Risk Assessment from Primary Mining of Precious Metal (Gold) and Possible Mitigation Route

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Abstract Mining is an important activity at the present time that causes severe environmental stress. The heavy metals (metalloids) easily released into the environment, surface water and groundwater contamination, and soil and air pollution are also potential risks to human health. Due to the stringent environmental rules and global thirst for achieving Sustainable Development Goals, human negligence cannot be affordable in the long run. It is time to recognize the need for people connected with safe and sustainable mining activities of lucrative precious metals like gold. Therefore, in this chapter, we assess the risks caused by the primary mining of gold and discuss mitigation routes involving various factors.

Keywords Precious metals · Artisanal gold mining · Amalgamation · Cyanidation · Acid mine drainage · Hazard index · Mining environmental liabilities

1 Introduction

Mining is related to the exploration of valuable geological minerals from the Earth and/or other astronomical sources that essentially cannot be grown by agriculture (Ilyas et al. 2021). For example, the exploration of coal, metals, gemstones, rock salt, oil shale, clay, petroleum, natural gas, etc. comes under mining activities. Among these, metal-related mining activities are one of the most important as they cater to

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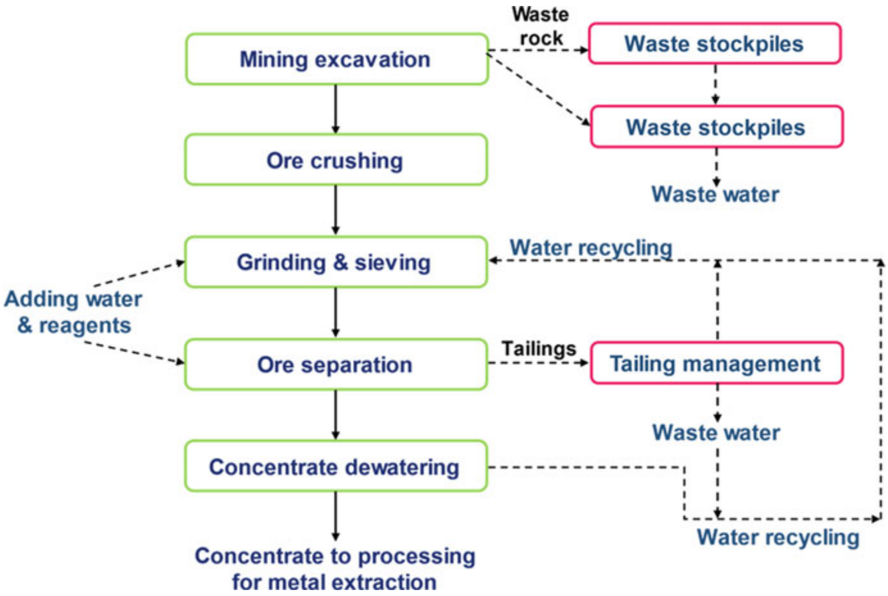

Fig. 1 Schematic representation of typical mining activities at a standard condition

our 24-hour needs (Ilyas et al. 2018). In general, the mining of minerals can be divided mainly into five stages: mining, crushing, grinding, ore concentration, and dewatering (Srivastava et al. 2023). The typical operations in any mining activities carried out at a standard condition are illustrated in Fig. 1. From these activities, mainly two types of waste are generated: waste rock piles (tailings) and wastewater. Wastewater is discharged from either the underground runoff water or the used water in grinding and ore separation, whereas tailings are produced from the grinding and ore separation processes and go to the tailing management facilities (Global Tailing Review 2020). In most cases, tailing dams are mining legacies that release potentially toxic elements (viz., Cd, As, Cu, etc.) into nearby water sources to be used in irrigation of agricultural land and sometimes uptaken by humans (Dong et al. 2020). Poor management of tailing waste has caused tailing dam failures in the past with catastrophic consequences (Grebby et al. 2021; Ouellet et al. 2022). Ideally, the wastewater should be recycled between the grinding, separation, and dewatering stages; however, it is not always easy to practice. On the other hand, the final product obtained after the mining activities, i.e., ore concentrates, is sent to the extraction and purification processes for the recovery of pure metals.

Mining activities can have both positive and negative impacts on society and the environment during the ongoing mining process or after the abandonment of a mine, both in direct and indirect ways. Exploration, construction, and operation often cause land-use change to have negative impacts on the environment due to associated issues like deforestation, soil erosion, contamination of water streams and wetlands, an increase in noise pollution due to machining, and air pollution due to dust and emissions (Cruzado-Tafur et al. 2021). Similarly, abandoned mines result in remarkable environmental footprints like soil and water contamination (Ngole-Jeme and Fantke 2017). Beyond the mining activities, the built infrastructure like roads, railways, ports, electricity, etc. can affect the flora and fauna leading toward the migratory routes (Rapant et al. 2006). Nevertheless, mining has positive impacts in terms of employment generation, not only in mining itself but also in other sectors like transportation, metallurgical and chemical industries, and mushrooming local businesses for daily needs. The concerns over environmental risks and public health issues are greater because damage cannot be compensated. Up to some extent, remediation of the potential environmental impacts by means of ecological restoration and wastewater treatment (Paniagua-López et al. 2021). As prevention is better than cure, the nations are trying to regulate the mining activities to control the damage; however, the full enforcement of regulations is always challenging.

The risk assessment of primary mining may be helpful to identify related issues, estimate the probability and severity of the consequences, and make strategies for environmental management (Cervantes Neira and Quito Quilla 2020). Accordingly, risk assessment is a process that comprises measuring the possible adversities resulting from the exposition of environmental stress, including the physical, chemical, and biological entities responsible for damaging the ecosystem (USEPA 1998). Given that mitigation measures can be implemented to avoid, eliminate, and reduce the negative or improved impacts, such measures must be outlined in environmental and social impact assessments before major mining activities (Arranz-González et al. 2021). The mitigation of environmental impacts in one system can influence other systems. For example, water or soil treatments are linked to the well-being and health of local inhabitants and biodiversity. A variety of technological advancements have been seen in the area of wastewater treatment and contaminated land (Cervantes Neira and Quito Quilla 2020; USEPA 1998). In contrast, the mitigation routes designed to alleviate negative impacts on the environment and society may not always be effective (Haddaway et al. 2019). Indeed, the risk assessment from primary mining of precious metals and possible mitigation routes have been poorly focused, as has been the aim of this chapter.

2 Risk Assessment

Risk assessment is related to the analysis and mitigation of risks in the form of natural disasters and mining accidents in terms of their impacts on the environment and society. The natural hazards and disaster risks include earthquakes, landslides, floods, etc., whereas the mining industrial hazards typically involve mine sliding, dam failures, fire and explosions, water leakage, the release of hazardous chemicals or radionuclides, etc. In order to assess the risk, the following approaches are desirable (EIA Guidelines 2018):

(i) Identifying the category of hazards and/or disasters from the historical available data
(ii) Considering the case of climate change and its implications for frequency and consequences
(iii) Estimation of spatial patterns, time, frequency, and intensity
(iv) Identification based on project design and layout, use and handling of hazardous substances from the case studies, available records, and media reports
(v) Analyzing cause and effect and the probability of events
(vi) Assessing the extent of damages by accounting for the layout and design of the project, exposure routes and environment, local inhabitants, etc.
(vii) Calculating the overall risk and comparing it with the acceptable levels
(viii) Identifying the need for mitigation measures

2.1 Mercury Load in Fish

Several routes exist for environmental risk assessment and modeling, along with their limitations and advantages (Kammen and Hassenzahl 2001). Determining the metal concentrations in fish and soil samples is simple to establish the safe-unsafe or maximum concentration level thresholds. Recently, Marcantonio et al. (2021) reported the mercury load in fish from a precious metal mine in Sierra Leone to be 302 ppb. Although the sampled fish were mostly short-lived freshwater species, the Hg concentration was average for albacore tuna (FDA 2018). About 87% of fish samples exceeded in Hg concentrations the FDA recommended value of 150–230 ppb for 2–3 meals/week consumption, whereas 15% of samples exceeded the zero meals/week threshold with >460 ppb Hg therein. The one-way ANOVA for Hg concentration and 95% confidence interval for the range of hazards index are shown in Fig. 2a, b, respectively.

2.2 Heavy Metals in Soil

The soils near the mining activities are always found to be severely contaminated with heavy metals and sometimes radionuclides as well, which pose potential risks to human health. The majority of soil samples near the primary mining of precious metals contain cobalt, chromium, lead, iron, and thorium in concentrations that exceed most established limits (as per Table 1). For example, the soils collected along the Pampana River in Sierra Leone (Africa) were analyzed to contain 115 ppm Th in comparison to the limit of 7.4 ppm (US-EPA 2019). Notably, the risk posed by heavy metals can be assessed by following the steps of the US-EPA (2014):

(i) *Hazard identification:* a process that determines whether exposure to a stressor increases the likelihood of adverse health effects

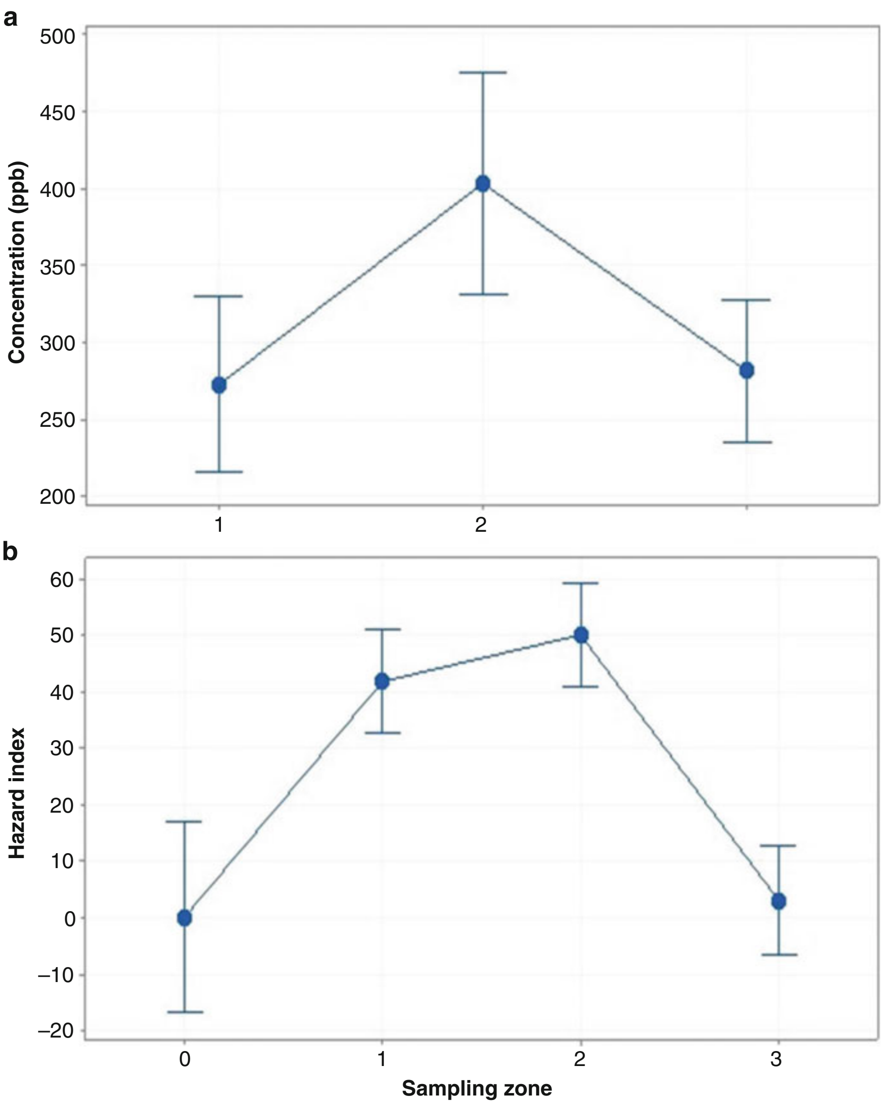

Fig. 2 Interval plots of testing for differences in Hg content in fish (**a**) and T-test results for greater probability of risk than EPA established noncarcinogenic risk acceptable risk: HI > 1 (**b**) (modified and adopted from the open supplementary source of Marcantonio et al. 2021)

(ii) *Exposure assessment:* a process that estimates the quantity of heavy metal exposure to a human being

(iii) *Dosage-response assessment:* a process that determines the human health problems associated with different uptakes of heavy metals

Table 1 Heavy metals' limits in soil samples as fixed by different countries (Atanassov 2008; Canada-MoE 2011; Kamunda et al. 2016; Li et al. 2019; Rodríguez-Eugenio et al. 2018; SA-DEA 2010; Tóth et al. 2016; UK-DoE 2009), NA = not analyzed

Heavy metals (mg/kg)	France	Belgium	Hungary	Germany	Netherlands	Finland	Poland	UK	Australia	Taiwan	Canada	South Africa	China
As	37	110	15	50	55	50	2	37	20	60	11	5.8	30
Cd	20	6	1	20	12	10	4	22	3	5	1	7.5	3
$Cr_{(total)}$	130	300	75	400	380	200	NA	130	50	250	67	6.5	1000
Cu	190	400	30	NA	190	150	150	NA	100	NA	19	300	NA
Hg	7	15	0.5	20	10	2	NA	10	1	2	0.16	0.93	2
Pb	400	700	100	400	530	200	100	200	300	300	45	20	80
Ni	140	470	40	140	210	100	NA	130	60	200	37	91	100
Zn	9000	1000	200	NA	720	250	300	NA	200	600	290	240	250
Co	NA	NA	NA	NA	NA	100	NA	NA	100	NA	19	300	NA

Table 2 Exposure parameters (SA-DEA 2010; US-EPA 2011)

Parameter	Unit	Adult	Child
BW—body weight	kg	70	15
CF—conversion factor	kg/mg	10^{-6}	10^{-6}
ABS—dermal absorption factor	n/a	0.1	0.1
FE—dermal exposure ratio	n/a	0.61	0.61
EF—frequency of exposure	days/years	350	350
DE—duration of exposure	years	30	6
IR_{air}—inhalation rate	m^3/day	20	10
IR—ingestion rate (IR)	mg/day	100	200
PEF—particulate emission factor	m^3/kg	1.3×10^9	1.3×10^9
SA—skin surface area	cm^2	5800	2100
AF—soil adherence factor	mg/cm^2	0.07	0.2
AT—average time (carcinogens)	days	365 × 70	365 × 70
AT—average time (noncarcinogens)	days	365 × 30	365 × 6

(iv) *Risk characterization:* a process that determines the extra risk of health issues for the exposed population

For the risk assessment, determining the average daily intake (ADI) is a vital factor, which is the intake value of a particular heavy metal from soil by any means of ingestion, inhalation, or dermal intake. ADIs are calculated using exposure parameters with respect to age, body size, respiration rates, etc. Hence, adults and children have different parameters, as summarized in Table 2 (SA-DEA 2010; US-EPA 2011).

Thus, ADI for three different intakes (i.e., ingestion, inhalation, and dermal intake) can be calculated using the following equations:

$$\mathrm{ADI}_{(\mathrm{ingestion})} = \frac{C \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \quad (1)$$

$$\mathrm{ADI}_{(\mathrm{inhalation})} = \frac{C_s \times \mathrm{IR}_{\mathrm{air}} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT} \times \mathrm{PEF}} \quad (2)$$

$$\mathrm{ADI}_{(\mathrm{dermal})} = \frac{C_s \times \mathrm{SA} \times \mathrm{FE} \times \mathrm{AF} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ED} \times \mathrm{CF}}{\mathrm{BW} \times \mathrm{AT}} \quad (3)$$

Further, the noncarcinogenic hazards are characterized by a unitless hazard quotient (HQ) representing the probability of individual health adversity (US-EPA 2014). It is the ratio of ADI and chronic reference dosage (RfD) of a heavy metal (given in Table 3) that can be written as below:

$$\mathrm{HQ} = \frac{\mathrm{ADI}}{\mathrm{RfD}} \quad (4)$$

Furthermore, the hazard index (HI) for *n* number of heavy metals can be determined as the sum of all HQ for a soil sample as follows:

Table 3 The chronic reference dosage (RfD) of heavy metals in mg/kg-day (SA-DEA 2010; US-EPA 2018)

Heavy metals	Ingestion RfD	Inhalation RfD	Dermal RfD
As	3.00E-04	3.00E-04	3.00E-04
Hg	3.00E-04	8.60E-05	3.00E-04
Cd	5.00E-04	5.70E-05	5.00E-04
Cr	3.00E-03	3.00E-05	–
Co	2.00E-02	5.70E-06	5.70E-06
Pb	3.60E-03	–	–
Ni	2.00E-02	–	5.60E-03
Cu	3.70E-02	–	2.40E-02
Zn	3.00E-01	–	7.50E-02

Table 4 The cancer slope factors (CSF) are in mg/kg-day (SA-DEA 2010; US-EPA 2018)

Heavy metal	Ingestion CSF	Inhalation CSF	Dermal CSF
As	1.50E+00	1.50E+01	1.50E+00
Cd	–	6.30E+00	–
Cr	5.00E-01	4.10E+01	–
Co	–	9.80E+00	–
Pb	8.50E-03	4.20E-02	

$$\mathrm{HI} = \sum_{k=1}^{n} \mathrm{HQk} = \sum_{k=1}^{n} \frac{\mathrm{ADI}}{\mathrm{RfD}} \tag{5}$$

If HI $<$ 1, heavy metal exposure is unlikely to cause health adversities. If HI $>$ 1, the exposure may be concerning for potential noncarcinogenic effects.

The carcinogen risk is the unitless probability of a person developing cancer from heavy metal exposure over a lifetime (US-EPA 2014). It can be determined as a total of the lifetime cancer risk of a person from the average contribution of the individual heavy metals for all the pathways as follows:

$$\mathrm{Risk}_{(\mathrm{pathways})} = \sum_{k=1}^{n} \mathrm{ADI}_k \mathrm{CSF}_k \tag{6}$$

ADI_k (mg/kg-day) is the average daily intake, and CSF_k (mg/kg-day) is the cancer slope factor, respectively, for the kth heavy metal and the n number of heavy metals. The CSF values for the incremental risk of an individual developing cancer can be seen in Table 4. A total cancer risk can finally be calculated as the sum of each individual pathway and heavy metal for a given soil sample as follows:

$$\mathrm{Risk}_{(\mathrm{total})} = \mathrm{Risk}_{(\mathrm{ingestion})} + \mathrm{Risk}_{(\mathrm{inhalation})} + \mathrm{Risk}_{(\mathrm{dermal})} \tag{7}$$

where $Risk_{(ingestion)}$, $Risk_{(inhalation)}$, and $Risk_{(dermal)}$ are the risks posed via by ingestion, inhalation, and dermal pathways, respectively.

The exposure risk quantified by Marcantonio et al. (2021) revealed a higher hazard index value for the inhabitants living near the Lake Sonfon area of gold mining. They used heavy metal concentration and the hazard index (HI) to determine the noncarcinogenic risk to adults and children separately in wet and dry seasons (refer to Fig. 3 adopted and modified from Marcantonio et al. 2021). For adults, the mean HI was 36.8 and 28.8 in the wet and dry seasons, respectively, and 67.6 and 54.1 for children. As per the US-EPA, a HI value greater than 1 represents excessive risk; hence, significantly high noncarcinogenic risks to both adults and children were observed. The results also revealed that HI risk greatly increases by going near the Lake Sonfon gold mine site. Furthermore, the evaluated values of carcinogenic risk (CR) causing cancer due to heavy metal exposure showed high risks closest to the gold mining area. Notably, the US-EPA guidelines state the threshold of 1×10^{-4} to 10^{-6}; however, the mean CR was found to be 1.01×10^{-3} and 9.42×10^{-3} for adults and children, respectively, indicating that the gold mining area is highly contaminated by heavy metal pollution with a great likelihood ratio.

2.3 Mining Environmental Liabilities (MEL)

On the other side, the Spanish Geological Survey proposed a simplified risk assessment of abandoned mine sites to evaluate the mining environmental liabilities (MEL) through the associated determined probability (IP) and severity indices (IS) (refer to Fig. 4). For mine waste deposits, the risk assessment was performed by adopting the protocol designed by the Spanish Geological Survey (Alberruche del Campo et al. 2014), whereas in the case of other (i.e., non-waste) deposits, the methodology outlined in the Environmental Risk Assessment Guide of the Ministry of the Environment of Peru was followed (MINAM 2010). The cartographic information was processed using Geographic Information Systems (GIS) through ArcMap 10.8.1 to identify the areas that represent a greater risk of affecting the flora and fauna. Such information gathering allows for better management actions in each evaluated area of concern.

In the recent past, gold mines have gone deeper, encountering arsenopyrite-bearing gold ores that inhibit the leaching process during gold extraction. The excavated ore undergoes amalgamation or cyanidation after the fine milling operation, which produces a large quantity of tailings. These tailings contain unbroken pyrites, which may lead to slow atmospheric oxidation (Naicker et al. 2003). Near Johannesburg in South Africa, the long exposure to oxygenated rainwater with the undisturbed tailings caused the oxidation of pyrite minerals up to 5 m below the soil surface (Marsden 1986). The sulfate produced via pyrite oxidation acidifies the groundwater and enters streams along with Witwatersrand, severely polluting the groundwater and soils. The gold-tailing impoundment in the Witwatersrand can

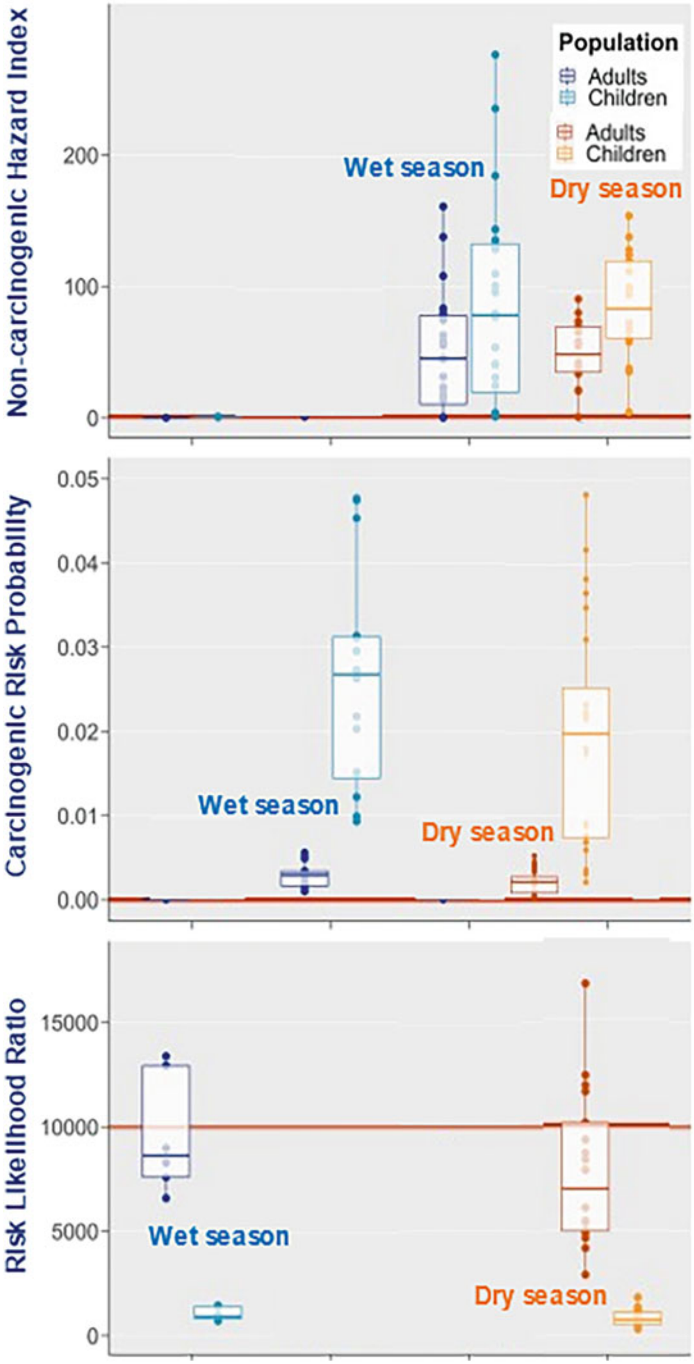

Fig. 3 Noncarcinogenic hazard index, risk probabilities, and likelihood ratio evaluated at two seasons of wet and dry and determined for adults and children (red line showing the threshold lines as described by Marcantonio et al. 2021)

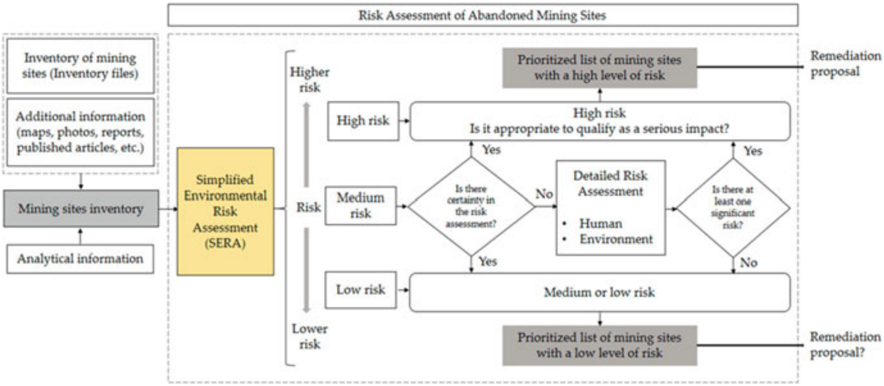

Fig. 4 Simplified schematic for the risk assessment of abandoned mining sites as designed by the Spanish Geological Survey (adopted from the open access source of Salgado-Almeida et al. 2022, MDPI)

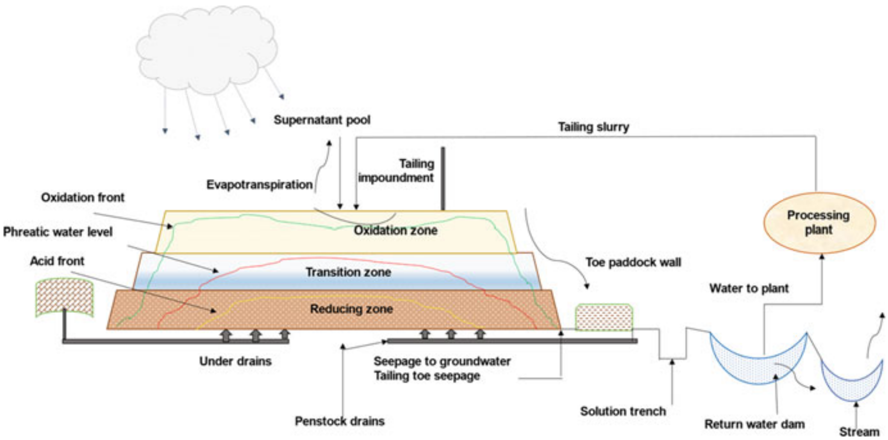

Fig. 5 A schematic of a typical gold-tailing impoundment in the Witwatersrand (modified and adopted from Hansen 2015 with copyright permission from Elsevier)

typically be understood by the scheme presented in Fig. 5 (Hansen 2015). Naicker et al. (2003) found that acid contamination in soil and groundwater varies seasonally. They found that the pH of the water near the mining area remains about 5.0, along with high concentrations of heavy metals and sulfate ions. This also leads to the precipitation of calcium as gypsum along the river banks.

3 Mitigation of Environmental Risks

In order to avoid and/or reduce environmental impacts, designing mitigation measures is an imperative action. In the case of non-avoidable environmental impacts, the restoration and rehabilitation plan should be considered on a priority basis. Additionally, the impacts should be offset through programs to improve lands, water streams, and/or facilities to offset biodiversity impacts, along with providing the facilities or compensation to offset the societal and economic impacts. Table 5 indicates the mitigation hierarchy for handling the environmental risks due to mining activities (EIA Guidelines 2018). As prevention is always better than expensive remediation, the proactive avoidance of negative impacts with precautionary steps is welcomed when the environmental consequences of mining activities can't be predicted and thus reliably managed.

A risk assessment study of MEL for their categorization and prioritization in gold-mining areas of Macuchi, Tenguel-Ponce Enriquez, and the Puyango River Basin in Ecuador, conducted by Salgado-Almeida et al. (2022), revealed that the impacts are mainly associated with artisanal and small-scale gold mining. Lack of regulations in many illegal mining activities (Rivera-Parra et al. 2021) has caused MEL accumulation. The same accumulation has facilitated the transportation of pollutants in different environmental compartments to spread severe anthropogenic contamination (SENAGUA 2011).

Table 5 Mitigation hierarchy for mining activity

Measures	Hierarchy	Actions
Avoid		• Mine site selection • Transportation corridor alignments • Mining layout for the facilities
Reduce		• Minimize the pollution and waste generation • Reduce the land take and disturbance • Limiting the use of water and energy
Restore and rehabilitate		• Exploration drilling sites • Rehabilitation of disturbed areas • Restoration of abandoned mines (vegetation, trees, wildlife, etc.)
Offset		• Provide facilities to offset societal and economic impacts
Enhance		• Community development programs for social benefits

Table 6 Categorization of priority area and proposed strategies for the pollution control under the mining environmental liabilities (MEL)

MEL	Proposed actions
Landfilling	Covering, sealing, and revegetation of deposits; physiochemical stability control and monitoring plan; water, soil, sediment, biotic component, and stability control
Mining galleries	Physiochemical stability control and monitoring plan; implementation of geoparks and museums, plugging of higher-risk mine entrances/galleries
Mine entrances	
Tailing deposits	Resource utilization of mine tailings; covering, sealing, and revegetation plan near the tailing ponds; water, soil, sediment, biotic component, and stability control
Abandoned infrastructure	Construction of a community meeting place; water, soil, sediment, biotic component, and stability control
Mineral processing plants	Control and monitoring of chemical stabilization of soils; dismantling infrastructures
Alluvial terrace	Restitution of flora and fauna; treatment of water bodies; physiochemical stabilization of tailings/riverbanks
Quarries	Physiochemical stability of soils; revegetation; water, soil, sediment, biotic component, and stability control

Table 6 belongs to the strategies and actions proposed for MEL management to mitigate the high risk for the flora and fauna (Salgado-Almeida et al. 2022). Puyango and Tenguel-Ponce Enriquez have been identified as priority control areas and urgently require a solid restoration and rehabilitation plan. To ensure the ecological restoration of the abandoned mine sites, actions like phytoremediation (Lam et al. 2017; Vela-García et al. 2019) and the creation of geoparks in low-risk areas (Franco et al. 2020), along with a continuous control and monitoring plan, could ensure the identical recovery and restitution of the land. In the entire restoration process, the collaborative efforts of different parties that involve mining companies, mine planners, investing organizations, local bodies, and societies (Popovic et al. 2015 are greatly required to achieve the Sustainable Development Goals. Lack of which may lead to an inefficient output. For a sustainable handling of mine tailings, their reutilization in metal recovery and reuse in other forms, like in the construction industry to fabricate bricks, cement, and ceramic materials, can lead toward a circular economy (Srivastava et al. 2023). Finally, a risk communication plan must exist to reduce exposure to potentially hazardous materials.

In order to respect human rights as a fundamental operating principle for mine workers and other actors as well, a typical compliance program can be designed as depicted in Fig. 6. In accordance with the Sustainable Development Goals, leading from the top and embedded throughout the organization, shared learning, partnership, and collaboration are the key factors to mitigate the negative impacts and ensure close monitoring of the mining activities.

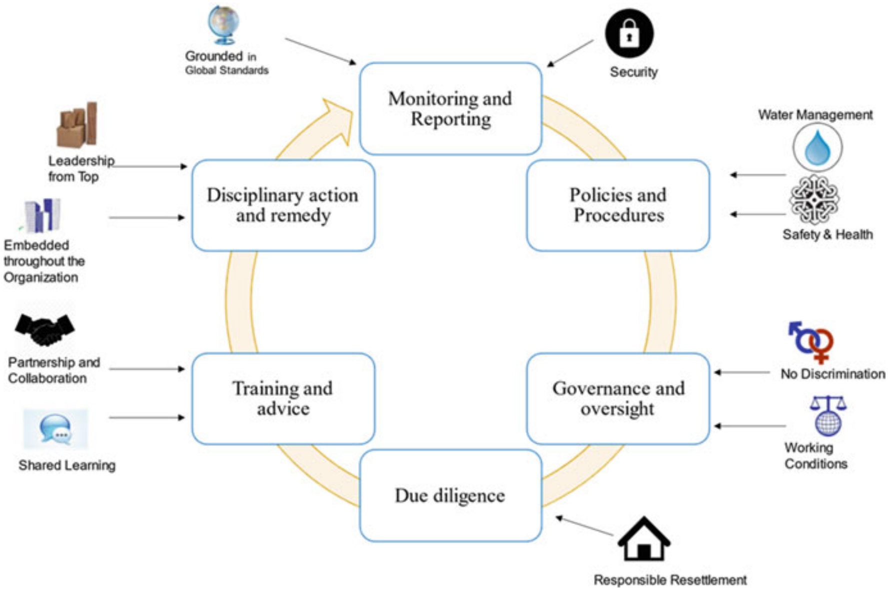

Fig. 6 The compliance program based on the Barrick Gold practicing

4 Mitigation of Water Pollution Risks

In addition to the large-scale mines, about 15%–20% of gold is extracted by artisanal and small-scale miners without any facilities or mechanical supports. Due to their informal activities, they often do not follow safety and environmental regulations, mainly resulting in cyanide and mercury pollution of water bodies and soils (Ilyas and Lee 2018). Even the highly toxic cyanidation is an industrial process of gold production, whereas the artisanal miners use mercury for dissolving the gold traces from the collected mud, soil, and rocks. As an estimate, about 140 kg of cyanide and a massive consumption of 700 tons of water are required to produce 1 kg of gold (Mudd 2007). The leached cake or slurry often contains waste rocks with heavy metals like arsenic and copper (biodegradation paper), which are stored either in open dumping or within a dam. On the other side, it is estimated that more than 2000 tons of mercury have been released into the Amazon River since the 1980s from mining activities (Malm 1998). Porcella et al. (1997) additionally claim to release 460 tons of mercury per year from small-scale mining alone. Arsenic is another toxicant of greatest concern because of its carcinogenic potential (RAIS 2021). As concentration in freshwater varies in the range of 0.15–0.45 μg/L (Singh et al. 2015), which can exceed in mining environments (Guzmán-Martínez et al. 2020). For example, the Central Andes region of Peru contains 14–23 μg/L of arsenic (Custodio et al. 2020), artisanal gold mine areas of Colombia contain 0.6–52 μg/L arsenic (Alonso et al. 2020), and mine sites in Slovakia contain 0.5–103 μg/L arsenic (Rapant et al. 2006).

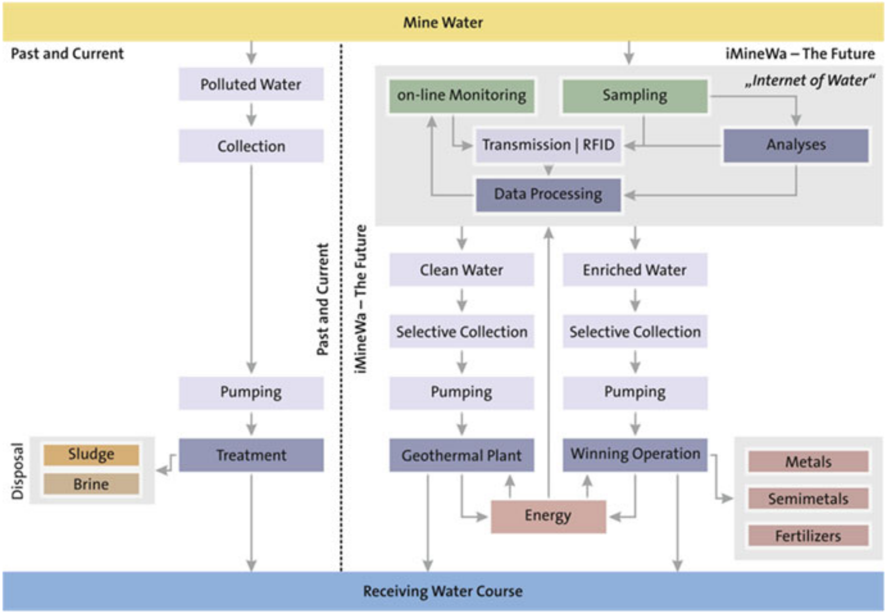

Fig. 7 Comparing the past and current mine water treatment practices with the future proposed digitized management of mine water (modified and adopted from More et al. 2020 with copyright permission from Elsevier)

Therefore, an effective treatment of mine water, especially in abandoned mines, is desperately sought. However, the current practices of mine water treatment are not ideal as they are based on the composition and volumes of water entering the plant (refer to Fig. 7a). It means that the treatment plant needs to react instantly whenever the volumes or chemistry of mine water change (More et al. 2020). Usually, no interaction is observed between water inflow into the mine, technological changes within the mine, water analyses, and outflow of treated water (More and Wolkersdorfer 2019). Here, the application of digital technologies can have a timely response by interacting with the factors involved, proving the need for a technological solution (as shown in Fig. 7b).

The polluting effect of acid mine drainage is particularly pronounced in the upper catchments of the Blesbokspruit and Klip Rivers in South Africa, which drain the southern Witwatersrand escarpment (Ilyas and Lee 2018). The water discharge of the accumulated volume in the voids of closed gold mines on the Witwatersrand to neighboring mines, generally of low quality, necessitates basic additional treatment by lime to raise the pH and air blowing to oxidize and precipitate the iron and other heavy metals. The iron was allowed to settle and disposed of on tailing dumps while discharging the water into local rivers. Although the water discharge has a neutral pH, it also has a very high sulfate (1500 mg/L) concentration and thus adds more pollution to the load already carried by the rivers in mining areas. The pollution arising from gold mines in the Central and Western Basins is well illustrated by the salinity of the Vaal River; a periodic release of water from Vaal Dam significantly reduces the salinity for downstream Vaal River users.

5 Sustainability in the Artisanal Mining and Amalgamation of Precious Metals

As per the definition of the term "sustainability," it depends upon the factors like society, environment (including socio-ecological factors), and the economy (related to the cost-effectiveness of the mining activities). Despite the issues in defining a sustainable mining operation, the experiences from the past and current activities can be helpful to design the ideal condition of artisanal mining, which include the following points of:

(i) Positive contribution of ASGM activities in development of rural area and regional empowerment
(ii) Legal framework in harmony with the national mining sector policies
(iii) Operation within international social standards, including the social security, occupational health and safety, and labor laws (that includes child labor), education and medical facilities, etc.
(iv) Environmentally sound operation with scientific and mechanized inputs
(v) Harmony between the small operations and large-scale mining operations
(vi) Ensuring high recovery yield, including a systematic development of the deposits and continuous operation

5.1 Technical Aspects

It has been observed that many problems existing with the artisanal mining can be resolved by the use of appropriate technical solutions. A prominent example can be of mercury emissions in an artisanal practice which can be resolved by using the end-of-pipe technology (involving filter, retort, and trap system). Technological issues often require technical solutions albeit an integral approach is crucial. In contrast to the traditional use of low and non-mechanized activities, the design of new milling and alternative to simple stone mortar amalgamation mills does not involve very high level of technological understanding. Hence, the conventional mining equipment are frequently modified and maneuvered by the miners to fulfill their demands for the high throughput and efficiency; however, in most cases, the suppression of security features are very unfortunate (e.g., water supply for drilling hammers). It is noteworthy that although it remained in practice since several centuries, it has been labeled as an unorganized practice, which makes it imperative to pay attention by the researchers and environmentalists as well.

5.2 Policy and Legal Framework

To achieve sustainability in artisanal mining of precious metals via integrating the rural development with the associated economic benefits, a policy framework development is desirable that can be based on the following strategies (Ilyas and Lee 2018):

(i) Poverty alleviation
(ii) Optimization of the business climate for the small mining sector
(iii) Insurance of sustainability
(iv) Stabilization of government revenues from the sector

Numerous reasons exist for the continuation of artisanal mining within the informal sector, majorly because of less understanding on the legal requirements. Lacking capacity to enforce penalties and to provide benefits, which should be associated with legalization, acts as a further disincentive to miners to be legalized. By recognizing the capability and contribution of the sector in the precious metal mining and metallurgy, the governments need to develop a consistent and holistic approach. In the recent times, the reforms in national policy has initiated the drive toward enabling a legal framework in the countries like Colombia, Peru, South Africa, and Tanzania, mainly beneficial to the sustainable management and exploitation of mineral resources along with the promotion of investment and licensing of the artisanal mining (Ilyas and Lee 2018). Additionally, the organization of this sector as a community or society should be promoted by the local administrations to formalize the informal structures via coordination and a harmonized management of the natural resources.

Currently, in many countries, the mining laws or other legal instruments do not support the development of small industries based on local mining production. This is especially valid for the production of informal artisanal mining activities, which is difficult to integrate into the formal economy. Training resources for healthcare providers that directly address artisanal- and amalgamation-related health issues are scarce. However, case studies, toxicology, and occupational health literature and publications from governmental and nongovernmental organizations do contain or suggest health components that could be developed further for use in this context. By using the principles of fair-trading, small-scale producers in developing countries are given the opportunity to trade their products under better selling terms and conditions. An improved awareness on health hazards is needed to practice a better, healthier, eco-friendly, and sustainable technologies in the mining of precious metals.

6 Conclusions

Looking at the importance of mining, despite the fact that it poses a threat to the environment and human health, this chapter provides a preliminary assessment of the risks associated with the present mining activities of gold involving artisanal, small-scale, and industrial gold mining. It has been found that heavy metals (metalloids) are easily released into the environment through surface water and groundwater contamination and soil and air pollution. Therefore, it is necessary to remediate the polluted mine sites and practice continuous monitoring to restore the ecosystems properly. In addition, the population's exposure must be restricted to high-risk areas through a communication plan about the risks. The mitigation hierarchy for mining activities is discussed to avoid, reduce, restore and rehabilitate, offset, and enhance communities, along with the proposed strategies for pollution control. For the potential mitigation of the risks, digitized mine water treatment and a compliance program for mine workers have been suggested to achieve the Sustainable Development Goals in the field of primary gold mining.

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