rey-Marti et al., 2023).

Table 1

Operational Definition of Sustainable Development Integrated Within the Cradle-to-Cradle Framework

Indicators	Economic effects	Social impact	Environmental effect	Cradle to cradle approach
	-Direct effects * GDP growth * Rate and level of employment * Employee creation * Wages and benefits * Revenue & tax payments to local governments -Indirect effects * Share of local procurement * Local & inter-industry purchase of output -Induced effects * Household spending on local goods and services * Cost of living expenses	* Establishing social license in advance * Engaging stakeholders * Setting rigorous government regulations & enforcement techniques * Fostering positive relationships between mining companies and local communities * Building roads * Establishing affordable safe living quarters for workers * Providing health care facilities * Providing and enhancing educational services * Providing extension service and inputs to mining neighborhoods * Mass migration and influx of people to mining communities * Displacement of homes and farmlands * Incidence of crime * Occupational injuries	* Ecosystem and vegetation destruction * Land degradation & loss of soil fertility & productivity * Habitat fragmentation * Deforestation * Producing waste contamination * Water contamination * Air pollution * Mercury and cyanide pollution * Destruction of aquatic life * Land use conflicts * Loss of vegetation (flora & fauna) * Greenhouse gas emissions * Ecological carbon footprint	* Recycling of waste for food sources * Use of renewable energy sources * Establishing diversity and the inclusion of local resources

Source: Morgan (2010); Rey-Marti et al. (2023); Worlanyo and Li (2021).

Types of Gold Mining Operations in Northwestern Tigray

The most conspicuous artisanal and small-scale gold surface mining operations in Tigray are found in the northern greenstone belt, located between 13 °42' and 14 °28' north latitude and 36 °23' and 37 °31' east longitude (Meaza et al., 2017; Meaza, 2025). There are mainly two types of mining: underground and surface (Worlanyo & Li, 2021). To extract gold underground, the industrial gold mining sector employs heavy mining equipment and uses high-level machinery and hard-rock mining methods with considerable sophistication and high labor demand. In contrast, informal artisanal and small-scale gold miners (ASGM) are undercapitalized, so they require relatively less initial investment and primarily use surface placer mining close to the earth's surface or exhume ores by washing sediments in a shallow pan with water to physically separate heavy gold from surrounding dirt, gravel, and lighter sand (Mensah, Siabi, Donkor, & Kurantin, 2022).

Industrial gold mining sector: To extract solid ore buried beneath the soil and expose near-surface ore deposits, industrial gold mining enterprises rely on excavators to clear vegetation and topsoil (overburden) for open-pit mining. Mountain-top mining, another destructive form of surface mining, uses excavators, bulldozers, and other heavy machinery to extract gold from hilltops.

The industrial gold mining sector also uses sluicing, a method that uses a sluice box lined with “riffles” at the bottom to separate gold from dirt and gravel by using flowing water. During the mining process, as the riffles direct water down the sluice box, gravity causes the high-density gold particles to sink and become trapped in the sluice. In other words, a pan with holes in the bottom or a griddle separates larger gold-bearing rocks from lighter sediments. Finally, after dewatering, the lighter residual materials, such as clay, sand, and gravel, are washed and stockpiled in tailings storage facilities, while the heavier gold particles remain behind (<https://www.google.com/slucing>).

Generally, large-scale mining operations add toxic chemicals, such as cyanide, to wet pan mills and sluice boxes to enhance gold recovery during the amalgamation grinding process. This leads to severe pollution and contamination of local drinking water and generates long-term health effects on miners and nearby mining communities. As previously discussed, the open mining pits and pools of stagnant water, left behind by miners after the sluicing process, can serve as breeding grounds for mosquitoes, contributing to the spread of malaria. Discharges deposit massive amounts of sediment and waste rock into rivers, raise riverbeds, increase flooding, and make the water too cloudy for sunlight to penetrate, potentially threatening the survival of aquatic plants and fish. As noted by Mathioudakis, Xiroudakis, Petrakis, and Manoutsoglou (2023), gold sluicing contributes to clearing large areas of forest to access riverbeds. This leads to soil erosion, landslides, river sedimentation, and the accumulation of mining waste materials (tailings).

Some large-scale firms employ capital-intensive mining techniques known as dredging. A gold dredge is a placer mining machine that extracts gold from sand, gravel, and dirt using water and mechanical methods. When used by large gold mining companies, the dredging process employs motorized floating pumps to extract gold ore from sediments in rivers, lakes, and other mineral-bearing waterways, including river bottoms and streambeds (MSHA Safety Services, 2024). In other words, gold dredging is a hydraulic process used to separate and recover heavier gold particles from lighter minerals, and the material is transported to onshore processing facilities (Mathioudakis et al., 2023; Website, 2023-2025; Shengo, 2021). During dredging, heavier gold material is separated from lighter material, or waste. This waste left on the onboard sluice box is returned to the running water for disposal. In addition, Schaanning, Trannum, Øxnevad, and Ndungu (2019) succinctly argue that silt and waste, generated by crushing and grinding ore during dredging, result in toxic chemicals, such as mercury and cyanide used in amalgamation, increasing river turbidity (muddiness).

Informal artisanal and small-scale gold miners (ASGM): Unlike the large-scale mining industrial companies described above, informal artisanal and small-scale miners are undercapitalized and use panning techniques. Panning is the predominant gravity-based technique used by artisanal and small-scale miners to separate gold from alluvial deposits in streams, rivers, and floodplains (Hustrulid, 2026; Manhattan Gold & Silver, 2011).

For instance, in Northwestern Tigray, most illegal small-scale artisanal miners rely on panning. This labor-intensive method separates heavy gold particles from lighter ones in alluvial deposits. From a riverbed or stream, the miner scoops up a mix of sand, silt, gravel, clay, and gold dust into a curved pan with water and thoroughly agitates the pan by swirling or moving it in a fast, twisting, circular pattern. Thereby, during agitation, the lighter materials remaining on the surface are washed away, while the extremely dense, heavier gold sinks to the bottom.

As mentioned before, during the panning process, it is possible that chemicals such as mercury, which are used to optimize recovery and extract gold from ore, contribute to the contamination of drinking water and pose health risks to animals and humans (Fonshiyinwa et al., 2024; Ukpanah, 2024; Timsina et al., 2022).

To summarize, during the post-war era, mostly informal artisanal and small-scale gold mining (ASGM) operations have been actively involved in undertaking gold extraction in Northwestern Tigray. Thereby, to analyze the economic, social, and environmental effects of gold mining activities in the region, a conceptual framework that is a mix of the three dimensions of sustainable development (economic, social, and environmental) and the three cradle-to-cradle nexuses that focus on employing waste as an asset, utilizing clean energy sources, and celebrating diversity are used.

The Economic, Social, and Environmental Effects of Gold Mining Operations in Northwestern Tigray

Following the Pretoria Peace Agreement in November 2022, Tigray experienced widespread economic depression and a lack of other economic opportunities. Consequently, to recover the severely damaged parts of Tigray during the Ethio-Tigray conflict, Tigray's regional authorities allocated plots of land to groups of 25 people to resume gold extraction in Northwestern Tigray during the post-recovery period. Girma and Endale (2025) document that, during this time, more than 100,000 traditional artisanal gold miners used mostly manual methods or basic equipment to mine gold, bringing fundamental rejuvenation to Northwestern Tigray. Accordingly, the three conceptual frameworks proposed by Morgan (2010) are used to analyze the direct, indirect, and induced economic ripples, or multiplier effects, of investments in Northwestern Tigray.

The *direct economic* impact analysis identifies direct economic effects, including initial spending and changes in output, employment (for example, miners, engineers, and geologists), income, and infrastructure development (such as building roads and power lines) resulting from mining companies' investments. The *indirect* effects assess changes in output resulting from supply chain procurement, including mining companies' purchases of raw materials from local suppliers, and assess inter-industry trade. Increased demand is expected to enable suppliers to hire more workers and create jobs beyond mining sites. On the other hand, induced economic outcomes result from direct and indirect employees spending income on local goods, housing, food, healthcare, education, recreation, and consumer goods, as well as from tax revenue paid, which could stimulate the local and national economy.

An analysis from a *direct economic* perspective showed that, though undercapitalized, the investment capacity of informal artisanal and small-scale mining companies in Northwestern Tigray was substantial. The gold extraction generated meager income for the region's economic growth. However, the mining ventures failed to drive substantial growth for the region's Gross Domestic Product. Infrastructure development, including the construction, expansion, and modernization of vital systems such as transportation, energy, and communication networks, was not adequately established to substantially support the local economy.

The highly skilled foreign workers, local engineers, and business operators were well paid. Nonetheless, those evicted from their agricultural land, youths who dropped out of school and migrated to mining centers in search of work, and ex-combatants who turned to artisanal mining to survive were hired at lower wages to perform manual labor such as digging, washing, panning, and processing gold-bearing quartz veins (Nyssen, 2022; Teku, 2025; Seifu, 2025).

A partial tax analysis also indicates that the mining companies failed to pay the required local taxes. Getachew Reda, then interim president of Tigray, reported that the Tigray government had not received a single penny in taxes from miners operating in Tigray (Gebremedhin, 2024). Interestingly, Dawit (2025) and Plaut (2025) reported that miners were actively minimizing tax liability. They evaded tax and smuggled large quantities of gold into Dubai, United Arab Emirates, via the black market.

When established, Tigray's gold mining sites were expected to stimulate local procurement and build resilient local supply chains by purchasing raw materials from local suppliers, fostering business-to-business transactions and creating a chain reaction throughout the supply network. An analysis of the indirect economic perspective clearly indicates that mining enterprises operating in Tigray rarely developed self-sufficient local ecosystems; they primarily sourced inputs from foreign suppliers. As reported by Tigray Liberty Media, the income of corrupt mining bureau officials and security officials largely came from bribes from unauthorized mining operations and were either spent on foreign products or invested outside the mining sector rather than on locally produced inputs (Seifu, 2025).

From the perspective of the induced economic impact analysis, the region's high inflation rate reduced workers' ability to buy local goods. The nominal wages of underpaid mining workers were rather insufficient to cover the cost of local goods and services. Because the region lacks consumer amenities, the high-income group generally leaked income out of the region, spending it abroad to buy amenities. More importantly, because workers were not unionized, they lacked the bargaining power to negotiate inflation-adjusted wages amid declining real incomes, thereby diminishing the multiplier effect that would otherwise amplify the local economy.

In a nutshell, gold mining projects are theoretically expected to yield three types of economic effects. Direct effects capture output, employment, and tax incentives. Indirect effects reflect supply chain reactions and the procurement of local goods. Induced economic effects result from employees' purchases of local goods and services. Given the combined direct, indirect, and induced economic effects of gold mining at local mining sites, the study indicates that the economic multiplier effects of gold operations' initial investment in the Northwestern Tigray region were negligible. The dampening of local economic activity and the underpayment of local workers in the mining regions yielded marginal financial return to the war-ravaged region. Instead, as noted by Plaut (2025) and the Kasahun (2025; 2024), Tigray's gold-rich landscape is losing resources without benefit for the region at a time when Tigray is trying to recover from two years of brutal war it had with the federal government and its allies (Plaut, 2025).

Social effects: Generally, the social effects of gold mining yield mutually exclusive outcomes. While it serves as a source of wealth for investors and countries, it can also be environmentally damaging and socially destructive. The *social impact analysis* in Northwestern Tigray indicates that when local people and farmers are displaced from their ancestral land without adequate compensation, it triggers a profound misunderstanding between gold miners and the community. Thus, before mines are approved, they need to be examined to mitigate misunderstandings that might arise between representatives of the gold-mining community and mining companies. In short, the parties should have established transparent social licenses tailored to enhance equity and diversity, employee training, affordable housing, and health and educational facilities, and reduce the risk of occupational incidents. Moreover, as Toure (2024) argues, aligning improved ASGM practices with the UN's Sustainable Development Goals could have alleviated poverty and environmental degradation in Northwestern Tigray. However, since most of the artisanal and small-scale miners operating in Northwest Tigray operated illegally and engaged in rent-seeking, there is no evidence that the companies held legal licenses requiring them

to pursue adequate social responsibility objectives, meet community expectations, improve the quality of life in the mining community, and enhance opportunities for their employees.

By design or default, the workforce in Tigray's gold-mining sector seems diverse. However, because most manual workers rely on rudimentary tools such as pans and chisels, nominal wages are paid to these workers, who are composed of people displaced from their ancestral lands and livelihoods in agriculture and forestry, internally displaced people (IDPs), refugees, and some young school-aged children who dropped out of school. These workers all live in very poor conditions. Plaut (2025) succinctly noted that several artisanal workers, particularly those in *Central Adiabo*, *Laelay Adiabo*, *Tahtay Adiabo*, *Asgede*, and *Tsembla woredas*, who worked in informal and hazardous settings, lacked essential infrastructure and resources, such as water, electricity, and sanitation, and lived in cramped, makeshift homes. In contrast, well-paid foreign engineers, geologists, machine operators, and business managers generally lived in well-furnished housing with private rooms and were served nutritious, high-quality meals. As noted by Wilmot and Endale (2025), foreigners who worked for firms such as Ezana Mining Development or the Canadian partnerships (such as Sun Peak Metals or East Africa Metals) generally resided on a dedicated, military-guarded campus established directly on the mining concessions. The rest settled comfortably in well-furnished, military-guarded housing in the town of Shire, the major logistics and post-war gold trade hub.

From an educational perspective, during the two periods of war (November 2020 to June 2020 and August 2022 to November 2022), students' learning across Tigray's mining sites was completely paralyzed, and school-aged children who survived the disastrous war period were left psychologically traumatized (Desta, 2018). Thus, rather than acting as bystanders, gold-mining entrepreneurs could have minimized educational disruption during the post-war period by repairing dilapidated schools, encouraging workers to continue their schooling, and providing essential resources to make workplaces environmentally safe. In addition, if miners undertook capacity-building initiatives, the renovated schools around mining sites could have served as training programs for school-dropout youth working at the mining centers. More specifically, after a mining site closes, retraining the workforce could enable upscaling other types of professional work at the centers (Rey-Marti et al., 2023; Mujumphi & Mpundu, 2025).

The proliferation of gold mining in Northwestern Tigray has also affected the health of the region's population. Toxic chemicals, like mercury and cyanide, to name a couple, used for the extraction of gold from ore, have been dangerously exposed to the miners as well as the region's residents. Women miners who wash soil with chemicals without following safety protocols while searching for gold have experienced skin discoloration, rashes, blisters, and peeling skin on their hands. In addition, Gebremedhin (2024) notes that residents living near the mining fields are affected by toxic mercury and cyanide. Cows in the mining area have developed deformed skin. As mentioned earlier, open-pit mines left by miners accumulate stagnant water during the rainy season, becoming a breeding ground for mosquitoes and contributing to malaria and long-term health problems for nearby residents. The toxic waste left by mining companies has not only polluted the environment but has also affected the surrounding drinking water. In addition, dust emissions, excessive noise, and heavy metal contamination have caused severe health issues, contributed to respiratory problems, and resulted in birth defects.

Artisanal and small-scale operators in Northwestern Tigray could be socially responsible and pursue the United Nations Sustainable Development Goals by systematically reducing Northwestern Tigray's ecological footprint and fostering long-term social growth. Being highly militarized, violent centers of chaos and

lawlessness, and exploitative enterprises with far-reaching consequences, Kasahun (2024) argues that artisanal and small-scale mining companies operating in Northwestern Tigray should be allowed to address safety, extremist, and health concerns affecting the unbenefited public (VOA, 2024). Moreover, in line with their social responsibility, ASGM operators in Northwestern Tigray need to endeavor to (a) utilize mercury- and cyanide-free gold extraction techniques, (b) construct health clinics for workers and residents, (c) provide health care facilities for workers, (d) establish safe living quarters for workers, (e) modernize and enhance educational services to boost learners' engagement, and (f) reduce the wage inequity between the men and women workers.

Environmental effects: As discussed above, in the absence of other economic opportunities in Tigray during the post-war period, more than 100,000 artisanal and small-scale mining companies are engaged in gold mining operations in Northwestern Tigray to enhance the region's economic development (Girma & Endale, 2025). However, due to a lack of effective regulations, operating mining firms are uprooting and displacing Northwestern Tigray's pristine environments. For example, many farmers in the *Asgede* and *Tsimbla* districts have abandoned their farmland because intensive clearing of forests and vegetation has caused land degradation and soil erosion, reducing the land's capacity to support vegetation growth. As Meaza (2025) notes, gold miners often follow mineral veins beneath trees, resulting in tree cutting and the destruction of root systems that stabilize soil, increasing the risk of downstream erosion. Furthermore, when excavators dig open pits, local hydrology becomes significantly contaminated, affecting soil and nearby water sources. Similarly, Timsina et al. (2022) argue that landscape degradation, primarily through surface and open-pit mining, contributes to deforestation, soil erosion, displacement, and toxic contamination, ultimately leading to environmental degradation. Yu and Zahidi (2023) also show that depleting organic content and nutrient-holding clay-sized particles in topsoil stockpiles significantly reduces the effectiveness of post-closure soil recapping and revegetation efforts.

As rainwater accumulates in unfilled gold-mining pits, it is likely to create breeding grounds for mosquitoes that carry the malaria parasite, and the resulting waste poses significant environmental threats that extend beyond merely detracting from green mining practices (Yu & Zahidi, 2023). Irresponsible mining practices have released substantial amounts of pollutants, including heavy metals and other chemical contaminants, into ecosystems, critically endangering local flora and encroaching on pristine land (Hardy, 2022; Timsina et al., 2022).

Like mining operations in Ghana (Earthworks, 2024), illegal mining activities in Tigray appear to pose serious health risks to marine life by contaminating drinking water systems and endangering biodiversity. River sedimentation and toxic substances, such as mercury and cyanide used for gold extraction, have leached into groundwater and streams, contributing to neurological disorders, tremors, and cognitive impairments in residents and posing significant long-term pollution risks. Furthermore, the tailings dams used to store toxic waste have contaminated the food chain (<https://www.google.com>).

As highlighted by Girma and Endal (2025), gold processing in Northwestern Tigray's mountainous and hilly areas is an energy-intensive operation that releases dust, heavy metals, and greenhouse gases, resulting in a significant environmental footprint at gold mining sites. Furthermore, Alvarez-Pugliese, Machuca-Martínez, and Pérez-Rincón (2021) reported mercury vapor emissions from burning amalgams; when inhaled, the vapor can enter the bloodstream and cause kidney damage.

The gold mines in Northwestern Tigray rely heavily on diesel and gasoline engines for grid operations and for pumping water out of deep pits during mining. However, since Tigray receives solar radiation ranging from 5.3 to 6.7 kWh/m² per day, making off-grid solar photovoltaic (PV) systems relatively cheaper to operate, it

would have been relatively economical or cheaper for artisanal and small-scale mining enterprises in Northwestern Tigray to use solar energy (Tesfay, Atsbeha, & Hailu, 2025).

In a nutshell, unregulated artisanal and small-scale (ASM) mining operations in Northwestern Tigray have depleted the pristine environment by causing deforestation, biodiversity loss, ecosystem destruction, soil erosion, water degradation, and substantial dust emissions. This massive, carbon-intensive footprint has endangered residents' health and caused severe environmental damage.

Summary, Policy Implications, and Research Options

After signing the Pretoria Peace Agreement with the Ethiopian Federal Government in November 2022, the Regional Government of Tigray, which has abundant gold reserves in the Northwestern Tigray zone, initiated gold operations. To support economic recovery in Northwestern Tigray, several illegal artisanal and small-scale gold mining (ASGM) groups and ex-combatant military officers restarted or initiated gold mining operations. Below is a summary of the findings, policy implications, and possible future research options.

Summary: To investigate the economic, social, and environmental impacts of gold mining in Northwestern Tigray, the study uses a conceptual framework that combines the three dimensions of sustainable development (economic, social, and environmental) and the three cradle-to-cradle nexuses, which focus on employing waste as an asset, utilizing clean energy sources, and celebrating diversity.

From a direct *economic value-effect* perspective, the analysis revealed that gold extraction in Northwestern Tigray attracted a diverse workforce and generated meager income for employees. The mining activities had little impact on regional economic growth. It failed to drive substantial growth in the mining region's gross domestic product. More specifically, the gold mines' operations failed to advance infrastructure development, including the construction, expansion, and modernization of vital systems such as transportation, energy, and communication networks. Instead, as noted by Dawit (2025) and Plaut (2025), the mine owners avoided paying required local, regional, and federal taxes and smuggled vast quantities of gold to Dubai in the United Arab Emirates.

Highly skilled foreign workers, local engineers, and business operators were paid commensurate with their responsibilities and roles. However, the workers who were pulled from their agricultural land and migrated to the mining centers in search of work to survive, the ex-combatants, and the youth workers who dropped out of school were relatively underpaid. Women workers hired to perform labor-intensive tasks, such as panning, were also undercompensated (Nyssen, 2022).

An analysis of indirect economic effects showed that mining enterprise owners did little to develop a supply chain and procure local inputs. The illegal artisans and small-scale firms, by and large, imported inputs from abroad and did little to enhance the productivity of other local companies. Also, because of high inflation, the induced economic analysis indicates that the real income of local manual workers in mining regions was very low, thereby reducing workers' propensity to purchase local goods and services.

From a *social sustainability perspective*, gold resources are expected to serve as a source of wealth for investors. However, because the ASMGs are unlicensed and the government has failed to enforce the law, gold mining in Northwestern Tigray has profoundly sparked misunderstandings between the local community and the gold miners. Seeking to get rich as quickly as possible, the ASMGs operating in Tigray sidestepped efforts to advance the mining region's social objectives. For example, health-related analyses indicate that gold mining companies contributed to exposing workers, livestock, and residents to hazardous chemicals such as mercury and

cyanide. More specifically, Gebremedhin's (2024) study indicates that women miners developed skin discoloration, rashes, blisters, and peeling skin on their hands. Leftover excavated gold-mining pits became breeding grounds for mosquitoes, contributing to malaria and long-term health problems. An educational analysis also indicates that miners paid little attention to repairing the war-torn. The war-torn and dilapidated schools were rarely used to train existing workers and were not used as potential sites for the future mining workforce (Rey-Marti et al., 2023).

An *environmental analysis* indicates that unregulated gold ASMGs and other miners operating in the northwestern zone of Tigray released greenhouse gases across the mining zones. The illegal miners have left a significant environmental footprint by: (1) stripping native woodland ecosystems; (2) destroying the carbon-storing vegetation; (3) leaving open-pit excavation holes; (4) removing topsoil and contributing to soil pollution; (5) destroying carbon-storing vegetation and habitats; (6) contaminating community drinking water supplies with toxic mercury and cyanide which have endangered the health of residents and miners; (7) releasing toxic waste; and (8) polluting the environment using energy-intensive operational models.

Policy implications: Current gold mining strategies in Northwestern Tigray largely rely on highly destructive practices. If the policy implications suggested below are grounded in adopting a cradle-to-cradle, virtuous-circle system, they will very likely leverage upcycled materials and renewable energy and promote diversified production. More fundamentally, they can reduce the environmental footprint of the abandoned gold-mining ecosystem and mitigate the deleterious impacts of artisanal and small-scale gold mining (ASGM) and other mining firms that are currently operating in Northwestern Tigray. Thus, here are some suggestions that could be brought to policy makers: (1) formalizing the activities of the ASGM sector to bring them into the formal sector through a regulatory and policy framework; (2) creating a joined-up governance of miners with the local community who are directly affected by mining operations; (3) offering public sensitization and environmental care training to ASGM; (4) legalizing mining firms to pay mandatory taxes; (5) restoring ecosystems to their natural state through revegetation and rehabilitation efforts and reducing deforestation activities; (6) phasing out the use of mercury and cyanide for gold extracting; (7) adopting renewable sources of energy that minimize environmental harm; and (8) providing legitimate capital or loans to formally legalized miners.

Finally, as noted below, to ensure that ASGM activities are transparent, deliberate, and drive sustainable development, policymakers need to undertake further intensive, primary-data-based, longitudinal, and empirical study. Steps of this nature are very likely to contribute to socio-economic and environmental benefits or functionality, including employment opportunities, support for local businesses by providing opportunities to supply goods and services to the mining project, and enhanced investment in community infrastructure such as roads, schools, and clinics (Sustainability Director, 2025). These will all serve as a viable route to economic transformation (Worlanyo & Li, 2021).

Limitations and research options: As undertaken in this study, drawing on credible, secondary data from academic repositories, institutional experts, government reports, and electronic databases such as Google Scholar and Scopus that align closely with geographical and demographic characteristics, is likely to be valuable. However, decision-making and strategic planning processes could likely be more effective if the study were grounded in intensive, longitudinal, primary, data-driven empirical analysis. Therefore, to further examine the economic, social, and environmental impacts of illegal artisanal and small-scale gold mining organizations operating in Northwestern Tigray, the present study could be strengthened by undertaking intensive, longitudinal, primary, data-driven empirical analysis to support rigorous and reliable policy decisions. Furthermore, a

longitudinal, rigorous approach could help design a trajectory for more productive and sustainable management of the remaining mining by-products or waste streams.

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