Needs and Options for Improving Gold Mining Waste Management Practices for Sustainable Development in Tanzania

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Abstract

The main objective of this study was to evaluate current mining waste management practices and their challenges. This study aimed to identify existing technologies and practices, and to present improvement needs and options for environmentally sustainable practices for mining operations. Other researchers have reported many practices and technologies for managing mining waste, but the efficiency, applicability, and need for customization were not specifically addressed for developing countries. This study used field observations, measurement methods, and laboratory analysis to collect data. This study showed a large amount of mine waste rock compared to the tailings wastewater from gold processing plant produced annually. This comprises approximately 5.2 million m^3 of mine contaminated water generated by leaching from the waste rock dump (WRD) and 2.3 million m^3 from the tailings storage facility (TSF). The study also identified the use of TSF cut-off trenches for seepage collection, the use of lime to treat acid mine drainage (AMD), the discharge of AMD into the TSF, and the recycling of TSF water as the best practices for managing mining waste. Furthermore, the study also found that the most common environmental problems were caused by TSF water and AMD water. However, mining waste management can be improved by modifying existing practices and adopting cost-effective technologies and practices to control and treat excess mining water.

Keywords: Acid mine drainage, mine waste, tailing storage facility, mine waste rocks, waste rock dump.

1. Introduction

Mining operations involve various functions such as the extraction and processing of minerals. In contrast with other industries operation, the social and environmental concerns related to mining operations are serious and complicated. Exploration, extracting, and processing mineral resources are extensively observed as environmentally and socially harmful activities [1].However, sustainable and innovative technologies have been implemented by mining companies as part of their efforts to improve waste management [2].

Mining is a prevalent economic activity in many developing countries. Its operations, whether small- or large-scale, are fundamentally disturbing to the environment [2], and can produce enormous quantities of wastes that can have harmful impacts that last for decades [3]. Mining has several common phases or activities, each of which has potential consequences on the natural environment, society and cultural heritage, the health and communities living near the operation areas [4].

Tanzania, as a developing country, has plentiful natural resources, including gold, diamonds, salt, gypsum, gemstones, iron ore, natural gas, phosphate, coal, nickel, cobalt, and tanzanite and the country's major goldfields are located in Geita, Musoma, Tarime, Chunya, and Mpanda [5]. Environmental challenges caused by improper mine waste management are among the serious concerns of mining industries worldwide and incorrectly management and unpermitted discharge into water bodies can cause many disasters and future environmental and social concerns [6]. The legacy of the poor management of mining wastes appeared to strangely shape of the status of the mining industries [7].

In addition, if waste is not managed appropriately, it can lead to significant problems within the community and mining operations to achieve sustainable development [8]. In one case, the mining operations of a Norwegian company were decreased based on an environmental assessment of their tailing discharge methods [9]. The use of best alternative practices led to huge improvements regarding sustainable development in mining operations [10, 11].

Sustainable development can be achieved by appropriately managing mining wastes [12]. Most mining industries have suffered from inadequate suitable technology and unwillingness to plan, and a lack of concern for the environmental impacts of mining operations, these issues have led to careless mining, poor resource recovery, the production of excessive mine waste, damage to landscapes, and a number of environmental issues [13]. Reusing and recycling mine waste, implementing practical technological improvements, and increasing environmental performance through overall quality management are some of practices that can be used to reduce the environmental problems associated with mining [14]. However, there are challenges in applying these technologies or practices because of a lack of knowledge, inappropriate implementation strategies, a lack of managerial commitment, technical challenges, and financial constraints. This study aimed to analyze the needs and options for improvement in the management of gold mine waste for sustainable environmental practices by measuring the amount of mine waste generated as well as investigated the current mine waste management facilities and its challenges

2.Materials and Methods

This section provides details of various mine waste management technologies and practices, as well as the processes and methods used to collect the data and results. The mine chosen was an open pit mine that used a method called carbon in leach (CIL) to process minerals. The waste or ores produced during operation are in the form of sulphide.

2.1. Amount of mine wastes generation

Mine wastes comprises with waste rocks and tailings, whereby waste rock stockpiled in mine site WRDs and tailings stored at TSF. Quantity of waste rocks obtained directly from mine heavy duty trucks loaded with 100 tons, equivalent to 40 m^3, or by using survey instruments and picked volume of stored waste rocks at WRD. While tailings were calculated based on daily production rate by considering quantity of tailings discharged through pipeline into TSF and measured through a flow meter. The amount of seepage or leachate or runoff from mine wastes storage facility was obtained from installed flow meters

2.2. Assessment of technologies and practices for mine waste management

This section assessed the performance efficiencies of the technologies and practices currently in use for the management of mining and mineral processing waste. The assessment of their performance was based on their suitability and the customisation that is required for improvement. WRDs for storing waste rock materials, TSF for storing tailings from gold processing plant. Other practices include TSF cut-off trench for seepage collection, recycling of decanted water from TSF (reduce TSF water by pumping back to the processing plant), lime application for AMD stabilisation (neutralisation of seepage of AMD leachate water), and discharge of AMD into TSF as final disposal (reduces excess water from WRD leachate pond).

2.2.1. Waste rock dumps

The mine operation manages and stores waste rock materials in the designed facility called the WRD. There are two kinds of waste rock dumps: Potential Acid Forming (PAF) and Non Acid Forming (NAF) stores. Before construction of the waste dump, it is essential to know the types of material to be placed so that their location within the dump can be planned. Materials that have AMD potential, high salinity, any other potentially polluting leachate or that are highly dispersive, should be appropriately encapsulated in the dump. The material that will be used for the outer surfaces when covered with topsoil, should be suitable for vegetation. Moreover, sampling was done of the existing boreholes around the WRDs to examine quality of groundwater to easily capture if the dumps develop uncontrolled mine drainage.

2.2.2. Tailings storage facilities (TSF)

Tailings from gold processing plant transported to the TSF via slurry pumped through a pipeline system, using centrifugal pumping systems. After passing through the detoxification plant, slurry was pumped directly to the TSF for final disposal. The discharge of tailings at TSF was done through spigot (multiple discharge points) disposal. Spigot disposal is used where the tailings are discharged, generally around the perimeter of the tailings facility to create a beach between the embankment and the supernatant pond. This practice reduces the possibilities of TSF failure and seepage.

2.2.3. Lime application for AMD stabilisation

A trench of dimensions 100 m length x 2 m width x 1 m depth has been constructed below the contaminated plume of PAF WRD. The trench was excavated using an excavator machine, and about one tonne of quick lime was placed in the trench. Appropriate PPE was provided to ensure there were no injuries during handling. A water quality test is regularly conducted in the dug pump well to check for the quality of AMD seepage before release or use.

2.2.4. TSF cut-off trench for seepage collection

The TSF cut-off trench has been constructed to collect seepage water from the TSF. The trench is lined from the bottom to prevent unwanted water access. Seepage water through the embankment is collected in the trench and directed to the TSF seepage sump and then pumped back into the TSF. This practice is designed to reduce water seepage from the TSF to the environment, and the amount of TSF seepage is measured and recorded using the installed flow meter.

2.2.5. Discharge of AMD water into TFS

AMD is pumped by gravity from leachate ponds where the WRDs are its main source. It is then transported from the leachate pond using a 7 km pipeline into the TSF. The AMD contains high levels of heavy metals concentration, low pH and high sulphite levels. Tailings are characterised by high level of pH (9) as a result of using lime during processing of gold in the plant. The mixing of AMD and tailings reduce the concentration of heavy metals and increase AMD pH.

2.2.6. Reuse and recycling of tailings decant water from TSF

The decant water is collected from the TSF decant tower and pumped back to the gold processing plant, which is returned for processing operations for another means of TSF water management practice. The tower consists of a platform that houses pumps connected to it, used to pump decant water to the processing plant. The decant tower is a raised structure constructed with filtered materials (waste rocks) in which tailings are percolated through filtered waste rocks into the tower. A pipeline is used to transfer decant water from the tower to the processing plant. The platform is accessible via the construction road using waste rocks. This practice of pumping decanted water reduces the amount of water within the TSF facility, and the return water is measured using an installed flow meter at the processing plant.

3. Results and discussion

3.1. Mine waste and generation

The amount of waste and type presented in Figures 1 to 2 and Table 1. It was observed that the amount of waste rocks produced by the gold mine annually ranged from 14 to 19 million tons, while 2 to 3 million tons of tailings were from the processing plants. This study established that the generated mine waste is considered very hazardous because about 80% of it is sulphide minerals that could generate AMD. [15]concluded that the extraction of minerals, especially on a large scale, is a serious matter of concern because the waste generated by mining processing has a severe impact on the environment.

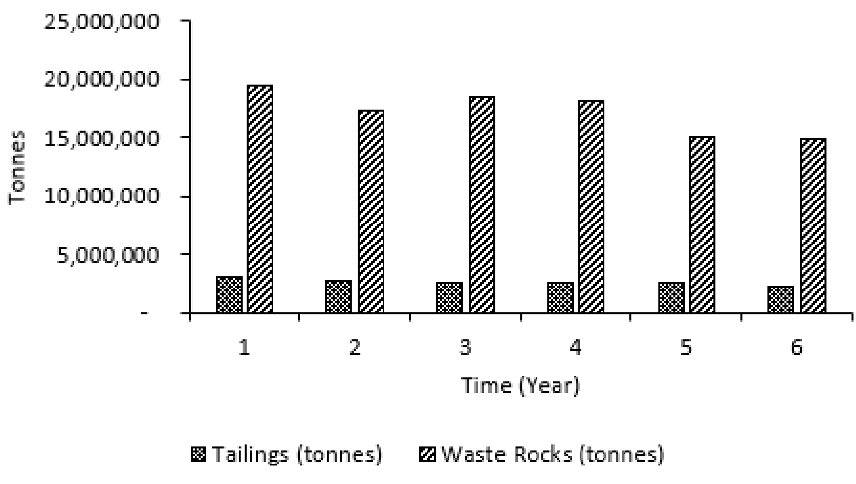

Fig. 1. Waste rocks and tailings production in a selected mine

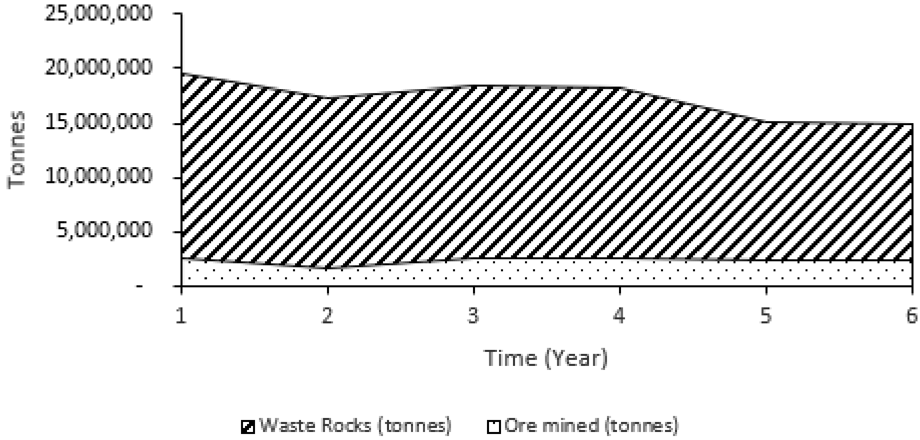

Fig 2. Waste rock produced and ore mined in a selected mine

Table 1. Strip ratio of gold produced during six years at mine site operation

Year	Waste Rocks (tones)	Ore mined (tones)	Strip ratio
1	19,434,186	2,624,443	7
2	17,342,430	1,710,657	10
3	18,426,489	2,619,238	7
4	18,200,206	2,568,801	7
5	15,034,675	2,437,302	6
6	14,897,654	2,440,684	6

Source: Author own work

A high amount of waste was generated in comparison with the amount of ore mined. As presented in Figure 2, the removal of approximately 1.7-2.6 million tons of ore generates not less than 14.8-19.4 million tons of waste rock (Table 1). This amount of mine waste provides the basis for mine waste management, especially in the design for storage facilities and the prevention of adverse environmental impacts. [15]reported that there is no estimation of how much mine waste is produced by mining operations globally; however, it is assumed to be an enormous volume.

The ratio of overburdened excavation to the amount of mineral ore removed is referred to as the stripping ratio [15]. Observations made in this study indicate that the stripping ratio of mining ranges from 6:1 to 10:1, which is very high, as mining produces a huge amount of waste rocks, leading to an increase in the number and severity of environmental challenges faced, especially in terms of footprint coverage and possible increases in mine impacted water (leachate). The main reason for the high production of waste rock is that open-pit mining operations were prominent during that period. According to [16], open pits generate 10 times more waste than underground pits. Another study pointed out that the stripping ratio for the surface mining of metal ores ranges from 2:1 to 8:1, depending on local conditions [16]. However, for underground mining, the ratio for solid waste is typically around 1:5. For example, open-pit mines of North Eastern Coalfields in Assam were reported to have produced mine waste at stripping ratio of 1:14 [17].

Having a dumping area for waste materials is important, especially during the early stages of mining. Mine waste materials, such as waste rocks and tailings, require sufficient space for the management of acid-forming and non-acid forming materials. This study revealed that over six years of operation, the studied mine required a dumping area with a volume of almost 3.8 million m^3 for waste rocks, and an additional volume of approximately 1.7 million m^3 for tailings. A study conducted by [16] documented that the total amount of land involved in 10 mining blocks was about 14 million m^3, of which 44% (6 million m^3) was actually excavated, while 12% (1.8 million m^3) was used for WRDs. This means a significant area of occupied land was neither being excavated nor put to any other use – this practice also rendered the land unproductive and unusable [16].

This study also observed that annually, the average amount of contaminated water from WRDs leaching was 5.2 million m^3 and that contamination through TSF, based on monthly precipitation was 2.3 million m^3 per year. Therefore, this mine water requires appropriate handling and storage as it is already contaminated and, thus, can have a serious impact on water sources and human health. [18] recommended that waste rock management should start at the earliest stage of mining operations, thereby providing the motivation needed to separate reactive and non-reactive wastes. This is because reactive wastes can generate oxidation or leachable products, which need to be managed at the surface storage level.

This study revealed that in open-pit mining operations, a huge amount of waste rocks is generated as compared to tailings, which, in turn, worsens environmental challenges such as mine drainage and its release into the environment. Similarly, [19] reported that more mine waste rock is produced than tailings and that the consequences last for ten years. In addition, the mining waste that is produced needs to be moved and managed. However, the safe disposal of mining waste is generally understood as the largest environmental challenge facing most mining operations worldwide [19]. Moreover, the environmental impacts of mining wastes can be widespread and continually cause problems and affect people's livelihoods and the environment. Mining wastes pose an environmental threat not only because of its excessive volume but also because of its toxicity. However, the amount and behaviour of the mining wastes that are generated during any mining operation depend largely on the characteristics of geological and host rock, the type of mining performed (e.g. open pit vs underground), and the scale of production [19]. [20] reported that, generally speaking, waste minimisation methods such as preventing waste production, recycling and reusing materials, and properly storing and treating waste should be adopted. Furthermore, volume reduction and pollution control should be considered.

3.2. Mine wastes disposal and storage practices performance

This study identified WRD and TSF as the main storage facilities used for the storage of mine waste at mine site

3.2.1. Waste rock dumps

This study established that before the construction of storage facilities, it is essential to characterize the type of material to be placed in that storage facility. Most of the materials identified in this study are potential acid-forming (PAF) materials, which are characterized by elevated metal concentrations, low pH, and high sulphate content. Furthermore, the study analysed and assessed groundwater quality in the vicinity and downstream of PAF WRDs. The pH ranged from 5.8-6.9, the sulphate concentration ranged from 61.9-71.8 mg/L, iron levels ranged from 13-112 mg/L, and manganese levels ranged from 0.41-10.7 mg/L (Table 2).

The results of this study, especially as they relate to groundwater quality around the PAF WRD, showed the possibility of seepage into water sources (Table 2). The findings from this study are in line with [21], who suggested that metal-rich drainage from mine WRDs can compromise the environmental quality of groundwater and surface water, and this situation can destroy aquatic life and increase human health risks. Oxidation of sulphide minerals in waste rocks leads to poor-quality leaching, which is typically characterized by a low pH and high heavy metal and sulphate concentrations [22]. Therefore, the current practice for managing WRDs should be improved based on proper design such that all waste rock materials are well characterized, kept in containment facilities, and regularly covered with appropriate materials to reduce groundwater contamination from leachate.

Table 2. Water quality in the vicinity and downstream of waste rock dump

Parameters	Min	Max	Tanzania drinking water standard
pH	5.8	6.9	6.5 - 8.5
$SO4^{2-}$ (mg/L)	61.9	71.8	500
Fe (mg/L)	13	112	5
Mn (mg/L)	0.41	10.7	5
Zn (mg/L)	0.15	1.2	5
Al (mg/L)	0.5	10.2	2

Source: Author own work

3.2.2. Tailings storage facilities

TSF was used to store wastewater (tailings) from a gold processing plant and prevent leachate water from leaching from WRDs. This study has revealed that the final design of the TSF is at RL 1280 m (above sea level) and can be achieved through a sequence of 5 m raising using a downstream construction method; the final height of embankment from the toe to crest was estimated to be 65 m with a freeboard allowance of 1.65 m. The final volume of the TSF was estimated to be 37,400,000 m^3, which included the water and tailings. This study established the water elevation level against the final raising of the TSF wall and used a specifically designed freeboard. The TSF was measured at elevations of 1264.124 m of which the minimum freeboard was 1.17 m although the recommended in the design was 1.65 m. Therefore, this freeboard was a risk level for TSF water management.

Moreover, this study has established that excess water in the TSF caused downstream seepage at a rate of 6.48 m3/hr. However, several practices for reducing water in TSF were also observed. These included enhanced evaporators, water treatment plant that performed reverse osmosis, and decant water recycling. A study by [23]warned that tailings facilities with excess water storage can increase the risk of failure as they are more susceptible to overtopping, piping, and liquefaction failure. [24] concluded that the high water level was the final link in the chain of a failure event of a TSF and, therefore, that water is arguably the most critical parameter in estimating potential release volume.

Table 3. Groundwater Quality around TSF management

Parameters	GW1	GW2	GW3	GW4	Tanzania drinking water standard
pH	7.5	7.7	7.6	7.6	6.5 - 8.5
EC (µs/cm)	1090	115	110	179	
$SO4^{-2}$ (mg/L)	61.9	20.3	14.7	172	500
Fe (mg/L)	2	5.7	3.9	0.67	1
Mn (mg/L)	0.96	2.6	4.2	0.59	0.5
Zn (mg/L)	0.04	0.05	0.06	0.19	15
As (mg/L)	0.003	0.09	0.016	0.066	0.05
Al (mg/L)	0.75	4.1	0.8	3.2	2
Cu (mg/L)	0.01	<0.004	0.01	0.013	3

Source: Author own work

GW = Groundwater boreholes

To improve the general understanding of the quality of groundwater near TSF, this study revealed that the pH of groundwater in all areas was nearly neutral (Table 3). Generally, the level of heavy metal surrounding TSF is very low, with the exceptions of iron, manganese and aluminium. However, even these are only slightly elevated in some of boreholes, which can be attributed to the geological characteristics of the area. A study by [24] reported arsenic concentrations of 0.0005 to 0.0063 mg/L within 500 m of TSF.

This study showed that even if there is any indication of seepage, the level of pollutants, especially heavy metals, is very low, both in groundwater near the TSF and the pond itself. Most heavy metals, with the exception of sulphate, precipitate within the TSF pond due to convenient environmental conditions (high pH levels). Sulphate removal was not successful because most of the sulphate reductions that occur within the natural environment do so in the presence of SRB or high percentages of lime/limestone.

In this study, the precipitation of metals depended on residual lime in the tailings. Contributions from other researchers [25]have reported that the chemical precipitation of sulphate with lime or limestone to gypsum is the only common method for sulphate removal, which can reduce it to below 1,200 mg/L, depending on its composition and ionic strength of the solution. In addition, according to [25], additional advanced technologies are required to lower the sulphate levels further.

3.2.3. Performance of technologies and practices currently used for mine waste management

3.2.3.1. TSF cut-off trench for seepage collection

This study observed that the TSF cut-off trench had been constructed to collect seepage water from the TSF. The trench was lined from the bottom to prevent unwanted water access. Water that had seeped in through the embankment was collected in the trench and directed to the TSF seepage collection sump and then pumped back into the TSF. This practice is designed to reduce water from seeping from the TSF to the environment.

TSF seepage formed a stream due to the uncontrolled flow of TSF seepage water downstream of the embankment and collected at designated pond. It was found that water seeped through TSF embankment at a rate of close to 6.48 m3/hr. [26] pointed out that seepage from conventional TSFs is inevitable. Another study conducted by [26]established that the seepage rate for an old tailings dam was 3.96 m3/hr with a water level of 851.9 m.

A similar observation was noted based on dry beach length of a tailings dam, whereby a dry beach length of 150 m produced seepage at a rate of 0.237 m3/hr.

However, this study measured 150 m of dry beach length and the seepage rate was 6.48 m^3/hr, much higher than the rates reported in other studies. Therefore, it can be concluded that having a higher water level in the tailings dam can accelerate the seepage rate downstream of the TSF embankment. Similarly, having a shorter beach in the tailings dam leads to a higher seepage rate due to greater hydraulic pressure along the TSF embankment, which increases water forces, thus leading to formed seepage that finds its way into the environment through the embankment. Therefore, this study implies that it is important to keep the TSF water level low to restrict seepage from the TSF.

3.2.3.2. Lime application for AMD treatment

The performance results obtained from using lime to treat uncontrolled AMD seepage water from PAF WRD are presented in Table 4. This study observed a large amount of uncontrolled AMD seepage water flowing downstream of the mining operation. This flow of AMD seepage water was directed into a trench containing lime, which served as the primary treatment to reduce soil, surface, and groundwater pollution. The usage of lime has been shown to raise the pH of AMD seepage water from 3.5 to 7.1. However, this system requires the regular addition of lime to the trench to improve its efficiency. Thus, the currently studied system was unable to reduce manganese to acceptable levels based on Tanzania’s effluent standards

Table 4. Water quality results after application of lime as in-situ treatment of AMD

Days	pH	EC (µS/cm)	SO_4^{-2} (mg/L)	Mn (mg/L)
0	3.5	3980	2780	8.5
1	3.8	3720	2680	8.1
2	4.2	3540	2670	8.3
3	4.3	3200	2480	7.9
4	4.6	3100	2420	6.7
5	4.7	3000	2300	6.4
6	4.8	2900	2200	6.5
7	4.9	2010	2117	6.2
8	5	2011	1980	5.8
9	5.1	1920	1601	5.4
10	5.4	1800	1500	5.4
11	5.4	2012	1200	5.4
12	5.6	1914	1130	5.4
13	6.1	1980	980	5.3
14	6.4	1700	801	5.3
15	6.6	1600	816	5.4
16	7.1	1200	819	4.6
17	6.4	1206	904	4.3
18	5.7	1420	1004	4.2
19	5.3	1500	1243	5.4
20	5.2	1620	1250	5.6
21	5.1	1650	1260	5.8
22	4.6	1980	1902	6.1

Source: Author own work

In Table 4, it can be observed that the water quality improved immediately after the application of lime and that the pH level increased from 3.8 to 7.1 within 16 days of dosing. Table 4 showed that the lime was very reactive from day 1 until day 16; however, from day 18 onwards, the reaction started to weaken until the water pH eventually returned near to its original level. This indicated that the solubility of lime had been completed and had reached its maximum. Similar findings were made by [27].

Manganese concentration reduced from 8.5 mg/L to its lowest value of 4.2 mg/L. Completing the reduction of manganese proved very difficult, as it required the maintenance of a sufficient water pH. A study by [28] reported that a pH of at least 9.3 is necessary to reduce manganese by over 50% from a solution using lime. Other studies have indicated that a pH value above 10 is necessary to reduce manganese concentrations to acceptable effluent standards for some mine drainage waters [29]. However, the need to raise pH can increase chemical treatment costs by 20% to 100% for the removal of iron

[29]. [30] observed that increasing the pH from 8 to 10 increased the required sedimentation basin area from 158 to 400 m^2 for NaOH and from 200 m^2 to 316 m^2 for lime. Finally, this study recommends the appropriate use of lime and design of treatment facilities to increase the contact time between lime and AMD seepage water. Also, the residue sludge of lime should be reused and recycled in cement factories or as building materials.

3.2.3.3. Discharging AMD leachate water from PAF WRDs into TSFs

The study observed that the large amounts of AMD leachate water in PAF WRDs and the insufficiency of available storage facilities have to lead to the mine's adoption of this practice. The results obtained from mixing discharged AMD leachate water and TSF water are presented in Table 5. The findings indicated that the pH of leachate water increased while the metal concentrations decreased in the TSF. Other studies [28] concluded that removal of heavy metals increases together with pH values raised.

Table 5. TSF water quality results after mixed with AMD leachate water

Parameters	AMD leachate water	TSF water
pH	3.0	8.2
EC (µs/cm)	3500	3410
$SO4^{2-}$ (mg/L)	2891	1250
NO_3^- (mg/L)	46	60
Fe (mg/L)	2.7	0.6
Mn (mg/L)	62	1.2
Zn (mg/L)	15	0.06
As (mg/L)	0.02	0.3
Al (mg/L)	120	0.1
Cu (mg/L)	0.5	0.1

Source: Author own work

In order to establish the mixing ratio in the results (Table 5), the findings from this study indicated that the AMD leachate water from the PAF WRD was discharged through a gravity pipeline (about 7 km) to the TSF as the final disposal site. This study also established that about 4.7 million m^3 of AMD leachate water is discharged into the TSF annually and that about 2.1 million m^3 of tailings are discharged from the processing plant. Therefore, this study calculated the ratio of mixed AMD leachate water and tailings to be about 3:1 (v/v). This implies that in order to neutralise 3 m^3 of AMD, 1 m^3 of tailings is required.

In Table 5, the results of the mixing of the AMD leachate and tailings serve as evidence of the fact that AMD can be remediated. The pH of AMD increased from 3.5 to 8.2, while the sulphate concentration reduced from 2891 mg/L to 1250 mg/L. This might have been caused by the low availability of dissolved lime in tailings that was utilised to facilitate the precipitation of sulphate in tailings. Other studies [31, 32] reported that the chemical precipitation of sulphate with lime to gypsum is the most common method for the removal of sulphate from mines that impact water. It can reduce the level of sulphate to about 1500-2000 mg/L; in some cases, depending on the composition and ionic strength of the solution, it can reduce sulphate to below 1200 mg/L.

Moreover, the concentrations of all heavy metals were significantly reduced, as the TSF contained some of the dissolved lime from the discharged tailings, which neutralised the AMD leachate water. Also, the high pH level facilitated the precipitation of dissolved metals within the TSF. The reduction efficiencies of metals were recorded in the following order: Cu > Fe > Ni > Mn > Zn. Furthermore, mixing AMD leachate water and tailings is effective in decreasing the levels of dissolved heavy metals. This is in line with other studies that used external materials to neutralise and remediate AMD, although the present study used internal materials available during the mining process [33]. The authors further pointed out that there is little work on the remediation of AMD using tailings as a neutralisation agent. These findings are strongly supported by other studies, such as that carried out by [34].

3.2.3.4. Reuse and recycling tailings decant water from TSF

This section determined the extent to which recycling tailings decant water contributes to reducing water levels in the TSF and saves water resources recovery. Tailings decant water was taken from the TSF and sent to the gold processing plant for use in gold processing. The results for the quantity of discharge (tailings) and reclaimed gold processing plant (tailings decant water) are presented in Table 6. The results showed the amount of TSF decant water pumped back to the processing plant and the amount of tailings discharged into the TSF during period of twelve months. The water reclaimed from the tailings was pumped back to the plant for use in processing operations. This study has collected one year's worth of information in this regard.

Table 6: TSF tailings discharge and tailings decant water returning to the gold processing plant at mine site

Month	Tailings discharge (m^3/month)	Tailings decant water return (m^3/month)
1	376314	219763
2	329363	172871
3	356130	218814
4	350182	210167
5	362788	218871
6	351378	219479
7	351150	216629
8	378294	212946
9	360563	192726
10	378484	192910
11	338498	170842
12	391911	213599

Source: Author own work

Table 6 showed that about 4,325,055 m^3 of tailings are discharged into the TSF in a year, while 2,459,617 m^3 of tailings decant water is pumped back into the gold processing plant.

This study has considered the current design of the TSFs, with its final volume being 37,400,000 m^3. At the current rate of TSF water recycling, the capacity will be reached in about 15 years; without recycling, it will be reached in about eight years. However, the findings showed that the current TSF operation receiving tailings and other mine wastewater sources can increase the water level, and, therefore, excess water will contribute to the challenges related to TSF water management (e.g. TSF water seepage through the embankment).

A study by [35]identified several incidents caused by tailings dams: slope instability, overtopping due to excess water in TSF dams, and seepage through the piping of solid materials into the dam foundation. This study also observed that there is a need to pump more tailings decant water back to the processing plant to reduce the current excess amount of TSF water in the dam. In this case, reducing TSF water remains imperative, as it also reduces the risk of overtopping and seepage through the embankment.

3.3. Environmental challenges associated with mine waste management practices

Environmental incidents that occurred for six years of mine operations were critically assessed (Figure 3). The incidents were related to gold processing activities (process spills), AMD spills, and NAF waste rock management (leachate spills) only. Most of the incidents were associated with processing spills, followed by AMD spills and leachate spills from NAF WRD. The results showed that about 121,163 m^3 of mine-impacted water was unintentionally discharged into the environment. This suggested that the main reasons behind the many environmental incidents were inadequate technology and a lack of known practices for managing mining and mineral processing wastes.

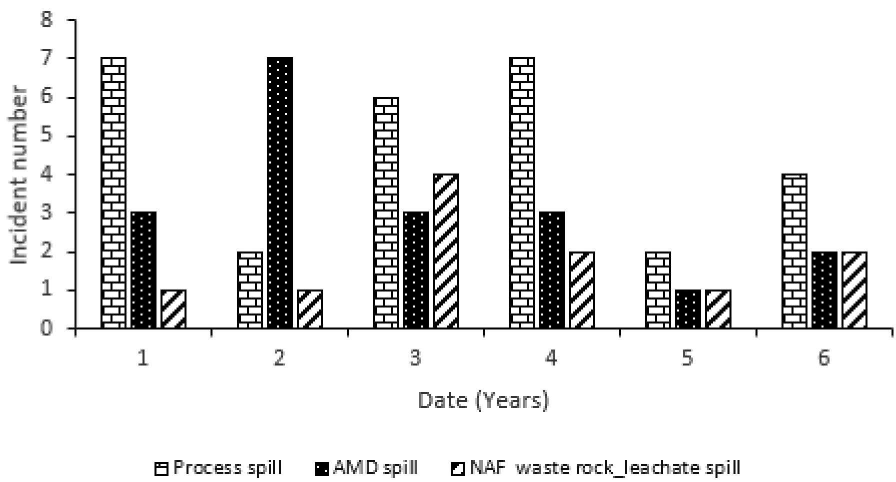

Fig 3. Number of spill incidents related to mining and mineral processing waste management during six years of mining operation

The observations presented in this study reveal that environmental incidents can be categorised as process spills, AMD spills, or leachate spills from NAF dumps. The data collected for six years shows that process spill incidents are the most frequent type, and they increase the amount of pollutants released into the environment. AMD incidents were higher in year 2, in which about 9,677 m^3 of AMD was released into the environment. The study also observed that over six years of mining operations, about 63,900 m^3 of process spills, 26,008 m^3 of AMD, and 32,005 m^3 of leachate spills occurred in NAF WRDs. As a result, approximately 121,163 m^3 of mine impacted water was released into the environment (Figure 3.8). Other studies [36] reported that in Spain, one tailings pond released about 4 million m^3 of AMD, thus eliminating aquatic communities. Moreover, an accident resulted in the destruction of crops and agricultural land [36]. In the Philippines, approximately 1.6 million m^3 of toxic tailings were released into a river. Furthermore, Witwatersrand (South Africa) established a daily discharge of 350,000 m^3 of AMD [37, 38]. Without appropriate technologies and practices, mining and mineral processing waste generation could persist in the environment for centuries [39].

This study observed that the main source of process spills was the overtopping of TSF seepage collection. The other prominent reason for AMD spills was direct seepage from the leaching of WRDs and the pipe transporting AMD to the TSF. This observation is in line with the findings of [40] who found that most environmental incidents are caused by unauthorised solution overflows or discharges and pipeline failures. Also, this study revealed that repeated environmental incidents at the mine occurred due to the poor construction of waste management facilities, such as TSF and WRD. It was found that leachate collection facilities are not sufficient to accommodate excess leachate water, especially during rainy seasons. Other researchers [41]have similarly observed that high rainfall can affect the stability of mine waste management facilities and cause the discharge of mine influenced water from the operation area. This study also observed a lack of awareness among community members involved in destroying mine waste management facilities. Moreover, workforces do not understand the environmental impacts associated with mining and mineral processing waste. One more reason for the frequent occurrence of environmental incidents is that there are no appropriate cost-effective waste management technologies and practices that meet the standards of sustainable mine waste management.

4. Conclusion

The amount of waste produced from mine site increased, leading to more contamination of the water in the mine and caused environmental issues. This study found that each year approximately 19 million tons of mine waste rock and 3 million tons of waste from mining processes were generated. However, this study observed various technologies and practices applied to the management of mine waste. These include TSF cut-off trenches for seepage collection, applying lime for AMD pre-treatment, blending AMD and tailings, and reuse and recycling of TSF water. The investigated mine site experienced several environmental challenges, including the unintended discharge of mine water. This study emphasized and highlighted the need for mine waste resource recovery and cost-effective treatment options for improving mine waste management.

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