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REVIEW ARTICLE

A critical review on environmental implications, recycling strategies, and ecological remediation for mine tailings

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Abstract
Mine tailings, generated from the extraction, processing, and utilization of mineral resources, have resulted in serious acid mine drainage (AMD) pollution. Recently, scholars are paying more attention to two alternative strategies for resource recovery and ecological reclamation of mine tailings that help to improve the current tailing management, and meanwhile reduce the negative environmental outcomes. This review suggests that the principles of geochemical evolution may provide new perspective for the future in-depth studies regarding the pollution control and risk management. Recent advances in three recycling approaches of tailing resources, termed metal recovery, agricultural fertilizer, and building materials, are further described. These recycling strategies are significantly conducive to decrease the mine tailing stocks for problematic disposal. In this regard, the future recycling approaches should be industrially applicable and technically feasible to achieve the sustainable mining operation. Finally, the current state of tailing phytoremediation technologies is also discussed, while identification and selection of the ideal plants, which is perceived to be the excellent candidates of tailing reclamation, should be the focus of future studies. Based on the findings and perspectives of this review, the present study can act as an important reference for the academic participants involved in this promising field.

Keywords Mine tailings · Environmental implications · Recycling strategies · Phytoremediation

Introduction

The past and present-day mining sector, having been recognized as an economic driver and essential cornerstone, can immensely facilitate economic growth worldwide (Yin et al. 2018a, 2018b). However, with steady societal demands for metal resources at the global scale, the exploitation and utilization of mineral resources tend to be profit maximization-oriented for mining enterprises, and the resulting negative environmental impacts have attracted attention in much research. In addition, owing to the increasing depletion of the high-grade metal deposits, the continuous generation of enormous amounts of profitless solid wastes remains a global challenge in the future.

In the past decades, significant quantities of mine wastes, generally referred to as mine tailings, have been tremendously growing in parallel with the annual extraction, processing and utilization of global mineral resources (Wu et al. 2019). Literature suggests that the amount of solid tailings produced accounts for roughly 97–99 % of total ore processed, whereas only 1–3 % is concentrate (Adiansyah et al. 2015). An estimated 5–7 billion tons of mine tailings is generated each year worldwide (Edraki et al. 2014). The statistical data from National Development and Reform Commission of China shows that the stocks of mine tailings are estimated at 14.6 billion tons by the end of 2013 (NDRCC 2014). In 2013 alone, China had accumulated 1.649 billion tons of tailings (Ye et al. 2017). Tailing discharges, mainly composed of finely crushed materials and commonly enriched with sulfidic polymetallic materials, are historically stacked in open-air tailing impoundments, situated

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close to mining sites year by year, though only a small part is effectively recycled and utilized (Sibanda et al. 2019). Even more problematic, these tailings not only cover innumerable mining land resources and waste valuable resources but also induce catastrophic environmental accidents (Xiang et al. 2018). It has been reported that the total area of land resource and mined lands damaged by waste tailings is above 2000 ha (Wang et al. 2017). Besides that, coupled with an increasing environmental hazards related to mine tailing repositories, the field researches of effectively ecological remediation and practices in mining areas necessitate the growing awareness within the global scientific community. On the other hand, tailing dam failures worldwide, such as Fundão dam collapse in southeastern Brazil in November 2015, are frequently resulted in enormous property losses, large-scale people mortality, and extensive environmental damage (Queiroz et al. 2018; Quadra et al. 2019). Such catastrophic accidents often occur as a consequence of poor facility performance. In view of their severe social, economic, and environmental impacts, it is of great necessity for mining industries to improve the contemporary tailing management of international scale.

During tailing stockpiling period, acid mine drainage (AMD) has been an unavoidable environmental concern in mining practices among all countries (Park et al. 2019). It is well acknowledged that AMD is an important consequence of the oxidative dissolution of reactive sulfidic minerals, especially pyrite, upon exposure to atmospheric oxygen (O_2), water, and microbial activities, which make harmful metallic species become more soluble and mobile (Anju and Banerjee 2010; Elghaliet Elghali et al. 2019; Naidu et al. 2019). Numerous evidences have shown that the migration of various dissolved elements into the neighboring environment receptors, including surface runoffs, soils, sediments, and other local ecosystems, could be traced directly back to the ongoing acid-producing process of AMD (Abraham and Susan 2017; Torres et al. 2018; Park et al. 2019). Thus, it has a long-term deleterious impact on public health and ecological environment (Liao et al. 2016, 2017).

While mining operations subsist, there is an urgent need for local authorities to minimize the pollution risk typically accompanied with the excessive accumulation of hazardous mining discharges generated from processing ores. To address this aim, current mining operations must be conducted in an environmentally sustainable and economically feasible manner, with the aim to significantly contribute to the cleaner production of mineral resources across the globe. In this context, effective recycling and reprocessing of tailing materials have been of great importance to all countries worldwide.

In response to the above concerns, the main purpose of this critical review is therefore to introduce the following three aspects: (i) the potential environmental implications of AMD formation, (ii) the strategies for comprehensive recovery and reutilization of tailing resources, (iii) the current techniques of tailing phytoremediation.

AMD pollution and associated environmental implications

Formation of AMD and secondary minerals

Environmental studies have reported that AMD is primarily formed from the oxidation of pyrite (FeS_2), the most abundant sulfide mineral in tailings, as described by the following simplified equations (Park et al. 2019):

$$FeS_{2(s)} + \frac{7}{2}O_{2(g)} + H_2O_{(l)} \rightarrow Fe^{2+}{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + 2H^+{}_{(aq)} \quad (1)$$

$$Fe^{2+}{}_{(aq)} + \frac{1}{4}O_{2(g)} + H^+{}_{(aq)} \rightarrow Fe^{3+}{}_{(aq)} + \frac{1}{2}H_2O_{(l)} \quad (2)$$

$$Fe^{3+}{}_{(aq)} + 3H_2O_{(l)} \rightarrow Fe(OH)_{3(s)} + 3H^+{}_{(aq)} \quad (3)$$

$$\frac{1}{2}FeS_{2(s)} + 7Fe^{3+}{}_{(aq)} + 4H_2O_{(l)} \rightarrow \frac{15}{2}Fe^{2+}{}_{(aq)} + SO_4^{2-}{}_{(aq)} + 8H^+{}_{(aq)} \quad (4)$$

The well-understood processes of AMD formation have been reviewed in many scientific literatures (Lowson 1982; Kefeni et al. 2017; Naidu et al. 2019). Pyrite is initially oxidized by O_2, resulting in the release of Fe^{2+}, $SO_4{}^{2-}$, and H^+ (Eq. (1)). In the presence of atmospheric O_2, Fe^{2+} is subsequently oxidized to Fe^{3+} (Eq. (2)), which significantly accelerates the oxidative dissolution of more pyrite and AMD acidification and further leads to the solubilization of associated trace metals into pore waters (Eq. (4)). In this reaction, Fe^{3+} dissolved in acidic solutions becomes the dominant natural oxidant (Singer and Stumm 1970). Fe^{3+} is precipitated as ferric hydroxides (given as Fe $(OH)_3$), while additional H^+ is simultaneously generated (Eq. (3)), which typically depends upon pH values of the systems. Due to the presence of iron oxide precipitates, the oxidation zones of the tailing impoundments are usually recognizable by its yellow-reddish color. It is noteworthy to mention that pyrite oxidation involves spontaneous and microbial-mediated reactions, where the final weathered products are not fully illustrated in formulas (Bao et al. 2018). The overall process is extensively represented by the following reaction (Eq. (5)):

$$FeS_{2(s)} + \frac{15}{4}O_{2(g)} + \frac{7}{2}H_2O_{(l)} \rightarrow 2SO_4^{2-}{}_{(aq)} + Fe(OH)_{3(s)} + 4H^+{}_{(aq)} \quad (5)$$

Under AMD environment, the rate of Fe^{2+} oxidation is quite slow and is identified as the rate-limiting step of the overall reaction (Hao et al. 2017). However, acidophilic chemolithotrophic microorganisms, growing optimally in extremely acidic conditions, can greatly promote the oxidation of Fe^{2+} to Fe^{3+} (Gleisner et al. 2006; Diaby et al. 2015). It is reported that, in the existence of acidophilic bacteria like *Acidithiobacillus ferrooxidans*, the oxidative rate is orders of magnitude faster than that of the previous reaction with pH below 3.5 (Anawar 2015). It has also been noted that microbially enhanced oxidation plays an active role in the precipitation of secondary weathered minerals, characterized especially by jarosite, schwertmannite ($Fe_{16}(OH,SO_4)_{12}$-$13O_{16}\cdot 10$-$12H_2O$), and some iron-bearing secondary minerals, such as hematite (Fe_2O_3), goethite (α-FeOOH), and lepidocrocite (γ-FeOOH) (Nieva et al. 2019).

The presence of neutralizing carbonates minerals like calcite and dolomite is able to neutralize the strong acidity generated by the oxidative weathering of pyrite in tailings. Gypsum is another typical secondary weathering product and also key cemented mineral. The mineralogical transformation of Ca-bearing carbonates to gypsum by consuming H^+ occurs by the following reaction (Lindsay et al. 2015; Liu et al. 2018a):

$$CaCO_{3(s)} + H_2SO_{4(aq)} + H_2O_{(l)} \rightarrow CaSO_4{\cdot}2H_2O_{(s)} + CO_{2(g)} \quad (6)$$

$$\frac{1}{2}CaMg(CO_3)_2 + H_2SO_{4(aq)} + \frac{9}{2}H_2O_{(l)} \rightarrow \frac{1}{2}MgSO_4{\cdot}7H_2O_{(s)} + \frac{1}{2}CaSO_4{\cdot}2H_2O_{(s)} + H_2CO_{3(aq)} \quad (7)$$

Geochemical properties of AMD

The geochemical properties of AMD vary with tailing types. Table 1 summarizes the recent case studies regarding the geochemical characteristics of AMD in metal mines worldwide. As clearly presented in Table 1, low pH values, elevated concentrations of sulfate ions (SO_4^{2-}), dissolved iron (Fe), manganese (Mn), aluminum (Al), and various trace metals such as cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn), and arsenic (As) are typically characteristic for AMD.

Environmental implications of AMD

In China, most metal mines are sulfide ore deposits (Chen et al. 2018). As a consequence, AMD pollution in mining areas resulting from the continuous weathering and oxidation of exposed sulfide tailings is of considerable concern. It can be expected that the resulting oxidative dissolutions of various sulfide minerals, such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), sphalerite (ZnS), and galena (PbS), are potential sources of released trace elements (Lindsay et al. 2015). Reich et al. (2013) documented that pyrite commonly hosts significant concentrations of toxic accessory elements, including Ni, Co, Cu, Pb, Zn, As, Sb, Se, Te, Hg, Tl, Bi, Au, and Ag. Furthermore, untreated AMD in tailing deposits significantly enhances the leaching, dissolution, and mobility of trace elements born in tailings and in turn has long-lasting detrimental effects on the nearby environmental media. For instance, Zhang et al. (2018) concluded that contamination of Anshan mine tailings and associated transportation are the principal sources of Cr, Cd, Cu, Zn, and Pb released to the soil environment. From this perspective, an increasing concern from mine tailing deposits is the migration and mobilization of large amounts of toxic heavy metals towards their surrounding areas, which are ecologically unacceptable to mine operators and environmental protection authorities.

As sulfide oxidation progresses, the cemented layers will widely develop on the surface of both fresh and aged sulfide tailings, which are hereafter referred to as crusts or even hardpans (Stumbea et al. 2019). These hardpan layers are typically comprised of primary and secondary mineral phases, as well as adsorbed heavy metals. In addition, various secondary minerals may precipitate within the oxidized tailings, with the most common being Fe(III) oxyhydroxides, Fe(III) hydroxysulfates, and gypsum (Kohfahl et al. 2010). On the one hand, the appearance of this oxidized layer may limit pore-water migration and oxygen ingress, and their barrier

Table 1 pH, SO_4^{2-}, and metal concentrations measured in AMD at metal mines worldwide

Countries	Mines	pH	SO_4^{2-}	Mn	Fe	Al	As	Cd	Cu	Pb	Zn	References
Spain	Poderosa	2.41	7532	–	1052	532	1257	362	96,870	130	60,510	Torres et al. (2018)
Spain	Lagunazo	2.38	26,238	76.93	10,210.65	1935.22	63,841	1064	403,003	–	391,841	Viers et al. (2018)
Spain	Almagrera	2.98	–	881.2	2230.6	627.6	14,290	2707	398,200	12.5	2,074,500	Macias et al. (2017)
America	Williams Brothers	3.9	100.67	1.23	4.6	–	6	–	74	–	133	Clyde et al. (2016)
Korea	Yongdong	2.41	–	10.35	137.48	–	450	270	22,780	NA	19,770	Choi and Lee (2015)
Poland	Wiśniówka	3.0–3.4	575	1064	9.1	18.9	15.1	0.52	1923	0.68	213	Migaszewski et al. (2016)
Germany	Ronneburg	3.8	5957	93.4	57.8	88.2	–	63	1397	0.5	4431	Grawunder et al. (2014)
Germany	Königstein	2.86	767	3.73	20.7	16.8	< 10	56.3	< 10	273	6450	Krawczyk-Bärsch et al. (2011)

The concentration units of SO_4^{2-}, Mn, Fe, and Al were given in milligrams per liter, and the concentration units of As, Cd, Cu, Pb, and Zn were given in micrograms per liter. "–" means not reported effects further inhibit the exposure of metal sulfides to oxygen within un-weathered tailings (Liu et al. 2018a). On the other hand, the newly formed hardpans may act as temporary sinks for polymetallic pollutants released through AMD (Blowes et al. 1991; Bao et al. 2018). The latter can slowly reduce the mobility of contaminative elements through natural attenuation mechanisms, such as re-adsorption, co-precipitation, and substitution (Liu et al. 2018b). This implies that in AMD systems, the secondary weathered minerals can exert a profound impact on the distribution pattern and potential mobility of hazardous trace metals released from tailings and largely control their potential environmental risks (Chen et al. 2018; Ouyang et al. 2019). Nevertheless, the AMD precipitates are generally unstable because of poor crystallinity and being highly soluble in acid waters (Chen et al. 2018; Liu et al. 2018b). As a result, once physico-chemical changes happen to AMD, toxic elements adsorbed in hardpans are most likely to be released into the surrounding water bodies. In light of these facts, a conceptual illustration of identified geochemical weathering mechanisms within mine tailings, commonly related to the mineralogical, geochemical, and sedimentological status, is summarized in Fig. 1. It is expected that the favorable mechanisms might be found from geochemical evolution, which would guide the local authorities to take remedial actions.

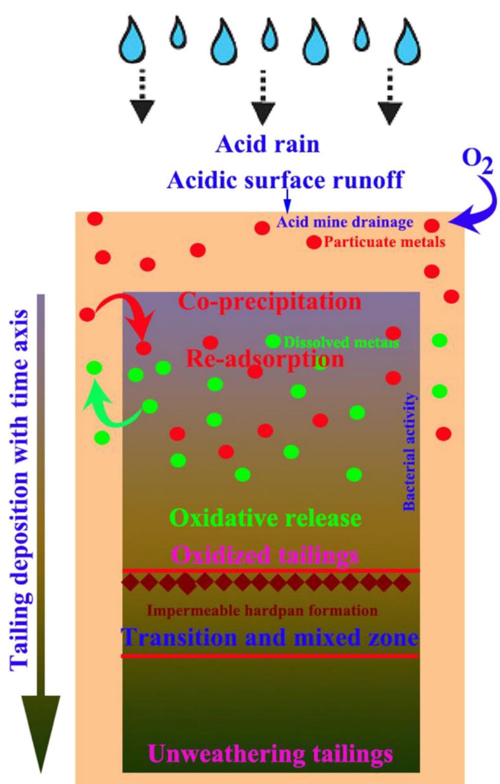

Fig. 1 Conceptual diagrams illustrating the geochemical evolution of metal sulfide tailings (modified from Chen et al. 2018 and Elghali et al. 2019)

Recycling strategies of mine tailing resources

To date, the main treatment methods for huge amounts of mine tailings are their reuse as cemented paste backfill (CPB) in open pits or underground mines and storage in tailing impoundments, aimed at improving the current tailing management at mine sites (Qi et al. 2018; Yao et al. 2019). For example, Lu et al. (2018) investigated that a new backfill procedure was applied to an engineering instance, Shirengou Iron Mine, Hebei province, China, where the recovery efficiency of waste tailings were 100%. In another related study, Sun et al. (2018) presented an approach where mining solid wastes such as tailings and rocks were utilized to prepare a paste for backfilling the subsidence areas and preventing secondary disasters. Ercikdi et al. (2015) and Lu et al. (2018) have also reported recycling waste tailings as CPB as an ideal option of tailing disposal, which can significantly facilitate cleaner and safer production in the mining industry worldwide. At present, several acceptable approaches of resources recycled from mine tailings, reported in most previous studies, are as the following: recovery of useful minerals and metals, production of economical building materials, and preparation of soil modifier and agricultural fertilizer (Li et al. 2010; Yin et al. 2018a, 2018b). In practical terms, these recycling strategies have positive effects on reducing the burden of tailings discharged, with the additional benefits of protecting precious resources, saving energy consumption, and minimizing security risks.

There has been an effort throughout the world to come up with proper strategies for decreasing the volume of mine tailings and increasing the associated economic benefits (Ahmari and Zhang 2012). It is reported that the utilization of tailings in China has been increasing from 13.3 % in 2013 to 28.9 % in 2015 (Lv et al. 2019). However, despite these efforts, the rates remain far lower than the average rates in developed countries (Shettima et al. 2016).

Recovery of precious metal resources

Tailings was defined as valuable metal stocks in the technosphere by Johansson et al. (2013), indicating that reprocessing might also be categorized into an innovative reclamation technology. There are various types of mine tailings discharged, including iron, gold, copper, manganese, lead-zinc, vanadium, rare earth, and platinum tailings (Abraham and Susan 2017; Galvão et al. 2018; Gandarillas et al. 2019; Yang et al. 2003). Thus, there have been significant interests in studying and developing technically feasible and environmentally acceptable technologies for metal recovery from different types of mine tailings. These technologies include, but are not limited to, the following representative technologies: acid leaching, bioleaching, and magnetic separation. Recently, studies have demonstrated that effectively recovering rare, precious, and strategic metals from mine tailings is feasible (Lan et al. 2019; Zhang et al. 2019). A considerable number of studies have been focused on valuable metal resources recycled from various types of mine tailings, as summarized in Table 2. As suggested by incomplete statistics, the typical amount of Au in gold tailings ranges between 0.2 and 0.6 g/t, the Fe grade of iron tailings ranges from 8 to 12 %, Cu concentration in copper tailings varies from 0.02 to 0.1 %, and the amount of Pb and Zn accounts for 0.2–0.5 % of lead and zinc tailings (Zhang 2012). In the near future, it in particular is of concern to evaluate the metal recovery potential from mine tailings through the investigated amounts and grades of the valuable metals in combination with metallurgical test work campaigns (Yin et al. 2018a, 2018b).

Production of building materials

As shown in Table 2, mine tailings are rich in various major elements such as Si, Ca, Mn, Fe, and Al and their main phase composition is carbonate, silicate, and quartz. In comparison with common building materials, tailings have similar physico-chemical, compositional, and mechanical characteristics in industrial application. In recent decade, more industrial researches are required to develop technical and economic routes that tailing materials are used to produce building materials (Onuaguluchi and Eren 2016). As summarized in the recent advances (Table 3), different types of mine tailings have been utilized as alternative raw materials to produce environmentally friendly building materials, such as bricks, concrete, ceramics, glass fibers, and paint.

Preparation of agricultural fertilizer

Mine tailings contain abundant various trace elements such as B, V, Mn, Cu, Zn, Fe, Mo, and P, which are essential micronutrients for plant growth and soil supplements (Zhang et al. 2009). As a result, there has been an increasing expectation that mine tailing can be reprocessed as various microelement fertilizers (Guo et al. 2009). Hu et al. (2017) have reported that low-release silicon fertilizers were prepared from iron tailings using solid-phase sintering, whose available SiO_2 was far greater than current Chinese agricultural standard for silicon fertilizers, and where trace elements would improve the growth of pakchoi. It is noteworthy that, unlike organic fertilizer, agricultural fertilizers prepared from tailings cannot be easily decomposed and meanwhile have insufficient fertility. To our knowledge, no other similar reports are found in Web of Science. It can be seen that recycling and reusing tailings as raw fertilizer materials are of great difficulty using new technical approaches, because the operational costs and technical difficulty will be significantly increased, and the successful industrial application is also greatly limited.

Ecological reclamation of tailing impoundments

Appropriate and cost-effective ecological rehabilitation at metal mines is an important measure for building green mines and also an important ecological practice to follow the green development concept. In comparison with traditional physical-chemical methods, phytoremediation, which might be a promising bioremediation technique, proves to be an eco-friendly and potentially cheap remediation strategy. This biological method has sparked renewed interests, because it is an adequate option for the in situ rehabilitation of highly polluted sites (Wei et al. 2019). Phytoremediation removes the pollutants without affecting soil aggregations, thus improving soil fertility and increasing organic matter and nutrient content for later uses (Salt et al. 1995; Álvarez-Mateos et al. 2019). However, compared with other common treatment procedures, phytoremediation has some drawbacks, such as slow growth rate of plant species and low bioavailability of heavy metals (Ashraf et al. 2019; Li et al. 2019a, 2019b). During the past decades, phytoremediation has often been carried out for rehabilitating tailing landscapes, in combination with multidisciplinary studies (Jia et al. 2017; Acosta et al. 2018; Hammond et al. 2018). As an example, Gil-Loaiza et al. (2018) found that the phytoremediation field trial at the Iron King Mine and Humboldt Smelter Superfund site could significantly decrease dust emissions and metal transport from mine tailings. Furthermore, mine spoil dumpsites and acid-generating tailings are widely regarded as an extreme and challenging case for rehabilitation, primarily as a result of nutritional deficiency, poor physical structure, and high levels of heavy metals, which inhibit natural plant growth (Wang et al. 2017). At the same time, the scarcity of natural top soils to reconstruct functional root system for vegetation establishment severely limits the rehabilitation progress of mine tailings (Wu et al. 2019). For this reason, proper measures should be proposed to improve the physical, chemical, and biological properties of mine tailings to enhance the colonization of plants and their metal accumulation capacity.

The concept of phytoremediation

Phytoremediation is mainly subdivided into phytovolatilization, phytostabilization, and phytoextraction, depending on different plant properties (Wang et al. 2017). The advantages and disadvantages of different phytoremediation types are given in Table 4. Phytovolatilization is the uptake of metal pollutants by plants, followed by their translocation into the aerial parts and then their release from plant foliage (Leguizamo et al. 2017). Phytostabilization is to immobilize toxic metals via sorption,

Table 2 Summary of the latest works on metal recovery methods of mine tailings

Tailing type	Chemical compositions (wt %)	Primary mineral phases	Recovery methods	Results	References
Iron tailings	SiO_2 (47.39), Fe_2O_3 (24.82), CaO (8.85), Al_2O_3 (7.42), MgO (0.097), Na_2O (0.32), K_2O (0.70), LOI (10.40)	Quartz, hematite, calcite, mica, and kaolinite	Magnetizing roasting process followed by magnetic separation	Under the optimum parameters, the Fe grade of magnetic concentrate was 61.3% and the recovery rate of iron minerals was 88.2%.	Li et al. (2010)
Gold tailings	Au (5.625 g/t), Ag (49.94 g/t), TFe (27.69), SiO_2 (23.9), Al_2O_3 (6.35), B_2O_3 (3.96), SO_3 (5.37), CO_2 (23.5), CaO (2.61), Na_2O (1.79), K_2O (1.41), MgO (0.848), PbO (0.513), TiO_2 (0.531), ZnO (0.510)	Hematite, quartz, and muscovite	A combination method of reduction roasting-water leaching process-magnetic separation	Under the proposed conditions, the grade of magnetic concentrate was 59.11% Fe, and recovery rate was 75.12%.	Zhang et al. (2012)
Manganese tailings	Al (5.49), Na (0.5224), Ca (2.44), S (0.6892), Si (30.4), Fe (4.72), K(0.621), Ti (0.2079), Mg (1.54), Mn (24.76)	Rhodochrosite, spessartine, quartz, birnessite, vermiculite, manganocummingtonite, and annite	Leaching with sulfuric acid	Under the optimized method, the average recovery of Mn was 95.5%.	Santos et al. (2015)
Platinum tailings	SiO_2 (17.4), Al_2O_3(12.2), Fe_2O_3 (23.3), Cr_2O_3(31.9), MgO (13.6), MnO (0.3), CaO (2.5)	Spinel group minerals, orthopyroxene, plagioclase, amphibole, and several alteration minerals, such as chlorite, talc, and serpentine	Thermochemical treatment followed by aqueous dissolution	The greatest extraction efficiencies were obtained for 60% Al and 80% Ca, and 35% Fe, 32% Si, 27% Cr, and 25% Mn were also extracted.	Mohamed et al. (2016)
Copper tailings	Cu (0.34), Fe (8.96), Al (8.12), S (11.2), SiO_2 (57.8)	Quartz, pyrite, kaolinite, and chalcopyrite	A combination method of flotation-high pressure leaching-solvent extraction	Under the optimal conditions, 91.3% Cu was dissolved into a stripped solution, whereas 98.6% Fe was removed.	Han et al. (2018)
Lead-zinc tailings	Ag (56.33), Ga (117.6 g/t), Fe (9.54), Pb (1.09), Zn (0.57), Mn (0.13), Si (14.79), Al (3.83), Ca (6.81), Mg (0.51), Na (2.74), K (2.79)	Quartz, magnetite, and calcite	Roasting followed by chloride leaching	At a roasting temperature of 900 °C and with the optimized leaching conditions, 9.98 mg/L for Ag, 18.62 mg/L for Ga, and 1506.12 mg/L for Pb in leaching liquor could be recovered.	Lei et al. (2018)
Rare-earth tailings	CaO (17.34), P_2O_5 (9.63), Fe_2O_3 (9.09), SO_3 (4.93), F (13.31), SiO_2 (1.09), MgO (3.46), BaO (1.59), MnO (0.37), Ce_2O_3 (23.42), La_2O_3 (11.84), Pr_6O_{11} (1.09), Nd_2O_3 (2.84)	Bastnaesite, monazite, and fluorite	Super gravity	98.38% Ce were firstly enriched into the rare earth oxyfluoride, 97.70% La were then enriched into the rare earth ferrate, and finally, the residual REEs were precipitated into britholite, respectively.	Lan et al. (2019)
Vanadium tailings	V (1.71), TFe (23.72), CaO (9.30), TiO_2 (9.67), Mn (3.25), Cr_2O_3 (2.33), MgO (2.44), Al_2O_3 (1.94), SiO_2 (12.12), P (0.02)	Calcium sulfate dihydrate, pseudobrookite, ferric oxide, and carmichaelite composed mainly of V, Fe, Ti, Cr, Mg, and Al	Pressurized leaching	Under the optimum conditions, 91.7% V, 60.1% Fe, and 46.5% Ti were recycled, and only 0.13% vanadium is remained in the leach residue.	Zhang et al. (2019)

precipitation, or complexation of plant's root systems and further reduce their bioavailability in the environment (Shim et al. 2013). Among these, phytoextraction is a widely applicable option of tailing reclamation, since this mechanism transports and concentrates metal pollutants into the aerial harvestable parts (Tang et al. 2019; Mahar et al. 2016). However, after harvest, the safe disposal of metal-enriched biomass of plants is quite challenging.

Combined techniques used for phytoremediation purposes

It should be noted that one reclamation method is on its own insufficient for rehabilitation, due to some limitations and weakness (Wang et al. 2017). Hence, phytoremediation is often combined with one or more of other traditional approaches to make it more effective, considering the extreme physical

Table 3 Environmentally friendly materials produced from mine tailings and their performances

Raw materials	Products	Physical properties	Future suggestions	References
Iron tailing, silicon sand, cement, quicklime, and calcium sulfate dihydrate	Autoclaved aerated concrete (AAC)	Under the optimal conditions, the bulk density of AAC was between 490 and 525 kg/m^3, with specific strength higher than 4700 N m/kg and compressive strength higher than 2.5 MPa.	It was feasible for manufacturing AAC blocks made of iron tailing.	Ma et al. (2016)
Lead-zinc tailings and fly ash	Inorganic porous ceramics	The porous ceramics, added 60 wt% of fly ash, exhibited excellent properties, such as bulk density of 0.93 g/cm^3, flexural strength of 11.9 MPa and porosity of 65.6%.		Liu et al. (2017)
Iron tailings, the curing agent system (fly ash, lime, and gypsum), and two admixtures (stearic acid emulsion and triethanolamine)	Eco-friendly bricks	The water resistance and compressive strength of the resulting brick were optimal, when an initial curing temperature was 60 °C with 0.3 wt% of the waterproofing and curing agent. For the unfired bricks made from tailings, the product met the Chinese JC/T422-2007 standard.	① The dissolving process conditions of the stearic acid emulsion could be further improved based on its water resistance mechanism. ② More comprehensive analysis regarding brick properties should be carried out. ③ The application range of this curing technology should be further expanded.	Li et al. (2018)
Gold tailing, red mud, waste limestone and ferronickel slag	Continuous glass fibers	Fiber-forming temperature of the product was in the range of 1466 K–1503 K, and viscosities and Young's modulus were log 2.5-log 3.0 dPas and 60 GPa–80 GPa, respectively.	The mining waste and smelting byproducts is applicable to produce for continuous glass fiber production.	Kim et al. (2018)
Titanium tailing, glass waste, sodium carbonate, diboron trioxide and ethyl alcohol	Glass-ceramic foams	Under the optimal preparation parameters, the glass-ceramic foam has a low apparent density of 0.30 ± 0.01 g/cm^3, with the compressive strength of 1.0 ± 0.1 MPa, the high porosity of 88.0%, the thermal expansion coefficient of 5.27×10^{-6} m/m/°C and the thermal conductivity of 0.060 ± 0.002 W/m/°C.	The product could be widely applied in building and construction industry.	Xi et al. (2018)
Iron tailings and four types of binders (polyvinyl acetate, high early strength Portland cement, acrylic resin, and hydrated lime)	The sustainable paint	The sustainable paint showed reddish color and suitable opacity, with some satisfactory results such as excellent coverage, abrasion, and weather resistance.		Galvão et al. (2018)
Copper tailings	Supplementary cementitious material	Under the optimal treatment levels, the mechanical performance of tailings could be improved by up to 40% at 90 days.	① The cementitious and pozzolanic should be further improved. ② The advanced characterization of the tailing should be carried out. ③ The other properties of the mortar and concrete should be studied.	Vargas and Lopez (2018)
Gold tailing and red mud	High porosity brick	The apparent porosity of brick was over 75%. And the increasing concentrations of gold tailing resulted in the increasing of both pore diameter and thermal conductivity.	The optimal mixing conditions of slurry should be investigated for the application to refractory and filtration systems.	Kim et al. (2019)

and environmental characteristics of tailing impoundments. In most recent cases, phytoremediation is generally assisted with common remediation techniques, namely soil amelioration, microbiological inoculation, as well as biogenetic engineering, which are conducive to provide an appropriate substrate for reducing heavy metal bioavailability, as well as increasing metal-accumulated plant biomass (Shim et al. 2013; Babu et al. 2014; Li et al. 2019a, 2019b). Some case studies of tailing phytoremediation, in conjunction with some assisted approaches, are presented in Table 5. Regarding future remediation challenges of mine tailings, plant-based remediation technologies may be the most potentially promising and effective method in metal mining areas, which have increasingly become an international research hotspot.

Table 4 Advantages and disadvantages of three phytoremediation types (Odoh et al. 2017; Leguizamo et al. 2017)

Phytoremediation types	Advantages	Disadvantages
Phytostabilization	Reducing the environmental risk associated with heavy metal pollution.	It cannot completely remove metal pollutants. And they may still be reactivated and further enter the recycling system, when the environment changes.
Phytoextraction	Being suitable for the rehabilitation of shallow soil layer slightly polluted by heavy metals.	Hyperaccumulators have small biomass and short growth cycles, and is hard to be harvested.
Phytovolatilization	Not necessary to harvest metal–enriched non-edible parts and often applied to volatile metal pollution, such as arsenic (As), mercury (Hg), and selenium (Se).	Its application range is relatively limited. In addition, volatile metals, present in gaseous form in the environment, can be absorbed back into the ecosystem through natural precipitation, and thus cause secondary pollution.

Role of amelioration in phytoremediation

Phytoremediation efficiency can be accelerated with the assistance of inorganic and organic ameliorations. These ameliorations can reduce the mobility of heavy metals, increase the biomass yield of plants, and also ameliorate the condition stress of polluted sites. For example, Yu et al. (2019) reported that Mn remediation efficacy by *Polygonum pubescens* was enhanced in the unexplored soil, mining soil, and tailing soil, with the chemical chelate (EDTA) treatments. This was because the application of EDTA greatly increased the water-extractable Mn content in all three soils. Another study carried out by Beauchemin et al. (2018) indicated that the application of oxygen-consuming organic covers for 4 to 5 years could greatly enhance tailing rehabilitation, because they reduced the water-soluble metals and increased nutrient and organic carbon contents in the oxidized Cu-Ni pyrrhotite tailings, while improving the microbial activity and diversity. In addition, Gandarillas et al. (2019) demonstrated that either pig slurries or their solid organic fractions that were incorporated into copper tailings significantly increase organic matter and nutrient contents in tailings, as well as the productivity and Zn accumulation of ryegrass.

Role of biogenetic engineering in phytoremediation

Recent results have shown that transgenic plants have gradually become an attractive candidate for increasing phytoremediation efficiency, due to their excellent performance regarding significant metal accumulation (Rizwan and Ali 2018; Rostami and Azhdarpoor 2019). For instance, Shim et al. (2013) suggested that after being transformed with heavy metal resistance gene (ScYCF1), poplar trees planted in mine tailing soil under greenhouse increased the accumulated amounts of Cd, Zn, and Pb in the root due to their enhanced root systems, in comparison with the non-transgenic plants. In addition, an early study performed by Bennett et al. (2003) also reported that all three types of transgenics significantly reduced the metal concentrations of tailing soil, in amounts ranging between 6% for Zn and 25% for Cd of the total soil metal content, and confirmed the importance of metal-binding peptides for the enhanced metal tolerance of plants.

Role of microorganisms in phytoremediation

It was confirmed that some species of plants can form mutualistic associations with selected bacterial or fungi strains for phytoremediation enhancement (Deng and Cao 2017; Li et al. 2019a, 2019b). It was reported that the symbiotic association among *Setosphaeria rostrata*, arbuscular mycorrhiza fungi (AMF), and *rhizobia* greatly increased *S. rostrata* plant uptake of uranium in uranium contaminated soils and its biomass (Ren et al. 2019). AMF could improve plants resistance to heavy metals, followed by sequestrating them between the mycorrhizosphere and the mycorrhizal roots (Chen et al. 2004). In addition, AMF hyphae could also alter the soil microbial community to increase the tolerant capacity of plants to environmental stress (Chen et al. 2019; Li et al. 2019a, 2019b). According to Yu et al. (2017), inoculating *P. pinnata* with rhizobia strain ($PZHK_1$), isolated from the V-Ti magnetite tailing soils, greatly promoted the translocation of Fe, Ni, and Cu to shoots. It has been argued that *P. pinnata* formed an effectively nitrogen fixing nodules with rhizobia, and this symbiotic association increased the biomass production of plants and its stress tolerance to metals (Arpiwi et al. 2013; Yu et al. 2017).

Plant species for phytoremediation

It is being increasingly recognized that identification and selection of suitable native wild plant species from metal-contaminated areas for planting on mine tailings is an effective route to meet the objectives of phytoremediation (Haque et al. 2008; García-Carmona et al. 2019). Qian et al. (2018) investigated 259 wild plants from the Wanshan District, eastern Guizhou Province, China, and proposed *Erica ciliaris* and *Acromyrmex hispidus* as potential candidates for phytoremediation of Hg mining-polluted soils. Likewise, Midhat et al. (2019) conducted a botanical survey in three abandoned mining sites in Morocco, and eight plants are found to be the suitable candidates for phytostabilization

Table 5 Phytoremediation techniques of mine tailings with assisted remediation measures in case studies

Enhanced phytoremediation	Supplementary materials	Plant species	Results and future suggestions	References
Genetic engineering of plants for phytoremediation	Glandulosa with a metal resistance gene, ScYCF1, was introduced into non-flowering poplar	Poplar	The transgenic plants might be useful for phytostabilization and phytoattenuation especially in highly contaminated areas.	Shim et al. (2013)
Phytoremediation together with microbiological inoculation	Metal-tolerant fungi (*Penicillium aculeatum* PDR-4 and *Trichoderma* sp. PDR-16)	Sorghum-sudangrass	Metal-tolerant, plant growth–promoting fungi, such as PDR-4 and PDR-16, were selected for the remediation of mine tailing sites and production of bioenergy crop.	Babu et al. (2014)
Phytoremediation together with microbiological inoculation or soil amelioration	Soil amendments ($CaCO_3$ and compost) and arbuscular mycorrhizal fungi	*Prosopis tamarugo*, *Schinus molle*, and *Atriplex nummularia*	Atriplex nummularia could be proposed as the most promising species for phytostabilization of Cd in tailings.	Lam et al. (2017)
A combination method of soil improvement, agronomic techniques, and phytoremediation	Soil amendments (marble waste and pig slurry) and surface tillage	*Atriplex halimus*	*A. halimus* was not able to phytostabilize metals in tailings, especially Pb and Cd. And some factors, having effects on phytoremediation, should be further studied.	Acosta et al. (2018)
The combined application of soil amelioration, microbiological inoculation, and phytoremediation	Soil amendments (organic fertilizer, rice husk, biochar, and ceramsite) and microorganisms (*Mucor circinelloides*, *Trichoderma asperellum*, and *Mortierella* sp.)	Soybean, rainbow pink, Kochia	The best options for phytoremediation was recommended as the combination effects of amendments (organic fertilizer:rice husk:biochar:ceramsite = 1:1:2:1), *M. circinelloides*, and soybean.	Li et al. (2019b)
Phytoremediation together with soil amelioration	Organic carbon	*Maireana brevifolia*	Eco-engineering inputs like organic carbon accumulation and the introduction of functional microbes and pioneer plants were together proposed.	Wu et al. (2019)

of mining sites due to their much higher ability to accumulate metals. Plant species for bioremediation should be extremely tolerant to a wide range of adverse growth conditions of the metal-impacted regions, such as high concentrations of toxic heavy metals, as well as variations in humidity, salinity, acidity, and temperature at site-specific systems. Besides that, the plants should be abundant in the specific areas and able to grow rapidly, develop an extensive root system, and produce large biomass (Shi et al. 2017). As described by Baker et al. (1981), metallophytes, termed hyperaccumulators, are currently recognized as the most ideal and attractive plants, due to their tolerance mechanisms that enable them to accumulate extremely high levels of heavy metals in their shoots rather than roots. However, there is a crucial consideration that the slow growth and low biomass yields of most hyperaccumulators are limiting factors of the remediation efficiency. Furthermore, plants obtained from harsh conditions are often performed better than those introduced from non-polluted areas, in terms of survival, growth, and reproduction (Yoon et al. 2006). As a consequence, studies on investigating native pioneer plant species in highly metal polluted areas, understanding their metal accumulation patterns, and evaluating their potential use have been performed by many scientists (Yoon et al. 2006; Qian et al. 2018).

Summary and future perspectives

Large amounts of abandoned tailings generated from different types of mines have resulted in a series of society, economy, resource, and environment-related concerns. This critical review underscores (i) AMD pollution and associated environmental implications, (ii) recycling strategies of tailing resources, (iii) ecological reclamation of tailing. AMD remains quite challenging due to its typically geochemical characteristics. AMD formation has crucial implications on the natural reduction of potential pollution risks. In addition, the current recycling strategies of tailing resources for different industries are described. Nevertheless, little information can be found regarding tailings utilized as microelement fertilizers. Finally, this review indicates that the combination of phytoremediation and other traditional techniques such as amelioration, genetic modifications, and biostimulation-assisted phytoremediation, can increase reclamation efficiency. Overall, this review shows that tailing management with related restoration efforts is of great importance to all countries worldwide.

More knowledge is needed on possible management strategies designed to prevent AMD generation for the mitigation of potential health threats. Moreover, the secondary exploration targets for mining industries will focus on the research and development of innovative and modern technologies, which are universal, suitable, and cost-effective for different tailing types to improve the utilization, while ensuring economic financial returns. In addition, future work on health risk assessment of population exposure to various types of hazardous tailings must be considered for remediation potential of tailing impoundments. Subsequently, how to combine multidisciplinary approaches and various restoration technologies to enhance the phytoremediation efficiency of tailings is an important direction. There is a crucial consideration that the tolerant capacity of ideal plants to metals is influenced by the combined effects of geochemical and environmental characteristics at tailings impacted sites. It is therefore important to identify the quantitative relationships between multiple factors and metal-accumulated amounts of plants using mathematical statistics.

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