Water Air Soil Pollut (2021) 232: 273
https://doi.org/10.1007/s11270-021-05198-w

Review of Practices in the Managements of Mineral Wastes: The Case of Waste Rocks and Mine Tailings

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Received: 29 January 2021 / Accepted: 24 May 2021 / Published online: 25 June 2021

Abstract Mining plays an essential role in resource-rich countries given that it constitutes a source of raw materials and incomes capable of contributing to the economic growth. However, with the intensive mechanisation of mining operations and the modernisation of the ore-processing technologies in view of increasing the productiveness, growing amounts of mineralised rocks are currently excavated from open pit and underground mines. The increase in mining productiveness observed worldwide raises the thorny issue of the mineral wastes' environmentally friendly management considering their great polluting capacity. Mineral wastes are composed of waste rocks and mine tailings from the flotation beneficiation of ores. The present research reviews over times the worldwide in-force practices in the management of mineral wastes, with particular focus to waste rocks and tailings generated by the flotation beneficiation of ores in view of extracting metals of interest. It discusses environmental issues in relationship with the management of mineral wastes from the DR Congo mining industry, analyses the applicability of both emerging and established techniques to their management, and identifies opportunities for further research with the aim of gaining extended knowledge that can enable considering alternative management solutions. Addressing in deep the relevant issue of mineral waste management, relying on relevant illustrations could help improve practices in the Congolese mining industry as well as gathering data intended for mining operators, researchers and academics interested in mineral waste management.

Keywords Resource-rich countries · Mining industry · Raw materials · Incomes · Increased productiveness · Mineral waste management

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1 Introduction

The mining industry has become one of the most important economic activities in the modern world (Ma et al., 2017) and this considering its crucial role in the economic and societal development of many countries (Aldhafeeri, 2018; Hancock et al., 2020; Ma et al., 2017; Shavina & Prokofev, 2020). Moreover, owing to its great contribution to the gross domestic product (GDP), mining constitutes nowadays one of the key economic drivers in a great number of resource-rich southern African countries as well as in many other countries acknowledged to have a long mining tradition such as the DR Congo (Manyuchi et al., 2019; Shengo et al., 2017). Indeed, mining has played an essential role in the economic development of industrialised countries such as the USA, Canada and Australia (Githiria & Onifade, 2020). Mining also contributed through its revenues to the economic vitality of European countries. Garbarino et al. (2020) argue that the European extractive industry comprises more than 17,500 companies employing more than half a million people. These companies are generating a turnover estimated at more than 200 billion euros. Mining has thus the potential to influence industrialised and developing economies by providing employments and incomes while offering various opportunities for economic growth and diversification (Shengo & Kime, 2021; Yilmaz & Yilmaz, 2018). However, the extractive industry is reputed to yearly generate large amounts of waste rocks and mine tailings that can negatively impact the environment when improperly managed (Aldhafeeri, 2018; Kwong et al., 2019; Ma et al., 2017; Manyuchi et al., 2019; Martinez, 2019; Lu et al. 2016; Yilmaz & Yilmaz, 2018). Each year, it is estimated that the European extractive industry produces more than 300 million tonnes of wastes in relationship with the metals extraction (European Commission 2009). Tailings are composed of wastes left over after the mineral products have been extracted from the crushed and grinded ore rocks (Ma et al., 2017; Martinez, 2019; United Nations Economic Commission for Europe 2014; Yilmaz & Yilmaz, 2018). In other words, tailings consist of inert rock particles with trace amounts of potentially harmful substances such as bioavailable fractions of trace metal elements and remnants of production chemicals (Benarchid et al. 2019; Elmayel et al., 2020; Koski, 2012; Rubinos et al., 2019). Yilmaz et al. (2012) indicated that each year a huge amount of tailings, with various compositions, is produced by mineral ore processing plants operated throughout the world. It is estimated that more than 90% of materials extracted from mines constitute polluting mineral wastes that are stored at mine sites after the extraction of valuable metals (Öhlande et al. 2012). According to Panagos et al. (2013), cited by Vareda et al. (2019), metal processing and mining contribute to 48% of the total release of contaminants from the European industrial sector. These contaminants can adversely impact the human health and wildlife in case of mine waste mismanagement (Lutandula & Banza 2013). Consequently, mining is looked at as a perilous business despite numerous benefits it can bring to communities living in areas where it is undertaken. The present research reviews over times the in-force practices in the management of mineral wastes, with particular focus on waste rocks and tailings generated during the flotation beneficiation of ores. It discusses environmental issues in relationship with the management of mineral wastes from the DR Congo mining industry, analyses the applicability of both emerging and established techniques to their management, and identifies opportunities for further research with the aim of gaining extended knowledge that can enable considering alternative management solutions. Addressing in deep the relevant issue of mineral waste management, relying on relevant illustrations could help improve practices in the Congolese mining industry as well as gathering data intended for mining operators, researchers and academics interested in mineral waste management.

2 Main Mineral Wastes Generated by Mining Activities

2.1 Mining Wastes

Mining is acknowledged as an industrial sector of high economic importance to mineral-rich countries (Mudd, 2009; NESMI, 2005; Lloyd et al., 2008; Sumi & Thomsen, 2001; Yongfeng, 2004) given that it provides the raw materials and incomes essential to economic growth and development (European Commission 2009; Sheoran, 2017; Sibanda, 2019). However, mining operation intensification observed worldwide has resulted in the generation of large quantities of solid wastes (Fig. 1) and polluted waters capable of endangering wildlife and human health in case of mismanagement (Bascetin et al., 2016; Chan et al., 2008; Charbonnier, 2001; EPA, 1994; Martinez, 2019; Manyuchi et al., 2019; Mudd, 2009; Rubinos et al., 2019; Safe Drinking Water Foundation 2008; Sheoran, 2017; Yongfeng, 2004).

Throughout the world, large quantities of mineralised rocks are daily mined from numerous ore deposits (Fig. 1) and comminuted through crushing

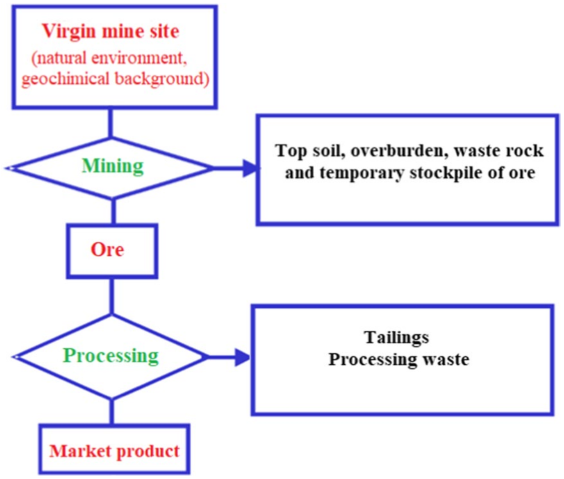

Fig. 1 Mining wastes and tailings from ore flotation (modified from Manyuchi et al., 2019)

and grinding. Come in next the physical and chemical processing in view of recovering minerals or metals of interest intended for the manufacturing of fertilisers, cars, electrical and electronic appliances, building materials and other consumer staples (EPA, 1994; Kudakwashe, 2019; Mudd, 2009; Sheoran, 2017). The extraction of an ore—being composed of an association of minerals containing one or more valuable metals such as gold, copper, zinc, lead and iron—from an open pit or underground mine requires the excavation of large quantities of barren rock followed by the recovery of the bearing minerals of metals of interest (Charbonnier, 2001; Garbarino et al., 2020). For economic reasons, waste rocks are usually stored near the mine (European Commission 2009; Hancock et al., 2020; Ma et al., 2017), with their quantities varying with the selectivity of the in-force mining method (European Commission 2009). Waste rocks consist of coarse-sized material resulting from the decomposition of unwanted mine rocks by weathering during mining without being processed (Yilmaz & Yilmaz, 2018). As for mine tailings, they consist of the gangue minerals discarded during either the ore flotation beneficiation or the metallurgical extraction process of valuable minerals by smelting or leaching of their bearing minerals. Table 1 gives an estimate of the production of mineral wastes during copper mining in some selected European countries (Charbonnier, 2001).

Table 1 Waste rocks and mine tailings from metals production in Europe (1986–1995)

Country	Metals production (Mt)	Accompanying wastes (Mt)
Portugal	989	443.926
Sweden	835	375.364
Spain	175	78.710
Finland	95	42.655
UK	4	1706
Germany	3	1392
France	2	808
Greece	1	584

The intensive mechanisation of mining operations as well as the modernisation of mining machines and techniques together with the use of up-to-date ore beneficiation methods is such that increasing volumes of mineralised rocks are currently excavated from mines (Anju, 2018; EPA, 1994; Hancock et al., 2020; Kugiel & Piekło, 2012; Mehta et al., 2020; Safe Drinking Water Foundation 2008). As a result, there is a significant increase in mine waste tonnage (EPA, 1994), hence, the thorny problem of the environmentally friendly management of mineral wastes (Kwong et al., 2019; Sheoran, 2017) knowing that they can imprint irreversible degradations on the landscape and, consequently, on the environment (Dino et al., 2020; Hancock et al., 2020). Mineral wastes can also negatively affect the quality of both water resources and soils in regions where mining is undertaken (Brantes & Olivares, 2008; Dimitrios & Giannopoulou, 2007; Dino et al., 2020; Kudełko, 2018; Lloyd et al., 2008; Mudd, 2009; Oelofse, 2008; Safe Drinking Water Foundation, 2008; Sumi & Thomsen, 2001; Yongfeng, 2004; Zloch et al., 2020). The reading of Table 2 enables realising the impact on human health and the surrounding environment that might be brought about by the management of waste rocks and tailings from the beneficiation of ores (Yongfeng, 2004).

The Canadian mining industry produces yearly about 1 million tonnes of mining wastes of which 950,000 tonnes are composed of tailings from the flotation beneficiation of ores. The production of a few hundred ounces of gold, for instance, generates a tonne of mine tailings (EPA, 1994). As for the production of 1 tonne of copper, it results in the

Table 2 Frequency of different types of impacts on human health and the environment

Type of impacts	Portion of damaged cases (%)
Surface water contamination	70
Ground water contamination	65
Soil contamination	50
Human health impacts	35
Flora and fauna damage	25
Air deposition or fugitive emissions	20

generation of an average amount of 80 to 99 tonnes of wastes composed of barren mineral materials resulting from the stripping and development of mining sites together with tailings generated by the beneficiation of ores in view of recovering metals of interest (Charbonnier, 2001; Kudełko, 2018; Safe Drinking Water Foundation, 2008; Wiertz & Marinkovic, 2005). According to Sheoran (2017), each tonne of copper, gold and iron produces on average about 100–125, 400–1000 and 2 tonnes of tailings, respectively (Cheng et al., 2016). As for gold, the large tonnage of tailings produced per tonne of extracted metal has been also noticed by Taskinen et al. (2018) who argue that in gold production, huge amounts of rock need to be mined to yield just an ounce of the precious metal owing to very low average grades in the ore deposits. The tonnage of tailings from the metals production is expected to climb as high-grade ores become scarce. The increase in the tonnage of tailings is also well explained by possibilities to process even lower grade ores owing to technological advancements accomplished with time by the mineral industry (Cheng et al., 2016). Indeed, the mass of waste rocks andmine tailings production was estimated at more than 18 billion m^3/yearat the beginning of the past decennia. By the next 20 years, this is at 2023,this valuation could double considering that, the mass will continue to climbas high grade ore become scarce (Cheng et al. 2016). Besides, large amounts of waste rock and mine tailings result from resource extraction and of which more than 90% of the extracted materials will become waste (Lu et al., 2016; Othlander et al. 2012). The Canadian mining industry, for instance, has generated in the last 30 years more than 6 million tonnes of tailings, with 90% originating from the mining of iron and gold (Cheng et al., 2016).

2.2 Tailings from Ore Flotation

Tailings consist of wastes left over after the mineral products have been extracted from the crushed and grinded ore rock (Schaanning et al., 2019). Ore flotation is a mineral processing operation that enables obtaining concentrates from which valuable metals such as copper, cobalt, zinc, lead, nickel, gold and silver are economically produced. Ore flotation effluents are made of pulps composed of mixtures of process wastewaters and tailings generated during the valuable minerals beneficiation process (Chan et al., 2008; Department of Industry, Tourism and Resource, 2007; ICME & Unep, 1998; Sumi & Thomsen, 2001). For instance, the flotation of one tonne of typical zinc–lead ore (6% Zn and 3% Pb) generates about 850 tonnes of solid waste as tailings, accompanied by an equivalent amount of wastewater containing less than 1 kg of unused reagents per tonne of ore processed (ICME and UNEP, 1998).

Copper ore flotation is usually conducted using pulps (Fig. 2) of which the proportion of solid particles varies between 25 and 45% (Brantes & Olivares, 2008).

Flotation is reputed a water-consuming mineral processing operation that is also one of the main sources of polluted waters encountered at a given mining site (Rao & Finch, 1989). During the flotation of copper–cobalt oxidised ores conducted in Katanga region of the DR Congo (Countois et al., 2003; Kalenga et al., 2006), it is reported that water supply flows in the range of 300 to 500 m^3/h whereas in Chile, acknowledged as one of the driest regions in the world, water consumption ranges from 1.5 to 3 m^3/t in copper ore flotation (Brantes & Olivares, 2008). The comminution process and flotation beneficiation of Pb–Zn polymetallic ores require water supply flows of about 6000 L/h (Jennett & Wixson 2005).

As evidenced by the change in the proportion of solids arising in the pulp during the ore processing beneficiation (Fig. 2), most of the feedwater from the ore flotation (80–90%) reports in the concentrator discharges. The thickening and filtration operations underwent by the final concentrate enable recovering as process wastewater a significant portion the feedwater (Brantes & Olivares, 2008; Countois et al., 2003; McMahon, 1965). The recovered water is either mixed with tailing water or recycled in the process

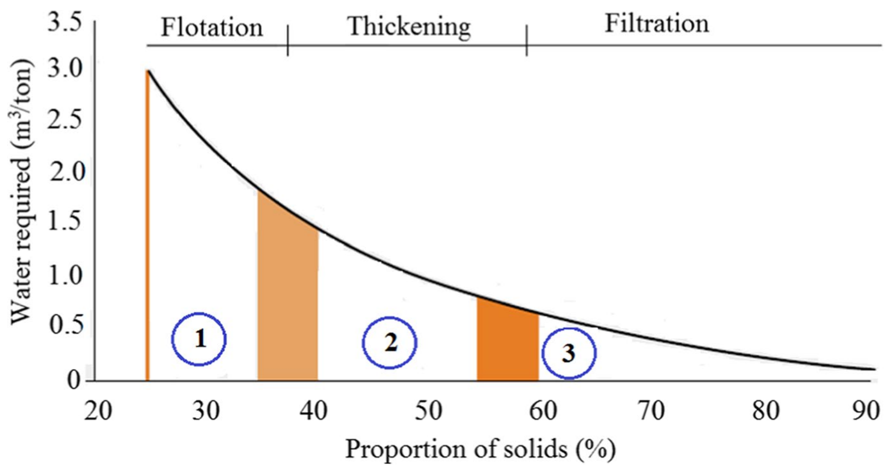

Fig. 2 Water consumption as a function of the pulp density (modified from Brantes & Olivares, 2008)

(Brantes & Olivares, 2008; Ng'andu, 2001; Rao & Finch, 1989).

Tailings consist of finely divided solids ranging in size from 0.001 to 6 mm. Schoenberger (2016) defined tailings as the fine-sized material left over after the process of removing the valuable constituents from the uneconomic fraction of the ROM ore. For optimum liberation of minerals of interest, the ores are subjected to comminution by crushing and wet grinding to prepare pulps that contain solid particles smaller than 0.1 mm. The physicochemical features of tailings depend on the type of ore and the processing beneficiation method used. The size distribution of tailings generated, for instance, by copper sulphide ore flotation carried out in Albania is given in Table 3.

It is obvious that this kind of tailings is rich in fine particles composed mainly of chlorites, quartz, carbonates and clays (Demi, 2003). In spite of the fact that tailings behave similarly to soils, their density and consistency remain low and increase over time as a result of water removal (ICME and UNEP, 1998).

Table 3 Size distribution of tailings from Albanian copper ores

Tailings dam from Kurbnesh		Tailings dam from Repsi	
Dimensional class (mm)	Weigh proportion (%)	Dimensional class (mm)	Weigh proportion (%)
+0.16	8.5	+0.16	24.40
+0.07	36.2	+0.07	22.20
+0.032	13.5	+0.032	16.90
−0.032	41.8	−0.032	36.50
Total	100	Total	100

3 Management of Mining Wastes and Tailings from the Ore Flotation

Management of mineral wastes from mining activities, namely waste rocks and tailings, is usually an undesirable financial burden for mining operators (European Commission, 2009). It is a process that normally begins at the early stage of a mine site opening (European Commission, 2009; Karlsson et al., 2018), that is from the mine development, ore exploitation and until the valuable metals' extraction using metallurgical processes. This is the reason why many mining companies have simply opted for incorporating land reclamation into mining design, construction and production processes (Department of Industry, Tourism and Resources, 2007; Zhang & Sun, 2020). Waste management is therefore a long-term process that begins well before any tailings to be managed are produced and pursued throughout the mine life until its closure and beyond (post-closure), the pursued objective being to safely store tailings and reduce the risks over the long term (Bjelkevik, 2005; KCB, 2017). According to the Mining Association of Canada (1998), tailings facilities pose a risk to be managed for the long term. They also tell a story to the public about how an industry manages its activities. Indeed, tailings facilities can pose a serious threat to humans and the environment in case of their improper design, handling or management (United Nations Economic Commission for Europe, 2014). These facilities account for a large capital investment and their proper operation is looked at as a key factor in the overall successful operation of a mining project (United Nations Economic Commission for Europe, 2014). Concerning the development of new mining projects and industrial process design, there is a growing effort to minimise the production of reactive mineral wastes, with the mitigation of any environmental impact (Fig. 3) (Department of Industry, Tourism and Resources, 2007; ICME and UNEP, 1998).

The management of mineral wastes constitutes therefore an environmental issue of concerns as well exemplified by the project for gold recovery implemented at the Kensington Mine in Alaska (Canada) or the production of copper and cobalt carried out at Kalukundi in the DR Congo (Digby Wells & Associates, 2008; Robinson et al., 2004). Today, environmental safety is looked at as one of the most prevalent criteria to be fulfilled by mining operators prior to the granting of a mining permit or license and its renewal (Carneiro & Fourie, 2018; Department of Industry, Tourism and Resources, 2007, Charbonnier, 2001).

3.1 Evolution of Tailings Management Practices

As stated by Bjelkevik (2005), during the nineteenth century the mining technology was rather primitive and only profitable to mine rich ores. Consequently, in the past ore beneficiation consisted simply in the gravity separation of valuable minerals from those of the gangue (Martin et al., 2002). This processing technology enabled producing tailings in easily manageable quantities (Bjelkevik, 2005) until the steam engine introduction into the mining industry. It is of great importance recalling that the management of mine tailings has remained and continue to be an environmental issue of concern to the mining industry (Anju, 2018; Elmayel et al., 2020; EPA, 1994; Manyuchi et al., 2019; Othlander et al. 2012; Rousseau & Pabst, 2020; Wiertz & Marinkovic, 2005), unfortunately not clearly understood in those days by mining operators. Indeed, as stated by Cheng et al. (2016), the proper management of tailings is and will remain a constant challenge to minerals and metals sector due to huge amounts of generated mineral wastes.

Fig. 3 Environmental impacts of tailings from ores flotation in DR Congo (modified from Shengo, 2008)

The problem of tailings management had therefore only really arisen with the advent of froth flotation as the beneficiation method of ores together with the use of cyanidation in gold mining (Bruce et al., 1997; Martin et al., 2002). Indeed, with the advent of these two major innovations, it had become possible to mining companies to handle and process large amounts of low-grade ores, with as outcome the obtaining of large amounts of tailings mainly composed of fine solid particles (Bjelkevik, 2005).

Waste rocks and mine tailings are most often stored for economic reasons either near to ore mines or in the neighbourhood of ore concentrators (Demi, 2003). They are also stored in the proximity of decommissioned mining sites or in pits (Elmayel et al., 2020). The method selected in the storage of mine wastes mainly depends on their chemical and physical features, the topography and climatic conditions of the storage areas together with the socio-economic context of the locality where a mine or an ore concentrator operates, including costs related to tailings processing, transport and deposition (Carneiro & Fourie, 2018; Department of Industry, Tourism and Resources, 2007; KCB, 2017; Wiertz & Marinkovic, 2005). When a mining operator is facing, for instance, to the management of tailings in the form of slurry or as thickened or filtered matters, the methods for tailings handling and disposal will not necessarily be the same and consequently, their management costs (Carneiro & Fourie, 2018). As can be realised through the reading of Fig. 4, waste rocks and mine tailings management practices have evolved over time around the world and this is thought to be the result

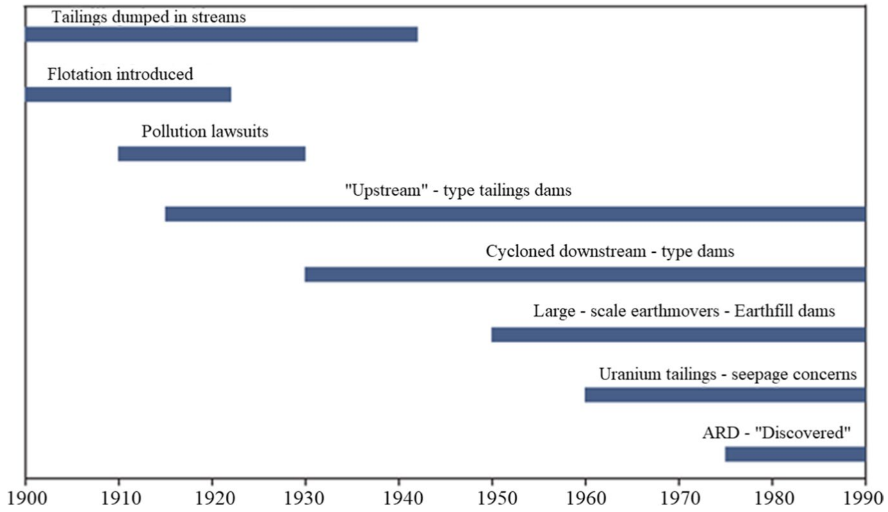

Fig. 4 Evolution over time of tailing management practices (after Bruce et al., 1997)

of an awareness of environmental risks or dangers related to nature of minerals existing in matters under storage.

The management of mine tailings has significantly evolved in the past hundred years from uncontrolled disposal towards today's well-designed and constructed storage facilities (Cheng et al., 2016). As stated by Bjelkevik (2005), citing Vick (1999), tailings dam technology has evolved from changes in the mining process and in the public's response to its effects. According to Franks et al. (2011), cited by Ma et al. (2017), the tailings disposal methods mainly consist of submarine tailings disposal, tailings dam disposal, backfill disposal and tailings reuse disposal (European Commission, 2009).

3.1.1 Tailings Discharge to Waterways

Historically, tailing dumping in streams was the only method to dispose of cumbersome mineral wastes (Bjelkevik, 2005; Bruce et al., 1997; EPA, 1994; Martin et al., 2002; Real & Franco, 1990). This management or storage method of mineral wastes had resulted in sediment deposition in receiving streams and blockage of water channels for crop irrigation, with various harms to fisheries resources and decreased agricultural yield (Bjelkevik, 2005; EPA, 1994; Martin et al., 2002). Spillage of tailings into waterways, lakes and oceans always suffers from the risk of their fine-grained fractions being transported by water over long distances (Bjelkevik, 2005; Countois et al., 2003; EPA, 1994; Department of Industry, Tourism and Resource, 2007; Martin et al., 2002, Real & Franco, 1990). This storage method has resulted in the containment of tailings in settling ponds (Kudełko, 2018) closed by earth dams or embankments constructed using tailings with coarse grains (EPA, 1994). The storage of tailings in settling ponds constitutes the widespread practice in the DR Congo mining industry (Countois et al., 2003). According to Martinez (2019), the most common methods for tailings disposal comprise backfilling into open pit or underground mines (Barfoud et al., 2019; Yilmaz & Yilmaz, 2018), hillside dams or cross-valley, dry-stacking of thickened tailings on land and raised embankments/impoundments (Hancock et al., 2020). The dry stacking of thickened tailings on land constitutes the so-called emerging methods for tailings disposal comparatively to usual ones (Yilmaz & Yilmaz, 2018) given that tailings are dewatered (containing 70–75% solids) prior to be dropped on surface in paste form (Yilmaz et al., 2010, 2014). Unit cost analysis conducted by Bascetin et al. (2016), as far as the management of tailing from a typical Pb–Zn ore mine is concerned, showed that surface disposal of tailings as paste (2.29 USD/tonne) is more expensive compared to their disposal as slurry deposited behind an embankment (2.25 USD/tonne). The unit cost is raised when cement is used during surface disposal of tailings (2.79 USD/tonne), but with more environmental benefits (KCB, 2017). The surface disposal of filtered solid residues is the widespread practice in the DR Congo mining industry in the management of tailings from the hydrometallurgical production of copper and cobalt (Countois et al., 2003; Shengo et al., 2017). It offers advantages in terms of process water recovery in spite of the fact that tailings are not either converted into pastes or stockpiled at waterproofed areas (geomembrane). On the contrary, they are exposed to rainfalls and winds, with as outcome the release of pollutants to the environment (Countois et al., 2003; Shengo et al., 2017). Surface storage of tailings has been carried out in DR Congo for several years and this leads, during the dry season where there are high winds, to dust plumes that disturb the riparian populations.

3.1.2 Tailings Containment in Impoundments or Constructed Ponds Protected by Dams

In most countries around the world, including the DR Congo, the most common tailings management method was and remains until nowadays the containment as pulps in settling ponds (Kudełko, 2018). For economic reasons, the storage facilities are located in the vicinity either of mine sites or ore concentrators (EPA, 1994; Sumi & Thomsen, 2001). The management of tailings as slurry deposited behind containment dams is practised at most mines in Canada (KCB, 2017). In arid regions, this management technique of tailings from the flotation of ores allows solid particles to be retained through settling, with the supernatant water recovered for reuse in the process or release to watercourses (Bjelkevik, 2005; EPA, 1994; ICME and UNEP, 1998). This practice is the widespread method implemented in the DR Congo mining industry at concentrators.

Containment of reactive tailings inside the soil is also worldwide practised. In this case, the soil forming the cover layer and the bottom of the storage facility is compacted and stabilised using a compacted thin laterite or moraine layer. In some cases, the pond is lined using a geotextile membrane in view of preventing groundwater contamination and infiltration of surface water into reactive tailings under storage (EPA, 1994; Stoltz, 2004). Phytostabilisation (Fig. 5), using vegetation as cover playing the role of an anoxic barrier and as a heavy metals sequestrant, is also utilised for the sake of inhibiting the oxidation process of reactive tailings, with minimisation of the

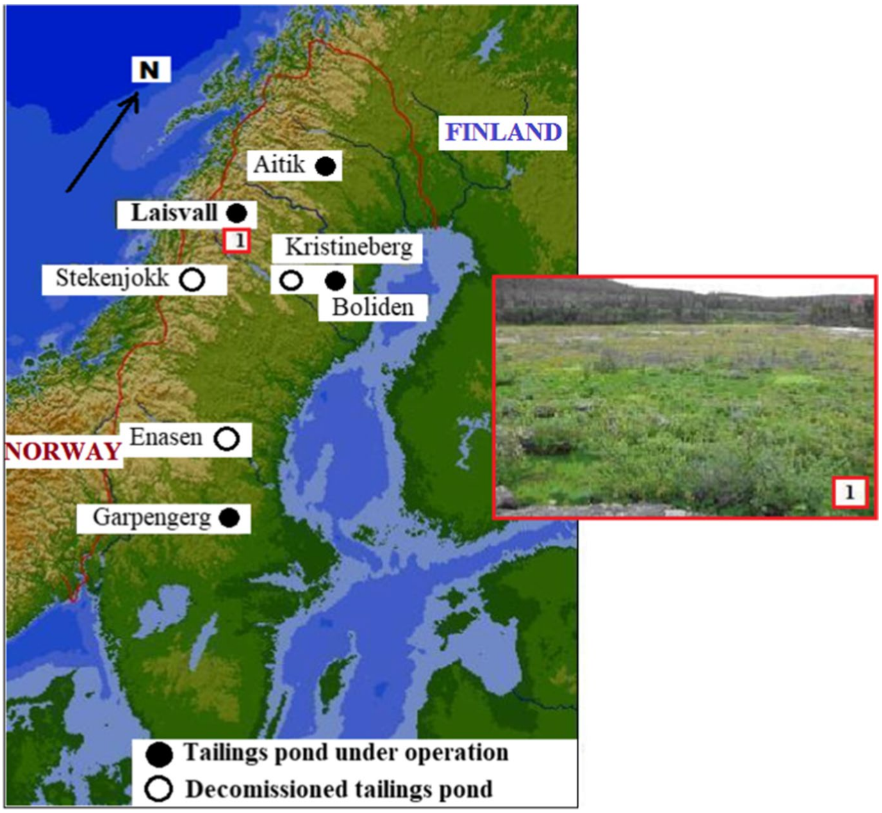

Fig. 5 Tailings pond phytostabilisation at Laisvall (modified from Johansson & Ljungberg, 2009)

release of heavy metal–bearing waters to the environment (Lu et al., 2016; Stoltz, 2004). It is important signalling that this mine tailings management method has not yet been applied in the mining industry of the DR Congo where huge amounts of sulphide-bearing tailings are often stockpiled in the open air and exposed to rainfalls during nearly the half of the year. The applicability of this tailings disposal technique in the Congolese mining industry needs to be carefully studied in view of preventing the environment pollution.

The re-vegetation of a storage site containing 68 million tonnes of tailings from gold mining conducted at Kidstone Gold Mine (Queensland) exemplifies the phytostabilisation of reactive tailings during their storage (Department of Industry, Tourism and Resources, 2007).

3.2 Tailings Management Practices in Europe and around the World

In Europe, the management practices for tailings with coarse-sized grain are ranked or classified in order of importance as follows surface storage through retention or containment in ponds, use as mine fill materials, underwater storage (lakes and oceans) and recycling in view of recovering valuable metals retained in tailings.

3.2.1 Surface Disposal of Tailings

Surface disposal of mine wastes is the most widely used technology in the world in the management of fine-grain solid mineral wastes such as flotation's tailings (Coal, 2001, EPA, 1994). It is practised in Papua New Guinea where waste rock and low-grade ore are often placed in rockfill dumps and stockpiles, with visible impacts on the landscape in the form of heaps, dumps or ponds (Bar et al., 2020; Dino et al., 2020; Hancock et al., 2020; Kudełko, 2018). According to Panchal et al. (2018), the surface disposal of tailings results in severe environmental impacts, occupation of large surface-footprint (Borra et al., 2016; Kwong et al., 2019) and excessive water inventory. This tailings disposal method is based on the construction of storage ponds closed by dams or embankments made, for economic reasons, with local materials or the tailings themselves (Stojanović et al., 2020). This enables alleviating significant costs associated with cover construction (Bashir, 2020). The tailings are placed permanently or temporarily inside a tailings storage facility (TSF) for further processing if the technology or economic viability of the process permits. It can include a tailings dam (impoundment and pond), decant structures and spillways and can be open pits, dry stacking, lakes or underground storages of which the service life may last for several decades (United Nations Economic Commission for Europe, 2014). Consequently, TSF dams are acknowledged to carry more risks (Panchal et al., 2018), and this justifies to monitor and manage them all the time until the process of disposal is completed in view of mitigating threat to lives and human health and the environment (Elmayel et al., 2020; Rubinos et al., 2019; Stojanović et al., 2020).

In fact, the general scheme for the management of tailings from ore flotation includes settling, size-based separation or classification using cyclones and storage in ponds in order to enable solid particles to settle with the supernatant wastewater sent to a stream after treatment if necessary or recycled in the process (Department of Industry, Tourism and Resources, 2007; ICME and UNEP, 1998). Tailings settling enables eliminating process wastewater, while size-based separation using cyclones provides particles with coarse size utilised as building materials for rising embankments or dams of the wastewater storage or tailings retention pond. Table 4 gives the proportion of water recovered through tailings dehydration (Department of Industry, Tourism and Resources, 2007).

In surface storage, tailings are pumped as pulps inside pipelines into retention or settling ponds, with the proportion of solids varying from 25 to 50% (EPA, 1994; Department of Industry, Tourism and Resources, 2007; ICME and UNEP, 1998; KCB, 2017; Kudełko, 2018; Sumi & Thomsen, 2001).

Table 4 Proportion of water recovered according to degree dehydration

Tailings consistency	Potential total water recovery (%)
Slurry	50 to 60
Thickened	60 to 70
High slump paste	≈80
Low slump paste	85 to 90

Unlike tailings of specific high-weight metalliferous rocks, pulps with a low proportion of solids are used in the pumping of less dense tailings such as those from coal treatment (Department of Industry, Tourism and Resources, 2007). The consistency of the pulp depends on the type of tailings, their particle size distribution, their specific weight and the degree of dehydration at the outlet of the concentrator.

The main difference between TSF and ponds dedicated to water retention resides in the way embankments or dams are built. In fact, the dams of the former are built to give them a variable capacity to store tailings throughout the life of the mine or concentrator contrarily to the latter which are built for a predetermined retention capacity (EPA, 1994; ICME and UNEP, 1998). Bjelkevik (2005), citing Caldwell and Robertson (1986), differentiated these two storage infrastructures from a geotechnical point of view in the following terms: TSFs consist of ground-up soil and rock, mostly placed on a soil foundation and retained by engineered soil and rock containment dikes or embankments, i.e. tailings dams contrarily to water retention dams designed for water loads only and can, at least theoretically, be removed when no longer adequate for use. Below are given some illustrations (Table 5) of surface storage of tailings from the treatment of polymetallic ores using containment in settling ponds as practiced at mine sites in Europe (Sol et al., 1999).

In some cases, the pulp of tailings is thickened through water removal prior to be introduced in a pond or to achievement of spreading. This technique helps optimising the storage capacity of the tailings pond while reducing the risk of overflow or collapse of the dam or embankment arising due to increased height (European Commission, 2009). The same technique also enables preventing groundwater from being polluted through infiltration as well as the loss of water via evaporation, particularly in arid regions. The main purpose of a storage pond is to retain safely tailings and the water that accompanies them. As part of the Kamoa-Kakula mining project managed by Ivanhoe Mines and its partners in the Lualaba region (DR Congo), it is expected that the most modern TSFs will be built with the implementation of the most efficient tailings management techniques, as evidenced by the proposals made in a report published in 2017 (Golder Associates Africa Pty Ltd, 2017).

3.2.2 *Mines Backfill Using Tailings*

This tailings management practice is reputed an environmentally friendly one that has emerged as an alternative method to the surface disposal of tailings (Aldhafeeri, 2018; Cervantes-Guerra et al., 2019; Panchal et al., 2018; Rousseau & Pabst, 2020). Indeed, the use of tailings as mine fill materials enables the mining industry reutilising hazardous materials, with the mitigation of harmful effects on the environment (Cervantes-Guerra et al., 2019; Panchal et al., 2018). This tailings management technique enables abstracting reactive tailings from the alteration due to exposure to water and air (Aldhafeeri, 2018; Cervantes-Guerra et al., 2019;

Table 5 Surface storage of mining discharges and tailings in Europe

Country (Province)	Mine's name	Mining method	Production (metal extracted)	Tailing management
Ireland — (*County Meath*)	Tara	UM	1–3 Mt/year (Zn–Pb–Ag)	CSCP
Sweden – (*Norrboten*)	Aitik	OPM	> 3 Mt/year (Cu–Ag–Au)	CSCP
– (*Vasterbotten*)	Boliden	UM and OPM	1–3 Mt/year (Zn–Ag–Au–Cu–Pb)	CSCP
– (*Norrboten*)	Laisvall	UM	1–3 Mt/year (Pb–Zn)	CSCP
Spain – (*Séville*)	Los Frailes	OPM	> 3 Mt/year (Zn–Ag–Cu–Pb–FeS_2)	CSCP
– (*Huelva*)	Rio Tinto	OPM	> 3 Mt/year (Cu–Ag–Au–FeS_2)	CSCP
– (*Huelva*)	Sotiel	UM	0.5–1 Mt/year (Zn–Ag–Cu–Pb)	CSCP
Portugal – (*Alentejo*)	Neves Corvo	UM	1–3 Mt/year (Cu–Sn–Zn)	CSCP
Italy – (*Sardinia*)	Masua	UM	0.5–1 Mt/year (Zn–Ag–Pb)	CSCP
– (*Sardinia*)	Monteveechio	UM	0.5–1 Mt/year (Pb–Zn)	CSCP

UM underground mine, *OPM* open pit mine, *CSCP* containment storage in a constructed pond

Yilmaz et al., 2004) of which the result is the formation and spreading of acid mine drainage (AMD). According to Yin et al. (2017), the cemented tailing backfill enables managing process tailings with significant environmental, technical and economic benefits (Aldhafeeri, 2018; Barfoud et al., 2019; Cervantes-Guerra et al., 2019; Yilmaz & Yilmaz, 2018). Indeed, tailings containing sulphide minerals such as pyrite, arsenopyrite and pyrrhotine are converted into paste backfill (Yin et al., 2017), that is, a paste composed of deslimed tailings or not (75–85% in solids), sufficient water (6–10 in.) and cement as hydraulic binder (2–7%) in order to ease transport to underground stopes by gravity or pump (Yilmaz & Yilmaz, 2018). The paste used as mine fill material is acknowledged to improve as aggregate ground support for mine structures, with the reduction of tailings disposal and rehabilitation costs (Panchal et al., 2018; Rousseau & Pabst, 2020; Wu et al., 2018; Yin et al., 2017). Consequently, a drastic reduction in environmental impacts associated with the management of sulphide tailings is achieved (Panchal et al., 2018). However, according to Rousseau and Pabst (2020), the possibility of AMD formation and spreading cannot be totally excluded owing to the fact that reactive wastes disposed as pastes in pits remain in direct contact with the surrounding rock with influx of dissolved oxygen or ferric ions from groundwater (Aldhafeeri, 2018; Barfoud et al., 2019). Moreover, contaminants contained in the waste pore water can also be dispersed in the environment. It is therefore recommended to control interaction between the waste and the storage environment (Aldhafeeri, 2018; Rousseau & Pabst, 2020; Yilmaz & Yilmaz, 2018). The use of tailings as mine fill materials is illustrated in Fig. 6a.

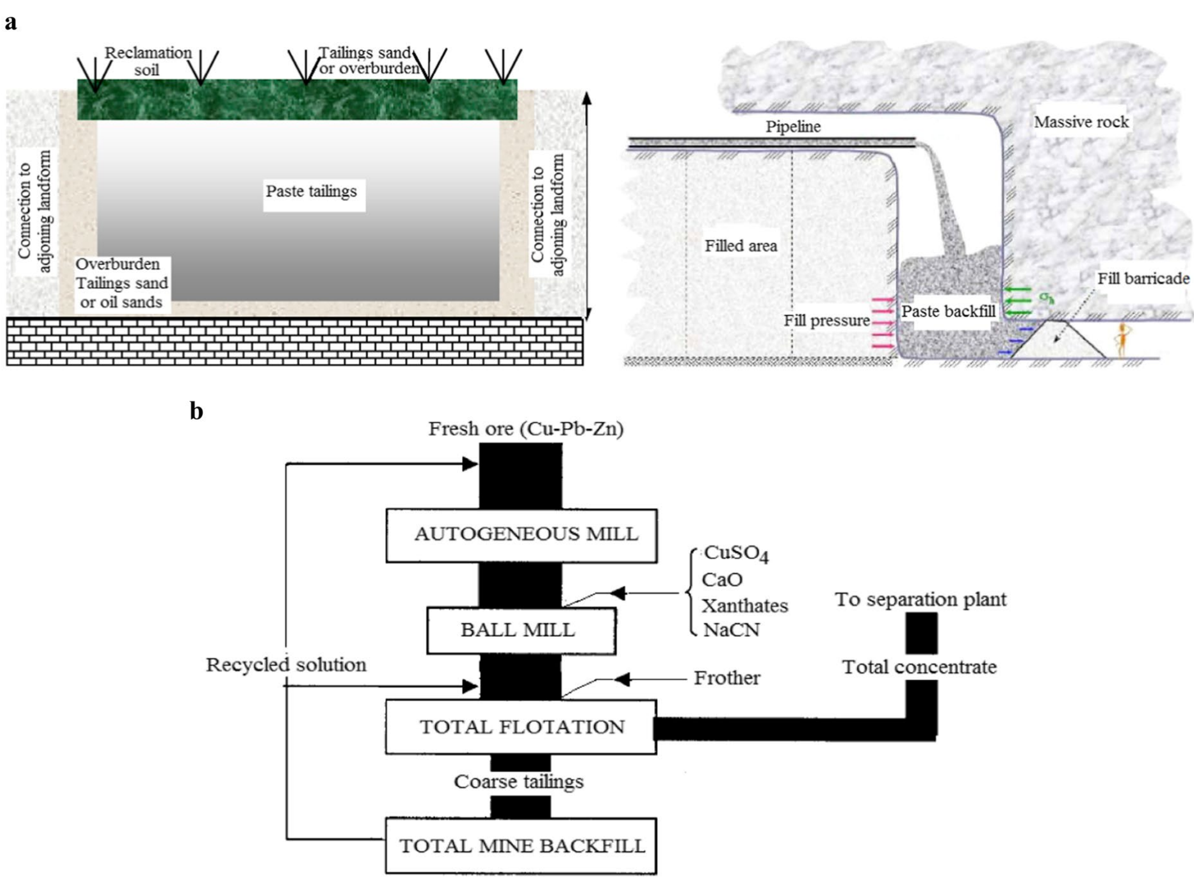

Fig. 6 **a** Surface and underground storage of tailings (modified from Yilmaz et al., 2004). **b** Total Cu–Pb–Zn ore flotation and mine backfill with tailings (after Villachica León, 2001)

It is important bearing in mind that only coarse tailings are used in the backfilling of abandoned mines or those under development (Bruce et al., 1997; Department of Industry, Tourism and Resources, 2007; European Commission, 2009; ICME and UNEP, 1998; Sumi & Thomsen, 2001). For stability reasons, backfilling of underground mines requires high-proportion sand tailings, with high permeability, reduced compressibility and low water retention capacity (EPA, 1994). These tailings are obtained through size-based separation of solids contained in pulps using cyclones in such a way that only the coarse-granulometry fraction are recovered and mixed with cement (a hydraulic binder) so that they can be utilised for increasing mechanical strength of matters after a mine is filled.

The non-selective flotation, associated with the rehabilitation of mine sites by filling with tailings (Fig. 6b), has been implemented in Peru as a best illustration of mining waste management in relationship with the processing of polymetallic sulphide ores (Cu–Pb–Zn) (Villachica León, 2001). This processing method provides mixed Cu–Pb–Zn sulphide concentrates while allowing subsequent extraction of each different base metals of interest using the selective flotation of ores. The total flotation of polymetallic ores is based on their comminution in view of obtaining solid particles with coarse granulometry that can be used, without prior size-based separation, during the progressive rehabilitation of the active mine sites. The same solid particles can be used as building materials for the storage pond's embankment requesting more stable tailings with large drainage capacity (Villachica León, 2001).

The backfilling of the underground mine with tailings had been practised in Sweden during the rehabilitation of the Laisvall mine (Johansson & Ljungberg, 2009). At Laisvall, quartzites made of coarse-granulated tailings resulting from the flotation beneficiation of lead and zinc ores were utilised as cement-based pastes for mine fill (Johansson & Ljungberg, 2009). As regards the backfilling of open-pit mines with tailings, it was once practised in Arizona (USA) during the rehabilitation of the copper mine at Pinto Valley. It is important to note that this tailings disposal method is not feasible at an operating mine considering that it may interfere with its development or subsequent exploitation of the contained mineral resources (EPA, 1994). As recommended by good management practices, 30–50% of mining wastes and tailings should be stored in decommissioned mines according to a European directive (Chan et al., 2008).

The disposal of tailings, based on the backfilling into an underground mine, was successfully implemented for many years in the DR Congo mining industry by Gécamines, the country's leading state-owned mining company, and later on by Kamoto Copper Company in the Lualaba region (Countois et al., 2003; Jabin-Bevans et al., 2014; Van der Schyff, 2011). This tailings management technique will be soon implemented at the Kamoa-Kakula Copper mine (Lualaba region) owned by Ivanhoe Mines (39.6%), in a joint venture with Zijin Mining Group (39.6%), Crystal River Global Limited (0.8%) and the Gécamines (20%) (Golder Associates Africa Pty Ltd, 2017).

3.2.3 *Underwater Storage of Tailings and Reactive Mining Wastes*

Although tailing storage in ponds constructed by closing a valley or watershed from a river using a dam or an embankment may be considered as the most widely used method in the world for tailings disposal (Real & Franco, 1990), other established methods such as underwater storage of tailings in a deep lake or ocean, practised in Canada at Kensington (Alaska) in the management of mine waste from gold mining (Fig. 7a), have already revealed efficient from the environmental safety standpoint (EPA, 1994; Robinson et al., 2004).

This tailings' disposal technique is also implemented (see Fig. 7b) at an open pit mine of polymetallic tungsten ores (Nguyen et al., 2019) operated in the Thai Nguyen Province (Northern Vietnam). The subaqueous storage of reactive tailings enables minimising the entrainment of air/oxygen, which process in turn minimises oxidation of sulphides in view of preventing AMD formation and spreading (Bashir et al., 2020; Nguyen et al., 2019; Schaanning et al., 2019).

According to Schaanning et al. (2019), the underwater disposal of tailings in lakes and in the sea is more preferred owing to the geochemical stability of sulphide minerals contained in tailings and considering that it enables minimising risks related to dam failure together with catastrophic downstream consequences (Martinez, 2019). Another advantage

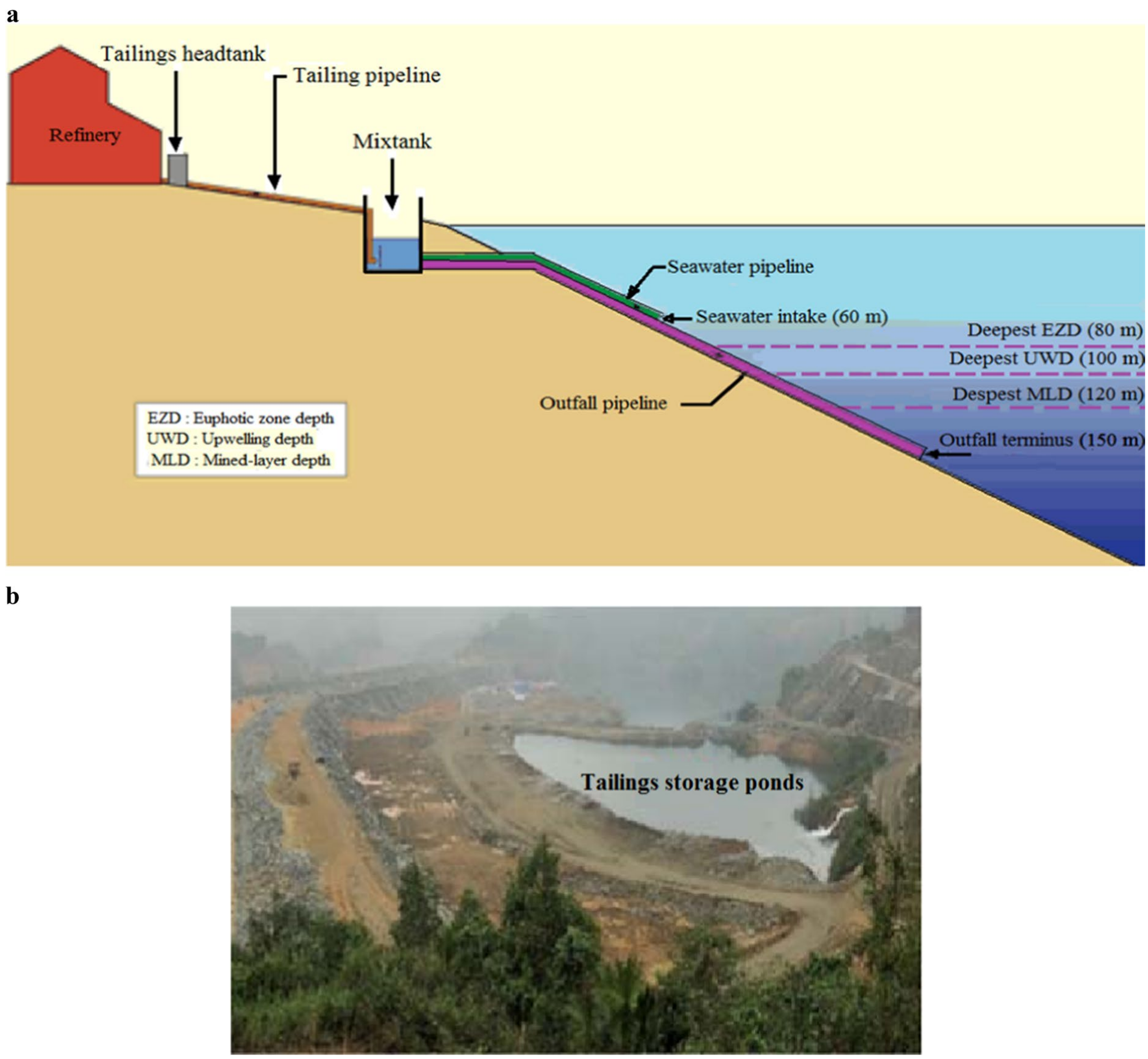

Fig. 7 **a** Underwater tailings storage facility in Alaska (modified from Robinson et al., 2004). **b** Underwater tailings storage facility in Vietnam (modified from Nguyen et al., 2019)

of the underwater disposal of tailings is a decrease in the visual impact on the landscape (Dino et al., 2020; Martinez, 2019). The underwater storage of tailings constitutes an alternative to the large deposits of tailings on land (Cervantes-Guerra et al., 2019). It is often practised in coastal countries such as Norway and in those confronted with the scarcity of suitable land areas together with regions where sea areas are available near the location of mineral ores (Cervantes-Guerra et al., 2019; Schaanning et al., 2019). Underwater storage of tailings is preferably carried out in regions with high precipitation and large seismic activities, that is when either local geology is not ideal to be used with these purposes (Poling et al., 2002) or when there are no large areas (Kwong et al., 2019; Zhang et al., 2011), building materials and when the topography does not fulfil certain requirements for the surface storage of tailings (Cervantes-Guerra et al., 2019). However, there are illustrations of the surface disposal of mine wastes in high rainfall and seismic regions (Bar et al., 2020). In these cases, tailings to be stored are composed of coarse-granulometry particles, with low sulphide content (EPA, 1994). Under these conditions, tailings that cover the bottom of the lake or ocean have no adverse effect on the pH of the water. However, increases in water turbidity were observed when tailings storage is not performed according to the rules of art.

Underwater disposal was applied in Portugal (1989) at the Neves-Corvo mine in the management of pyrite-rich tailings from the flotation of copper ores (Real & Franco, 1990). Sea deposition of tailings from Titania has been applied in Norway from 1960 until 1994 (Schaanning et al., 2019). Although this storage practice of sulphide-bearing tailings is considered to be among the best available techniques for preventing AMD formation and spreading (Charbonnier, 2001; Yilmaz et al., 2004), it is not approved as an environmentally friendly one by the Australian regulation owing to the pollution it can bring about in the receiving waters together with adverse effects on the health of surrounding communities (Charbonnier, 2001; Department of Industry, tourism and Resources, 2007; Martinez, 2019). According to Kwong et al. (2019), tailings disposal in rivers is not globally allowed even if it is practised at three operating mines in Papua New Guinea and one in Indonesia.

According to Ma et al., (2017), the submarine disposal of tailings in Chile dates back to 1938, with the pouring through a channel or a pipe system of copper mine tailings into the ocean. Koski (2012) considered the deposition of mine wastes in coastal areas as an important source of heavy metal contamination even if this practice constitutes a way to free mining operators from the high costs of proper management of tailings (Cervantes-Guerra et al., 2019; Ma et al., 2017). Besides, many cases of the environment pollution in relationship with the sea deposition of tailings have been reported in the world (Ma et al., 2017). In Norway, for instance, the sea deposition of tailings was ended in 1994 due to the fact that the leaching of trace metals (Fe, Cr, Ti, Ni, Cu and Co) was identified as a source of toxicity in fresh water samples (Schaanning et al., 2019). In Vietnam, the subaqueous storage of sulphide tailings negatively impacted the surrounding community owing to a rise in groundwater level brought about by surface seepage and flows (Nguyen et al., 2019). The rise in groundwater level rendered unsuitable the well water for general use necessitating constructing a drainage system in view of reducing the water table level (Nguyen et al., 2019). In China, the storage of slag generated by a tin mining company in an old lake resulted in the poisoning of 3,000 people with arsenic (Yongfeng, 2004).

During the underwater storage of sulphur-bearing tailings, a water cover of 1.5 to 2 m height can be used as an anoxic barrier in view of slowing oxidation reactions (Bashir et al., 2020), preventing erosion as well as resuspension of fine solid particles (Fraser & Robertson, 1994; Real & Franco, 1990; Stoltz, 2004). Relevant illustrations of the use of a water cover to prevent oxidation of reactive tailings are available through the reading of the research from Bjelkevik (2005) who studied the tailings management in Sweden. It should be noticed that the dumping of tailings into streams was once practised at Ok Tedi Mining in Papua New Guinea and also in the region of Katanga of the DR Congo (Chadwick & Cattaneo, 2005; Hendry et al., 2005). The underwater storage of tailings has the disadvantage of negatively impacting the environment, in particular through the sowing of river beds, the flooding of surrounding lands as well as the damage to aquatic fauna and flora (Bashir et al., 2020; Demi, 2003). Indeed, a water cover may result in increased percolation rates requiring the environment monitoring as well as the treatment of any discharge in view of complying with environment standards (Bashir et al., 2020). Cervantes-Guerra et al. (2019) provides a great number of illustrations in relationship with the underwater storage of tailings (Table 6).

Since in the DR Congo ore deposits are neither located in coastal areas nor even near the ocean on the one hand and on the other hand, areas for the surface storage of tailings are available, this management technique will not be considered at this time.

3.2.4 Tailings Reuse

Tailings represent potential resources from which valuable metals may be extracted in the future (Borra et al., 2016; Craw et al., 2017; Dino et al., 2020; Ma et al., 2017; Mehta et al., 2020). The reuse of tailings has become a growing practice given that it enables minimising the costs of managing wastes from the mineral industry (Almeida et al., 2020; Chan et al., 2008; Kudełko, 2018; Martinez, 2019). It also helps minimising waste production and consumption of unexplored resources (Dino et al., 2020; Ma et al., 2017; Mehta et al., 2020). Moreover, industrial wastes

Table 6 Illustrations of underwater storage of tailings throughout the world

Name	Country	Operator	Pipe final depth (m)	Deposition depth (m)	Amount of mining tailings (tonnes/day)	Start	Closing
Pellets de Huasco Plant	Chile	Pacific Mining Company	35	130	3300	1991	Continues
Boulby Potash Mine	England	Chemicals Israel	1100		550	1973	Continues
Batu Hijau	Indonesia	Newmont Corporation	108	> 2000	140,000	2000	Continues
Lihir Mine	Papua New Guinea	Lihir, Rio Tinto Management Group	128	> 1000	3500	1996	Continues
Ramu Nickel Mine/Basamuk Refinery	Papua New Guinea	Ramu NiCo	150	1500	14,000	2012	Continues
Cayeli Bakir Mine	Turkey	Inmet Mining	275	> 2000	30,000	1994	Continues
Minahasa Raya	Indonesia	Newmont Corporation	82	> 160	2000–3000	1996	2004
Misima Gold Mine	Papua New Guinea	Placer Dome	112	≈1500	20,000	1998	2004
Island Copper Mine	Canada		30–50	> 100	50,000	1971	1995
Atlas Copper Mine	The Philippines	Atlas Consolidated Mine	10–30	350 to > 500	70,000–100,000	1971	1995
Black Angel Mine	Greenland		30	≈80		1972	1986
Kitsault Molybdenum Mine	Canada	Avanti Mining Corp	50	> 350	20,000	1981	1982

such as tailings constitute renewable resources of which the processing and extraction of metals of interest usually do not require an additional cost (Tsukerman & Ivanov, 2020). This management practice values mine wastes or coarse tailings based on their geotechnical and geochemical characteristics either as building materials for roads construction or as additives in cement manufacturing (Borra et al., 2016; Charbonnier, 1994, Department of Industry, Ma et al., 2017; Tourism and Resource, 2007; Stoops & Redeker, 1970). However, any management practice that makes the subsequent use of tailings uneconomical or prevents the future development of mining activities is not encouraged. The use of tailings in the backfilling of underground or open-pit mines is therefore only one last possible management option for tailings disposal (Department of Industry, Tourism and Resources, 2007; Kudełko, 2018). Tailings from the flotation beneficiation of copper ores can be used, in combination with other components, in ceramics production as well as aggregate in road construction (Kudełko, 2018). Throughout the world, there is an increasing number cases of tailings reprocessing in view of extracting valuable metals (Almeida et al., 2020; Borra et al., 2016; Rubinos et al., 2019). Tailings generated by the processing of ores from the Macraes gold mine (New Zealand) contain gold encapsulated in pyrite and arsenopyrite. These gold-bearing sulphide minerals were reporting in tailings from the flotation beneficiation of ores (Craw et al., 2017). In 1999, tailings were economically reprocessed for residual gold recovery when the pressure-oxidation system was added to the processing plant circuit (Craw et al., 2017). In the context of the DR Congo mining industry, various ancient and recent studies related to the management of tailings demonstrate the possibility of recovering metals of interest (Shengo & Kashala, 2013; Shengo, 2021a). In the Lualaba region (DR Congo), for instance, the mining company Metalkol, owned by Eurasian Resources Group Sarl in partnership with the Gécamines, is reprocessing historical cobalt–copper tailings that accumulated over decades of mining by previous operators. They include the Kingamyambo tailings deposit and those accumulated in the

Musonoi River offering the possibility of recovering retained copper and cobalt (Eurasian Resources Group, 2019).

3.3 Environmental Issues Related to the Management of Mining Wastes and Flotation Tailings

Today, the efficient operation of wastes storage infrastructure, including the biogeochemical stabilisation of sulphur-bearing tailings, their containment or the abatement of their pollution potential and the neutralisation of acidic wastewater that they can generate, the biodegradation of unconsumed reagents retained in the wastewater together with the stability of dams constructed at tailings ponds, constitutes the greatest challenges and environmental obligations pertaining to mining and metallurgical activities (Bioteq, 2003; EPA, 1994; ICME and UNEP, 1998; UNEP, 2000; Sol et al., 1999).

3.3.1 Environmental Impacts Related to Surface Storage of Waste Rocks and Mine Tailings

Surface storage is the most widely utilised practice in tailings management (Ma et al., 2017; Panchal et al., 2018). From an environmental perspective, it is held responsible for the pollution in about half of the world's regions negatively impacted by mining activities (Department of Industry, Tourism and Resources, 2007). For example, over 100 cases of severe environmental accidents that occurred in China were attributed to surface storage of waste rocks and mine tailings (Yongfeng, 2004). Macklin et al. (2006), cited by Ma et al. (2017), reported that in the USA, from 1917 to 1989, there were 185 tailings dam incidents and this happened at active mines where the surface storage of tailings was implemented. According to Fonseca do Carmo et al. (2017), for instance, the collapse of the Fundão tailings dam (Brazil) in 2016, with the release of more than 43 million m^3 of iron tailings, resulted in the pollution that affected 688 km of watercourses. This tailings dam failure was qualified as the largest environmental tragedy the country has never been confronted with. Among the main causes of tailings dams' failures, there is the lack of control of the water balance together with that of the construction as well as the lack of understanding the features that control safe operations of the storage infrastructures (Department of Industry, Tourism and Resources, 2007). Dam failures are most likely to happen for one of five reasons: overtopping, foundations defects, cracking, inadequate maintenance and upkeep as well as piping (Department of Industry, Tourism and Resources, 2007). The storage and behaviour of water within the facilities is looked at as one of the elements responsible for the tailings dams' failure, and consequently, the Canadian mining industry has adopted tailings dewatering prior to deposition among alternatives to conventional practices (KCB, 2017).

In addition, the magnitude of the environmental impacts related to mining activities can be seen through the stripping of more than 20 million ha through exploration that enabled discovering in 1990 diamond deposits in north-western Canada (Sumi & Thomsen, 2001). The environmental impacts observed in the eastern Canadian boreal region (Fig. 8a) are indicative of the harms in relationship with the surface storage of mine wastes and flotation tailings (Lloyd et al., 2008).

Although during many decades there has not been a case of environmental pollution incident of a similar magnitude to that caused in 1998 by the dam breaking at Los Frailes (Spain), including recent cases of tailings dams' failure recorded in 2016 and in 2019, respectively, in Brazil and qualified as human and environmental tragedies (ICMM, 2021), the management of mine wastes and flotation tailings cannot be looked at, even in the most industrialised countries, as an environmental riskless operation (Bruce et al. 1997; Martinez, 2019; Sol et al., 1999; Sumi & Thomsen, 2001). Supporting this statement, Bjelkevik (2005) arrived at the conclusion that tailings dams are not safe enough today, to be regarded as long-term stable without measures taken. Consequently, TSFs are constantly under increased scrutiny, especially in the wake of recent failures so that the mining industry becomes more sustainable through enhancement of the safety of TSFs across the globe, that is during all phases of their life cycle until their closure and post-closure (Carneiro & Fourie, 2018; ICCM, 2021; KCB, 2017). In fact, there have been cases of pollution related to the release of waters by abandoned or orphan mines and the accidental spillage of wastewater or residues stored in ponds all around the world as exemplified by tailings accidents recorded in the UK, Sweden, Spain, Italy, Portugal, South Africa,

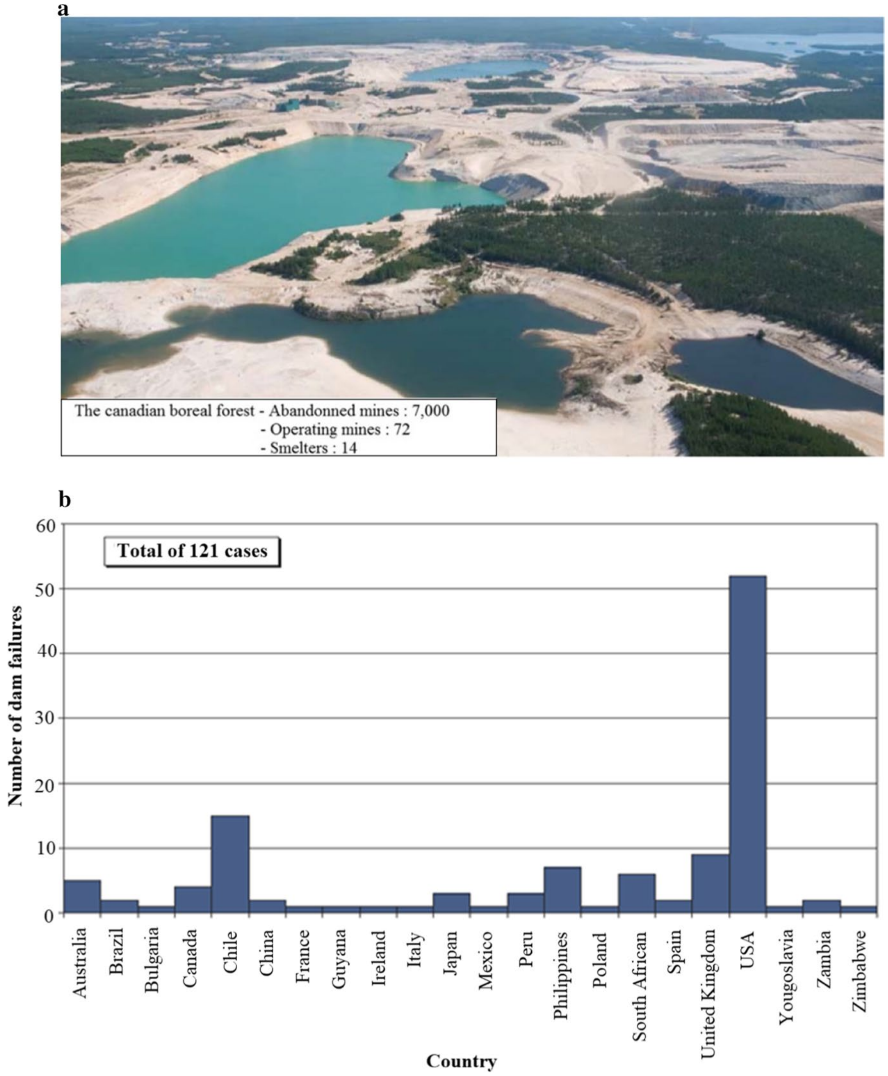

Fig. 8 **a** Impact of mining on the Canadian boreal forest (modified from Lloyd et al., 2008). **b** Breakage of tailing pond dams from 1917 to 1996 (after Bruce et al., 1997)

Brazil, etc. as well as in the DRC of which astonishingly there is a sort of omerta as one will notice it below (Bascetin et al., 2016; Countois et al., 2003). It is in the USA and Chile that many cases of dams breaking have been observed at ponds utilised for tailings or water storage. According to Martinez (2019), there have been more than 230 cases of tailings dams' accidents around the world during the period 1917 to 2009 (Fig. 8b). Data from different sources (Mining Journal Research Services, 1996; UNEP and ICOLD, 2001; US Committee on Large Dams, 1994) enable identifying 149 cases of tailings dam failures around the world during the period 1960–2020, with 22 cases recorded from 2016 to 2020 (Table 7), a period during which a tailings dam failure occurred in the City of Likasi (Haut-Katanga region) in the DR Congo. Astonishingly, this case as well as other ancient cases of tailings dam failures has not yet been reported through the literature in spite of the fact that the output of copper and cobalt presently enables the country to classify itself as the leading producer on the African and world chessboard, respectively.

3.3.2 Water and Soil Pollution Due to sulphurSulphur-Bearing Waste Rocks and Mine Tailings

Water and soil pollution results mainly due to formation and spreading of AMD. The same pollution may occur due to contaminated water from abandoned

Table 7 Tailings dam failure recorded in the world from 2016 to 2020

No	Date	Location	Parent company	Ore type
1	2020, July 2	Hpakant, Kachin state, Myanmar		Jade
2	2020, May 1	San José de Los Manzanos, Canelas, Durango, Mexico	Exportaciones de Minerales de Topia SA (EMITSA)	Lead, zinc
3	2020, March 28	Tieli, Yichun City, Heilongjiang Province, China	Yichun Luming Mining Co., Ltd	Molybdenum
4	2019, October 1	Nossa Senhora do Livramento, Mato Grosso, Brazil	VM Mineração e Construção, Cuiabá	Gold
5	2019, July 10	Cobriza mine, San Pedro de Coris district, Churcampa province, Huancavelica region, Peru	Doe Run Perú S.R.L	Copper
6	2019, April 22	Hpakant, Kachin state, Myanmar	Shwe Nagar Koe Kaung Gems Co. Ltd., Myanmar Thura Gems Co. Ltd	Jade
7	2019, April 9	Muri, Jharkhand, India	Hindalco Industries Limited	Bauxite
8	2019, March 29	Machadinho d'Oeste, Oriente Novo, Rondônia, Brazil	Metalmig Mineração Indústria e Comércio S/A	Tin
9	2019, January 25	Córrego de Feijão mine, Brumadinho, Região Metropolitana de Belo Horizonte, Minas Gerais, Brazil	Vale SA	Iron
10	2018, June 4	Cieneguita mine, Urique, Chihuahua, Mexico	Minera Rio Tinto	Gold, silver
11	2018, March 9	Cadia, New South Wales, Australia	Newcrest Mining Ltd	Gold, copper
12	2018, March 3	Huancapatí (Huancapetí), Recuay province, Áncash region, Peru	Compañía Minera Lincuna SA (Grupo Picasso)	
13	2018, February 17	Barcarena, Pará, Brazil	Hydro Alunorte/Norsk Hydro ASA	Bauxite
14	2017, September 17	Kokoya Gold Mine, Bong County, Liberia	MNG Gold Liberia	Gold
15	2017, June 30	Mishor Rotem, Israel	Rotem Amfert Negev Ltd	Phosphate
16	2017, March 12	Tonglvshan Mine, Hubei province, China	China Daye Non-Ferrous Metals Mining Limited	Copper, gold, silver, iron
17	2016, December 28	Satemu, Hpakant, Kachin state, Myanmar	Jade Palace Company	Jade
18	2016, October 27	Antamok mine (inactive), Itogon, Benguet province, Philippines	Benguet Corp	Gold
19	2016, August 27	New Wales plant, Mulberry, Polk County, Florida, USA	Mosaic Co	Phosphate
20	2016, August 8	Dahegou Village, Luoyang, Henan province, China	Luoyang Xiangjiang Wanji Aluminium Co., Ltd	Bauxite
21	2016, August 4	Ujina, Pica, Tamarugal Province, Tarapacá Region, Chile	Compañía Minera Doña Inés de Collahuasi SCM	Copper, molybdenum
22	2016, May 22	Ridder, Kazakhstan	Kazzinc	Zinc

mines (Martinez, 2019), wastewater discharged by ore concentrators and leachates emanating from storage sites of mining and metallurgical wastes (Bioteq, 2003; Countois et al., 2003; Sol et al., 1999; Sumi & Thomsen, 2001; UNEP, 2000). The pollution of water and soil by copper, zinc, iron and sulphate ions that had been experienced between 1935 and 1996 in Albania in relationship with the storage, alongside abandoned mines, of approximately 15 million tonnes of sulphide-rich solid wastes (pyrite) and 11,830.945 tons of flotation tailings generated by the selective flotation of copper ores (18%) deserves to be mentioned for illustrative purpose.

While special attention had been paid to maintaining the stability of the dams constructed at ponds intended for the storage of ore flotation tailings, since the environmental catastrophes of the 1960s as well as those of the 1990s, the study of the geochemical behaviour of mine wastes and sulphur-bearing tailings during their storage had been neglected (Bruce et al., 1997; Wiertz & Marinkovic, 2005). In China, for instance, the lack of an environmentally friendly management of mine wastes and hazardous residues from metallurgical processing of mineral resources in the past was such that some mining companies have opted for the surface storage of mine tailings. This practice resulted in contamination of surface and groundwater with apparition of health and environmental issues of concern (Yongfeng, 2004).

3.3.3 Environmental Issues Related to AMD

AMD is an acid-generating process that occurs due to exposure to air and water of reactive wastes made mainly of sulphur-bearing tailings (Anju, 2018; Lu et al., 2016; Remešicová et al., 2018; Stoltz, 2004). AMD constitutes the greatest environmental issue mining companies are often confronted with, especially during the rehabilitation phase of mine sites' out-off operations (Lu et al., 2016; Oelofse, 2008; Schaanning et al., 2019; Taskinen et al., 2018; Yilmaz et al., 2004). In 1989, it was reported that approximately 19,300 km of rivers, 72,000 ha of lakes and water reserves were seriously impacted by polluted waters of mining origin (Oelofse, 2008). It is difficult to stop an AMD and cannot do so on its own (Al Zoubi et al., 2010; Matsumoto et al, 2016), as evidenced by the continuous release of acidic waters by abandoned mines exploited around 1700 in Norway (Oelofse, 2008; Sumi & Thomsen, 2001). In addition, the costs of containment or abatement of pollution that an AMD can cause are such that they can engulf the long-term economic gain from a previously profitable mining. What precedes is revealing the negative economic impact AMD can have on operating costs of a mining project when reactive mine wastes are improperly managed (Cánovas et al., 2019). The treatment of AMD-polluted water at the decommissioned site of Equity mine costs the mining company more than $1.2 million per year (Sumi & Thomsen, 2001). It was estimated that the acid generation process can be maintained for up to 150,000 years (Sumi & Thomsen, 2001), which means it can last for hundreds or even thousands of years (Elmayel et al., 2020; Lu et al., 2016; Othlander et al. 2012).

Acid generation is a process that takes place itself under certain natural conditions (Remešicová et al., 2018). The processing of base and precious metals from the sulphide ore deposits usually results in production of large amounts of sulphur-bearing tailings of which the management constitutes a serious environmental problem (Martinez, 2019; Anju, 2018; Remešicová et al. 2018). Indeed, mining activities are acknowledged to exacerbate AMD through the excavation and comminution of sulphide minerals together with their exposure to air and water, which means out of their natural environment in which anoxic conditions prevail. The extent of an acid generation process is determined by the sulphur content of mining wastes or tailings (Anju, 2018; Sumi & Thomsen, 2001). AMD results from natural oxidation of sulphur-bearing or pyrite-rich tailings (Cánovas et al., 2019; Fan et al., 2016; Remešicová et al., 2018; Yilmaz et al., 2004; Warhurst & Noronha, 2000). It is initiated by oxidation of sulphides with a generation of sulphuric acid as per the following reactional sequence (Yilmaz et al., 2004):

$$FeS_2(s) + \frac{7}{2}O_2(g) + H_2O \rightarrow Fe^{2+}(aq) + 2SO_4^{2-}(aq) + 2H^+ \quad (1)$$

$$Fe^{2+}(aq) + \frac{1}{4}O_2(g) + H^+ \rightarrow Fe^{3+}(aq) + \frac{1}{2}H_2O \quad (2)$$

$$FeS_2(s) + 14Fe^{3+}(aq) + 8H_2O \rightarrow 15Fe^{2+}(aq) + 2SO_4^{2-}(aq) + 16H^+ \quad (3)$$

$$Fe^{3+}(aq) + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+ \quad (4)$$

$$FeS_2(s) + \frac{15}{4}O_2(g) + \frac{7}{2}H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-}(aq) + 4H^+ \quad (5)$$

AMD is therefore responsible for the release of contaminated waters together with acidic and sulphate-laden waters reputed to be harmful to the environment (Lu et al., 2016). AMD can affect water quality in a variety of ways (Cánovas et al., 2019; Sumi & Thomsen, 2001) especially by lowering the pH resulting in high dissolution of heavy metals to toxic concentrations for all life forms (Anju, 2018; Koomson et al., 2017; Lu et al., 2016; Schaanning et al., 2019). Copper and arsenic were encountered at Buck Creek in Alabama (USA) to concentrations accounting for 750 and 20 times their natural levels in surface waters. This phenomenon helps realising the extent at which an AMD can affect water quality in regions where it occurs (Sumi & Thomsen, 2001) rendering water unfit for any traditional use (Lu et al., 2016). Arsenic is also a metal of great concern encountered in tailings from extractive industries of Finland, USA, Canada and Australia (Taskinen et al. 2018).

AMD constitutes a source of significant environmental damage (Fig. 9), including deforestation (Askaer et al., 2008) of large areas of land and pollution of surface and groundwater (Aubertin et al., 2015; Cánovas et al., 2019; Lu et al., 2016; Martinez, 2019; State of Alaska and US EPA, 2008).

3.4 AMD Prevention Strategy

Environmental desulphurisation of reactive tailings is a technique for preventing the AMD formation and spreading. It is used in restoration of sites affected by AMD (Cheng et al., 2016). Indeed, it is a process consisting in an environmental neutralisation or stabilisation of the sulphur-bearing tailings based on the lowering of their contents in acidogenic minerals such as pyrite and arsenopyrite prior to their storage; a process that enables reducing the content of sulphide minerals to a lower level so that tailings behave as chemically inactive materials (Bashir et al., 2020). This environmental stabilisation is carried out using the non-selective flotation of sulphide minerals with the aim of increasing the neutralisation potential of the tailings (Kitobo, 2009; KCB, 2017). As a result, acidogenic materials are prevented from reacting via bacteria-catalysed oxidation of sulphides in order to stop the formation and spreading of AMD (Benzaazoua et al., 1998; Cheng et al., 2016; Remešicová et al. 2018). Froth flotation enables separating sulphide-rich concentrate involved in acid generation through AMD formation, that is, obtaining desulphurised tailings consisting of materials that are chemically stable (KCB, 2017; Nakhaei & Irannajad, 2017). This environmental stabilisation of sulphur-bearing tailings was implemented during the restoration of mine sites confronted with AMD in Quebec where it has been considered as an economically viable alternative for minimising the environment pollution due to the surface storage of reactive tailings (Benzaazoua et al., 2008; Bussière et al., 1997).

Fig. 9 AMD formation during the storage of mine wastes in Katanga region (after Kitobo 2016)

The environmental desulphurisation of sulphur-bearing tailings is fundamentally different from the stabilisation of tailings through immersion in water playing the role of an anoxic screen that blocks the start of reactions involved in the formation and spreading of AMD (Stoltz, 2004). While immersion in water allows the AMD prevention through creation of a storage environment capable to inhibit reactions involving acidogenic minerals contained in tailings (Nguyen et al., 2019), environmental desulphurisation relies upon the extraction of reactive minerals, a process that renders possible their storage under oxidising conditions. As stated by Cheng et al. (2016), the successful separation of sulphides and non-sulphide portions of tailings enables the better management or repurposing of the material that is via the economic extraction of metals of interest or the reuse of tailings as building materials, for instance.

The stabilisation of acidogenic mine wastes through desulphurisation had been considered at the laboratory scale in the Katanga region as an economically viable technique for recovering sulphides of base metals of interest retained in mine wastes, with the possibility of converting reactive tailings into chemically stable materials (Kitobo, 2009). It was expected that this management procedure could enable obtaining oxidised tailings that consist of mineral wastes ridded of sulphide minerals and thus chemically stable materials in the presence of water and air. However, it is important noticing that this management method of reactive tailings has not yet been scaled up at the industrial level in view of recovering valuable metals of interest such as copper, cobalt, zinc and nickel (Shengo, 2021a). The concerned metals are present to recoverable concentrations in mine wastes and tailings from the processing of ores in the Katanga region presently confronted with the environment pollution.

3.5 Practices in the Management of Tailings from Ore Flotation in DR Congo

While environmental regulation is being strengthened worldwide in view of improving the management of both solid, liquid and gaseous effluents from the mining industry (Chan et al., 2008; Ghose & Sen, 1999), it is inconceivable that in some regions of the world such as in the Katanga region of the DR Congo water resources (surface waters and groundwaters) and soils remain threatened by the pollution due to the mismanagement of mineral wastes and metal-laden waters from either abandoned mines or operational ones together with industrial wastes from the mining industry (Oelofse, 2008; Sol et al., 1999; Zhang et al., 2011).

It is important recalling that in the aforementioned region, large piles of mineral wastes from ancient mining operations and the metallurgical processing of different types of mineral ores have been improperly managed for several decades (Andrews et al. 2008; Countois et al., 2003; Kalenga et al., 2006). Their surface storage has negatively impacted the landscape and watercourses together with the soil in the cities of Lubumbashi (8 Mt, 15% Zn), Kipushi (25 Mt, 2.73% Zn and 0.4% Cu), Kolwezi (112 Mt, 1.49% Cu and 0.32% Co), Kakanda (18 Mt, 1.2% Cu and 0.1 4% Co), Kambove (36 Mt, 0.89% Cu and 0.19% Co), Shituru and Panda (13 Mt, 1.5% Cu and 0.23% Co).

The management of waste rocks and mine tailings resulted in the environment pollution owing to weathering processes of solid materials leading to the leaching of metals such as Cu, Ni, Co, As, Cd and Zn (Vande Weghe et al., 2005). A careful analysis of the management practices of tailings and wastewaters from the flotation of copper ores (Countois et al., 2003) revealed that both very rudimentary and non-environmentally friendly management methods had been used in Katanga region (Countois et al., 2003; Kalenga et al., 2006, Shengo, 2013). Consequently, waste rocks from previous mining operations were stockpiled at mine site with percolates or leachates allowed to spill out in the environment or to flow into watercourses. As for mine tailings generated by the flotation beneficiation of ores, they were simply pumped as pulps into surface storage facility (ponds) preferentially constructed inside the valleys of watercourses closed by dams until the available volume filling up, with the clarified supernatant waters allowed to pour out in neighbouring watercourses (Fig. 10) (Shengo & Mutiti, 2016, Shengo, 2021b).

Sometimes, pulps of tailings were managed through spreading on land in view of separating out the accompanying water by drainage, with solid matters exposed to erosions by wind and rainfall resulting in the environment pollution by airborne and waterborne particles of toxic pollutants. As for water recovered through drainage, it was allowed to flow into waterbodies or to soak in the soil bringing about the pollution of groundwaters.

The aforementioned watercourses were also utilised as spillways for wastewater from mineralurgical processes and this without first being treated regardless of environmental impacts that have resulted in the pollution of water resources endangering the aquatic flora and fauna and human health.

The extinction of aquatic life known by the King and Queen rivers in Tasmania (Countois et al., 2003), as a result of 75 years of mismanagement of xanthate-bearing flotation effluents, enables predicting what could be the environmental status in the days to come if corrective measures are not taken now. The pollution of water resources in Macedonia, where the flotation of copper (0.25%), silver (9 g per tonne) and gold (0.4 g per tonne) complex ores was conducted since 1979 (Jordanov et al., 2007), and other similar cases found throughout the world are portraying the mining activities conducted in Katanga region. Indeed, tailings contain metals of interest to recoverable concentrations and are pumped as pulps into spreading ponds regardless of water resources safeguarding (Shengo, 2021a). This tailings waste management practice radically contrasts from the in-force environmental practices established in areas where modern and green technologies are implemented in the ore-processing sector (Clark et al., 2000).

Fig. 10 **a** Discharge of flotation tailings into a settling pond constructed by closing a valley with a dike. **b** Supernatant clarified water from tailings settling from ore flotation (after Shengo, 2008). **c** Discharge of clarified water into a watercourse (modified from Shengo, 2008)

3.5.1 Regulatory Framework for the Management of Discharges from the Congo Mining Industry

Both environmental issues related to the Congolese mining industry and their origins are well identified and documented (Andrews et al., 2008; Countois et al., 2003; Kalenga et al., 2006; Nordbrand & Bolme, 2007; Vande Weghe et al., 2005). The DR Congo has a long mining tradition that dates back to more than a century, and the mining industry footprint on the environment is so great due to the delayed update of its environmental regulation

Fig. 11 **a** Liming of a soil impacted by acid tailings in the Katanga region (after Omari 2016). **b** 6 months and **c** 1 year after restoration of soil polluted by acid tailings (modified from Shengo, 2016)

(Andrews et al., 2008; Nordbrand & Bolme, 2007; UNEP, 2000; Verlinden & Cuypers, 1956). The environment degradation brought about by previous and non-friendly environmentally practices during the management of mine wastes and polluted waters have speeded up the adoption of more constraining management rules, as illustrated by reforms carried out in 2002 and later on, in 2018 by the Congolese legislator. Indeed, the mismanagement of mineral wastes exemplified by the discharges in watercourses of polluted waters from the flotation beneficiation of ores will remain the main source of conflicts between the mining industry and local communities. The contamination of water resources together with the drop in the soil agricultural yield induced by the mismanagement of mineral wastes does not constitute new issues of concern to communities living in the neighbourhood of mine sites (Martin et al., 2002).

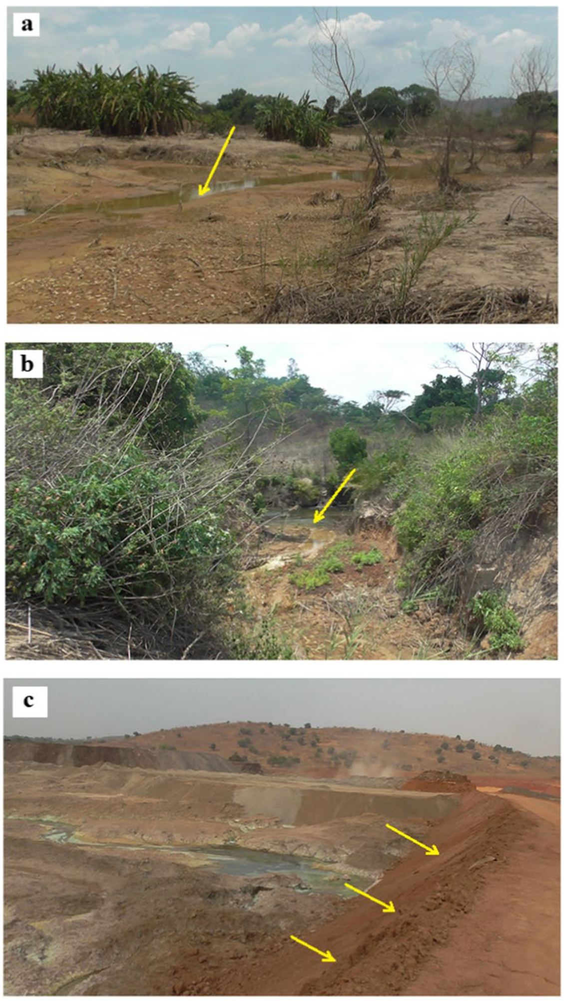

Fig. 12 **a** Water Flow in the Kiantete River. **b** Kiantete River discharge point in the Mura River (modified from Shengo, 2016). **c** Tailings pond dam reconstruction in Katanga region (modified from Shengo, 2016)

Juridical actions brought about by the strengthening of environmental regulations throughout the world, namely in North America and Europe, led the developed countries to adopt the banishment since 1930 of all non-environmentally friendly practices in the management of mineral wastes (Martin et al., 2002).

3.5.2 Major Environmental Incidents in the Congolese Mining Industry

Cases of watercourses and ground water contaminations by polluted waters and industrial solutions are common facts in Katanga region of the DR Congo (Countois et al., 2003). Currently, embankment N°3 of the TSF constructed by the Gécamines (Shengo, 2021b), in the area of Kipushi (Haut-Katanga region), has lost stability so that the collapse can happen at any time, especially during the rainy season, if repairs are not done as quickly as possible. In the city of Likasi, for instance, due to torrential rains in 2016, the embankment of a TSF utilised for the storage as pulps of solid residues from the hydrometallurgical production of copper disrupted and released to the environment huge amounts of highly acidic muds (Fig. 11a).

The concerned muds buried and stranded both the source and the bed of the Kiankalamu River located in the vicinity of the TSF. Polluted waters liberated by the settling of solid matters flowed out bringing about the pollution and the burning of the vegetation as well as the soil along their way until they covered a distance estimated at nearly 2000 m (Fig. 11b). The aforementioned polluted waters content ended their course in the Mura River used as spillway for rainfalls, a phenomenon that facilitated the spreading of the mineral pollution over several kilometres from the tailings pond.

Different ingenious measures were taken in view of mitigating harmful effects of the pollution brought about by the tailings dam failure. They encompass the immobilisation of dissolved pollutants together with the lowering of their individual concentrations in water through the stripping of superficial layers of the soil (±2 m), in combination with the river's bed and

Table 8 Physicochemical characteristics of water from the tailing pond and its surrounding wells

Water origin	Well depth (m)	pH	Electrical conductivity (µS/cm)	Total dissolved salts (mg/L)	Saltiness
Liquid waste n°1		7.8	68.7*	3.77**	47.7
Liquid waste n°3		3.7	70.2*	3.84**	48.4
Domestic well n°4	8	4.2	68.5*	3.72**	46.7
Domestic well n°5	13	6.0	255	135	0.1
Domestic well n°6	17	4.9	13.49	7.16	0.0
Domestic well n°7	21	5.1	13.88	741	8.0
Domestic well n°8	18	5.0	13.76	7.30	0.0
Domestic well n°9	16	5.0	8.12	4.41	0.0
Drilled well n°10	34	4.5	10.82	5.69	0.0

*Result expressed in mS/cm

**Result given in g/L

banks liming (Fig. 12a, b) with the aim of decreasing the flowing water acidity. Great amounts of highly acidic muds were recovered and re-dumped in the tailings pond of which the disrupted embankment had been quickly reconstructed (Fig. 12c).

As for the contamination of groundwater, in the region of Lubumbashi, for instance, it can be exemplified by the mismanagement during many years of process wastewaters from the hydrometallurgical extraction of copper and cobalt conducted at a plant operated in the neighbourhood of the City of Lubumbashi and of which the outcome was the pollution of water table. Indeed, process wastewaters were formerly stored in a retention pond that was improperly waterproofed. This practice resulted in infiltrations of polluted waters that impacted the quality of underground water (Table 8) as can be seen through reading of results related to the quality of water from domestic wells (8 to 20 m) located in the vicinity (10 up to 15 m) and far (more than 15) from the wastewater retention pond.

4 Conclusion

It is well established that mining plays an essential role in the creation of wealth and contributes through its revenues to the economic and social development of mineral-rich countries. However, the exploitation and production of the metals are held responsible for environmental pollution, in particular because of the generation of great quantities of solid wastes and metals-laden wastewaters capable of endangering wildlife and human health. Consequently, mining is considered as a perilous business despite the numerous benefits it can bring to people living in areas where it is undertaken. Management practices for mine wastes and ore flotation tailings have evolved over time. This development is directly related to changes in the mining industry technology and the awareness by mining operators of the environmental problems associated with each practice in the management of mineral wastes. In each particular circumstance, a given management method has been worldwide adopted as the most performing given its benefits on the economic and environmental standpoint. As far as the mining industry of the Katanga region (DR Congo) is concerned, various major environmental incidents have been recorded in relationship to old practices in the management of mine wastes and flotation tailings. In parallel, the country regulatory framework has evolved over time as a result of experience acquired in addressing environmental issues related to the mining industry. It is expected that various discussions done in the context of the present research, based on the relevant case studies, have shown new paths to be followed and alternative management solution to be considered in the future as far as the management of mineral wastes is concerned. Besides, data have been made available to mining operators, researchers and academics interested in the management of mineral wastes and will help them provide solutions to practical problems.

Acknowledgements I gratefully thank professors Pierre Kalenga Ngoy (posthumously), Arthur Kaniki Tshiamala and Kitobo Samson from the Applied Sciences Faculty (University of Lubumbashi) as well as academics and practitioners, from different regions of the world, given that their different researches and high quality publications on the management of

mine wastes and flotation tailings, and particularly those generated by the copper industry of Katanga (DR Congo), have usefully inspired and served me in the preparation of the present article.

Declarations

Conflict of interest The author declares no competing interests.

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