Rev Environ Sci Biotechnol (2016) 15:327–354
DOI 10.1007/s11157-016-9398-6

REVIEW PAPER

Abandoned metalliferous mines: ecological impacts and potential approaches for reclamation

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Published online: 12 May 2016

Abstract The lack of awareness for timely management of the environment surrounding a metal mine site results in several adverse consequences such as rampant business losses, abandoning the bread-earning mining industry, domestic instability and rise in ghost towns, increased environmental pollution, and indirect long-term impacts on the ecosystem. Although several abandoned mine lands (AMLs) exist globally, information on these derelict mines has not been consolidated in the literature. We present here the state-of-the-art on AMLs in major mining countries with emphasis on their impact towards soil health and biodiversity, remediation methods, and laws governing management of mined sites. While reclamation of metalliferous mines by phytoremediation is still a suitable option, there exist several limitations for its implementation. However, many issues of phytoremediation at the derelict mines can be resolved following phytostabilization, a technology that is effective also at the modern operational mine sites. The use of transgenic plant species in phytoremediation of metals in contaminated sites is also gaining momentum. In any case, monitoring and efficacy testing for bioremediation of mined sites is essential. The approaches for reclamation of metalliferous mines such as environmental awareness, effective planning and assessment of pre- and post-mining activities, implementation of regulations, and a safe and good use of phytostabilizers among the native plants for revegetation and ecological restoration are discussed in detail in the present review. We also suggest the use of microbially-enhanced phytoremediation and nanotechnology for efficient reclamation of AMLs, and identify future work warranted in this area of research. Further, we believe that the integration of science of remediation with mining policies and regulations is a reliable option which when executed can virtually balance economic development and environmental destruction for safer future.

Keywords Abandoned metal mines · Heavy metal pollution · Reclamation · Phytoremediation · Phytostabilization · Soil health

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1 Introduction

With the turn of the millennium, many countries realized that historic metal mining operations are one of the major contributors of severe degradation of the environment (Sheoran et al. 2010). The fact is that the mines themselves have limited lives, the ore expires and the mining becomes no longer cost-effective resulting in abandoning them as waste sites. Abandoned mine lands (AMLs) are therefore referred to as 'areas or sites of former mining activity for which no single individual, company, or organization can be held responsible', and such sites are also known as 'derelict' or 'orphan' mines (www.mrt.tas.gov.au). Most mines that operated earlier and around late sixteenth century are the open sources of pollutants today (Kossoff et al. 2016) as there were no proper laws binding the mining operations. Hence with the passing of time, land leases lapsed, records were lost and the original ownership of the mines became unclear. Though now abandoned, the legacy of the mining era remains in the form of river and floodplain sediments grossly polluted with metals (Yenilmez et al. 2011). Accessible adits, shafts and workings at the abandoned mine sites form the hazards to human and animal life (Kim et al. 2016). In the absence of remediation, mines after their closure impact the environment by contaminating air, water, soil, and wetland sediments from the scattered tailings as well as pollution of groundwater by discharged leachate (Laurence 2011; Bacchetta et al. 2015). Persisting erosion of AMLs can affect land stability, revegetation efforts and water quality. Thus, mining causes substantial damage to the environment worldwide although it is an important economic activity.

Even when the mining activities cease, the impacts onsite and offsite continue as a consequence of which all the surrounding compartments of the ecosystem (adjacent vegetation, soils, groundwater, etc.) are exposed to very high concentrations of heavy metals (Pereira et al. 2004; Ji et al. 2011; Khalil et al. 2013). Potentially toxic heavy metals present in the tailings or 'spoils' of abandoned mines migrate to the surroundings and cause severe and widespread contamination of farmland soils and water bodies including the geo-environment disasters (Wong 2003; Beane et al. 2016; Ma et al. 2016). Another endemic problem with abandoned and derelict mines is the generation of large-scale acidic waters containing elevated concentrations of metals and metalloids (Clarke 1995; Naidu et al. 2013). The toxic metals can be dispersed in the vicinity of AML and accumulated in plant and animal bodies as a result of direct or indirect consumption (Nouri and Haddioui 2016). Typically, a mine degraded wasteland comprises of stripped areas (59 %), open-pit mines (20 %), tailing dams (13 %), waste tips (5 %), and land affected by mining subsidence (3 %) (Miao and Marrs 2000), but the spread of pollutants is continuous. Faced with such an expense, many mining companies realized that in the absence of proper legislations it was cheaper to simply abandon their mines rather than to remediate. However, modern mines are operated in accordance with the 'best practices' and government regulation of both exploration and mining (Davis and Duffy 2009; Laurence 2011).

Several papers concerning problems of mined tailings and waste, and contamination of soil, groundwater and sediment have been published (Donahue et al. 2000; Williams 2001; Aykol et al. 2003; Megharaj et al. 2011; Yenilmez et al. 2011; Khalil et al. 2013; Kossoff et al. 2016; Ma et al. 2016). Some studies have focused on the effects of surface mining and the mobilization of heavy metals (Bhuiyan et al. 2010; Rashed 2010; Ciszewski et al. 2012), and have often revealed a high degree of metal toxicity in mine spoils and soils affected by the oxidation of pyritic material (Pérez and de Anta 1992; Taylor et al. 1992, 1993; Monterroso et al. 1999; Clark et al. 2001; Iavazzo et al. 2012). However, information on the occurrence of AMLs all over the world together with the pollution database is not available in the form of a comprehensive review. In this context, we present here the current scenario on global occurrence and ecological implications of AMLs, and discuss about the potential approaches for their reclamation.

2 Worldwide occurrence of AMLs

Mine closure process as well as the management of post-mining hazards concern every country that is, or at least has been, involved in mining activity. In some countries like Japan and France, the decrease in mining activity led to almost the disappearance of active mining industries, leaving some 4000–6000 abandoned mines all over these countries (http://www.ineris.fr/centredoc/CDi__mineclosure_29_11_08-ang.pdf). According to the UNEP (2001) estimate, there are more than one million AMLs globally. Table 1 presents the occurrence of major abandoned mines worldwide, indicating the mined metal and the pollutants of mining activity. At present, details regarding the total number of AMLs are available only for some of the nations that are outlined in the following sections.

2.1 Africa

A country where mining industry is the largest sector, employing an estimated half a million people is Africa. While gold, diamond, base metals and coal mining contribute to over 40 % of the nation's economy, it has left a legacy which impacts on all aspects of the African society (Bempah and Ewusi 2016). According to the Department of Agriculture and Rural Development in Gauteng, the South African province that includes Johannesburg and Pretoria, toxic and radioactive mine residue areas cover 124 square miles (http://e360.yale.edu/feature/the_haunting_legacy_of_south_africas_gold_mines/2931/). It is estimated that currently, about 6150 officially listed abandoned mines lie dormant across South Africa alone (UNESCO 2013). The impact of abandoned mines on public and environmental health has become so serious in Africa that the government faced with a liability of more than US$4.2 billion to rehabilitate its abandoned mines around the country. Further, the South African Department of Mineral Resources in its national strategy for abandoned mines has set a reclamation target of 12 mines per year. However, there are between 8000 and 30,000 illegal miners at the AMLs in the country, largest illegal Artisanal miners being at Ghana according to the South African Human Rights Commission (https://www.yahoo.com/news/gang-wars-erupt-over-abandoned-mines-south-africa-032412096.html?ref=gs; Bempah and Ewusi 2016) posing a serious threat to the society.

2.2 Asia

Over 1500 mines of metals such as gold, copper, lead and zinc are scattered all over the Republic of Korea, and about 900 of them were abandoned by 2000 AD when the ore was depleted (Lee et al. 2005a, 2005b; Kim et al. 2008). Moreover, Korean Ministry of Environment Report (2005) indicated that there are about 2500 mines in total, which include 900 metals mines, 380 coal mines, and 1200 non-metallic mines. More than 80 % of these mines are now closed since they have been a long-term source of environmental pollution. Mining waste and acid mine drainage from these abandoned metal mines released several toxic metalloids or heavy metals into groundwater, surface water, and geological environments because of their solubility and mobility (Mulligan et al. 2001).

With more than 21 % of the world's population living on cultivated land which is <10 % of the total area available on the Earth, the loss of China's extremely scarce arable lands to industrial expansion, urbanization and current operation of about 6800 mines is really alarming (Li et al. 2007). For instance, mining activities alone in China by over 8000 national and 230,000 private companies resulted in creation of 200,000 km^2 of derelict land which includes the loss of 370,000 ha of agricultural land, and many of the metalliferous mines have been abandoned that generated about 3.2 Mha wasteland, and this figure is increasing at a rate of 46,700 ha $year^{-1}$ (Li 2006). Recently, the Indian Bureau of Mines has identified 297 abandoned mine sites at the national level (http://ibm.nic.in/index.php?c=pages&m=index&id=90&mid=18818).

2.3 Australia

On the other side of the globe, mining has been operational in Western Australia for just more than 150 years with presence of many sites that were abandoned after exploration or mining (Strickland and Forbes 2010). Consequently, at present there are about 1800 final mine voids and 150 operational open cut mines in Western Australia (Doupé and Lymbery 2005). Moreover, approximately 2000 derelict (abandoned) mine sites exist in New South Wales, Australia from mining and prospecting activities that date back to the mid-1800 s (Grant et al. 2002). In particular, there are abandoned mines of uranium in Australia along with several other countries like Canada, USA, Portugal, Democratic Republic of Congo, Madagascar, Kyrgyzstan, Tajikistan and Japan (Abdleouas 2006).

2.4 Europe

The United Kingdom (UK) has thousands of AMLs stretching from base metal mines in Scotland to gold and copper mines in the Cambrian mountains of Wales

Table 1 Occurrence of major abandoned metal mines in different countries

Country	Place	Mine name or mined metal	Pollutants detected	Reference
Australia	Blue Mountains, NSW	Silver Peak	As, Mn, Fe, Cd, Cu, Pb, Zn, Ni	Archer and Caldwell (2004)
	Conrad, Inverell, NSW	Base metal	Ag, Pb, Zn, Cu, As and Sn	Gore et al. (2007)
	Drake	Gold and Copper	Cd, Zn	Clark et al. (2001)
	Kapunda and Burra	Copper	Cu	Guo et al. (2009)
	Mount Todd	Gold	Cu, Zn, Al, As	van Dame et al. (2008)
	New England Tablelands,	Howell and Moll River	Zn, Cu, Ag, Pb and As	Grant et al. (2002)
	Northampton, WA	Lead	Pb, Zn	Mann and Lintern (1983)
	North-Eastern NSW	Gulf Creek Copper	Ag, As, Cd, Cu, Pb, Zn	Lottermoser et al. (1999)
	Rum jungle, Darwin	Uranium-Copper	Cu	Mudd and Patterson (2010)
	SE Queensland	Mount Perry Copper	Au, Ag, As, Cu, Fe, Mn, Mo, Pb, Zn	Ashley et al. (2003)
	Thomson River, Victoria	Gold	Hg, As	Bycroft et al. (1982)
Canada	Vancouver Island, British Columbia	Copper	Cu, Zn, Cd	Laurinolli and Bendell-Young (1996)
	Howe Sound British Columbia	Britannia copper	Cu, Zn	Grout and Levings (2001)
China	Nanjing	Jiuhua copper	Cu, Cd, Zn	Wang et al. (2009)
	Guangdong Province	Lead–Zinc	Pb, Zn	Young (1988)
	Guangdong Province	Lead–Zinc	Pb, Zn	Zhang et al. (2001), Pang et al. (2003)
	Guangxi Zhuang, Guangdong Province	Manganese	Cd, Mn	Li et al. (2007)
	Shantou City	Tungsten	As	Liu et al. (2010)
	Wanshan district, Guizhou province	Mercury	Hg	Qiu et al. (2005)
France	Massif Central	Zinc	Cd, Pb, Zn, Cu, Sn, Au, Sb	Schafer and Blanc (2002); Audry et al. (2004)
	La Petite Faye	Gold	As, Pb	Roussel et al. (2000)
	Salsigne	Sulphide minerals	As, Cd, Cu, Ni, Pb, Zn	Pérez and Valiente (2005)
Germany	Lengenfeld and Neuensalz-Mechelgrün	Uranium	U	Mkandawire et al. (2004)
	Saxony and Thuringia	Uranium	U	Mkandawire and Dudel (2005)
India	Rakha, Jharkhand	Copper	Cu, Ni	Das and Maiti (2007)
	Kolar, Karnataka	Gold	As, Cr, Co, Cu, Pb, Sr, Zn	Krishna et al. (2010)
	North Karanpura, Ranchi	Coalfield	Ni, Pb, Cd	Maiti et al. (2002)
	Raniganj	Coalfield	Zn,Cu, Ni, Co, Cr, Pb, Cd, As	De and Mitra (2004)
	Zawar, Udaipur	Zinc	Pb, Cu, Zn, Mn	Misra et al. (2009)

Table 1 continued

Country	Place	Mine name or mined metal	Pollutants detected	Reference
Ireland	Avoca, Wicklow County	Copper	Zn	Gray and Delaney (2008)
	Tippery County	Silver	Pb, Zn, Cu, Ba	Aslibekian and Moles (2000), Connelly et al. (2005)
	Wicklow County	Avoca	Cu, Zn Pb	O'Neill et al. (1998)
	Wicklow County	Glendaiough	Zn	Beining and Otte (1996)
Italy	Ingurtosu, Sardinia	Lead–Zinc	Pb, Zn, Cd	Caboi et al. (1993)
	Ingurtosu, Sardinia	Lead–Zinc	Zn, Pb, Cd, Ni, Cu	Podda et al. (2000), Zuddas and Podda (2005)
	Southern Tuscany	Copper	Cu	Benvenuti et al. (1997)
	Monte Narba, SE Sardinia	Lead-Silver	Pb, Ag	Concas et al. (2004)
New Zealand	Blackwater	Gold	As	Haffert and Craw (2008)
	Endeavour Inlet	Antimony smelter	Sb	Wilson et al. (2004)
	Mount TeAroha	Tui base-metal	Zn, Pb, Cu, Cd, Ag, Au	Morrell et al. (1996). Moreno et al. (2004)
	North Westland, SE Otago	Gold	As	Craw et al. (2007)
	SE Otago	Wangaloa	As, Cu, Zn	Black and Craw (2001)
Philippines	Manila	Mercury	Hg	Maramba et al. (2006)
	RapuRapu	Lafayette mine	Cu, Zn, Au	Cotter and Brigden (2006)
Poland	Bukowno	Lead–Zinc	Pb, Zn, Cd, As	Verner et al. (1996)
	Upper Silesia	Warynski smelter site	Cd, Cu, Pb, Zn, Mn	Wcislo et al. (2002)
Portugal	Aljustrel, Loussal	Piles and dumps	Zn, Cu, Pb	Rowe et al. (2007)
	Baixo Alentejo	Pyrite	Fe, Pb, Hg, Cd, Mo, Ni	Sánchez-Chardi et al. (2007)
	Castelo Branco county	Sarzedas	As, Sb, W	Pratas et al. (2005)
	Cunha Baixa	Uranium	Al, Mn, U	Neves and Matias (2008)
	Cunha Baixa, Mangualde	Uranium	Mn, Fe, Al, U, Sr	Antunes et al. (2007)
	Campo de Jales	Gold	Pb, Cd	Coelho et al. (2007)
Slovakia	Zlataldka	Ag-Au-Sb	As, Sb	Rapant et al. (2006)
South Africa	Johannesburg	Gold	Cr, Zn, Pb, Cu, Co, Ni	Naickera et al. (2003)
	Karoo Uranium Province	Uranium	U, Mo	Scholtz et al. (2005)
	Potchefstroom	Machavie Gold Mine	As, Co, Cr, Cu, Ni	Aucamp and van Schalkwyk (2003)
South Korea	Duckumand Myoungbong	Au–Ag	As, Pb, Au	Chang et al. (2005)
	Dongil, Duckum, Dongjung, Myoungbong and Songchun	Au–Ag	As, Cd, Cu, Pb, Zn	Kim et al. (2005), Lee et al. (2006)

Table 1 continued

Country	Place	Mine name or mined metal	Pollutants detected	Reference
	Duckum	Gold-Silver	Pb, Zn, Cd, Cu, Ni	Lee (2006)
	Dongil, Okdong, Dongjung, Gubong and Samkwang	Gold-Silver	As	Lee et al. (2003)
	Gunwei county, Gyeongsanbuk province	Goro	As	Lee et al. (2007)
	Okdong		Cu, Pb, Zn	Lee et al. (2004)
	Hwacheon	Lead–zinc	Au, Ag, Pb, Zn	Lee et al. (2004)
	Myungbong	Gold	As	An et al. (2011)
	Southeastern part	Lead–zinc	Pb, Zn	Lee et al. (2005a, b)
	Southwest Province	Myungbong	Au–AgAs	Lee et al., 2008
	Ulsan, Kyungsannamdo	Dal-Chun	As	Jang et al. (2007)
Spain	Alcudia Valley, Ciudad Real	Lead–Zinc	Pb, Zn, Cd, Cu	Rodríguez et al. (2009)
	Asturias	Mercury	As, Hg	Loredo et al. (2003)
	Huelva	Piles and dumps	Zn, Cu, Pb	Rowe et al. (2007)
	Iberian, SW Spain	Pyrite	As, Cu, Pb, Zn, Hg, Cd	Fernández-Caliani et al. (2009)
	Monica, NW Madrid	Pyrite	Fe, Mn, Cu, Zn, Cd	Moreno-Jiménez et al. (2009)
	Murica	CabezoRajao	Pb, Zn, Cd, Cu, As	Navarro et al. (2006, 2008)
	Sierra de Guadarrama, Madrid	Barium	Zn, Cd, Cu	Hernández and Pastor (2008)
	Cartagena–La Unión	Lead–Zinc	Pb, Zn	Consea et al. (2006)
United Kingdom	Anglesey	Mynydd Parys	Cu, Pb, Zn	Jenkins et al. (2000)
	Central/N Wales, Central/N Pennines	Lead–Zinc	Pb, Zn	Johnson et al. (1997)
	Cumbria	CarrockFell Mine	Cu, Zn, As	Wilson and Pyatt (2006)
	Dartmoor, SW Britain	Granite	As	Erry et al. (2000)
	Frongoch, west Wales	Lead	Pb, Zn, Cd	Milton et al. (2003)
		Metalliferous	Pb, Zn	Ireland (1983)
	Minera, North Wales	Lead–Zinc	Pb, Zn	Roberts and Johnson (1978)
	Scotland	Leadhills	Pb	Rowan et al. (1995)
	Mendip Hills, SW England	Charterhouse Pb	Van, Pb, Zn	Cotter-Howells and Caporn (1996)
USA	Alaska	Mercury	Hg	Gray et al. (2000)
	Atlanta, ID	Gold	Hg	Ellis and Eslick (1979)
	California	Copper	Cu, Zn, Cd, Pb, Al	Ranville et al. (2004)
	Graham County, Arizona, Nevada County, California	Klondyke mill	Pb, Zn	Mendez et al. (2008)

Table 1 continued

Country	Place	Mine name or mined metal	Pollutants detected	Reference
	Spencerville	Copper	Cu, Zn	Levy et al. (1997)
	Southwestern Indiana	Pyritic coal	Al, Zn	Bayless and Olyphant (1993)
	Lee County, VA	Black Creek Watershed	Al, Mg, Mn, Fe	Cherry et al. (2001)
	West-Central Nevada	Mercury	Hg	Gray et al. (2002)
Zimbabwe	Beatrice, Sanyati Valley	Gold	Pb, Zn, Ni	Ravengai et al. (2005)
	Midland province	Mined tailings	Ni, Zn, Cu, Pb, Sb, As, Se, Au	Meck et al. (2006)

to tin mines in Cornwall (http://www.srkexploration.com/en/newsletter/focus-waste-geochemistry/united-kingdom-has-thousands-abandoned-metal-mines). Mining in the UK peaked in the eighteenth and nineteenth centuries with more than 2000 active mines, all of which are now abandoned. For instance, the Mynydd Parys Mine (Anglesey, UK), standing as the world's most important copper mine in the late eighteenth century with the operation dating back to Roman Empire, ceased to operate since 1911 (Jenkins et al. 2000). This mining industry was historically a centre of economic prosperity proven by the fact that it used to mint 'Parys Mountain Penny' during 1787 and paid its workers and stake holders until it was replaced by national currency in 1817 (http://angleseynature.co.uk/webmaps/mynyddparys.html). Sweden alone in Western Europe has at least 10,000 AMLs, and Ireland is estimated to have more than 100 abandoned coal and metal mines (Mayes et al. 2009).

2.5 The Americas

Approximately 550,000 abandoned mine sites in the United States alone have generated 45 billion tons of mine waste, including waste rock and tailing material with many of the sites found in arid and semiarid regions (US EPA 2004). The inventory of AML from the Bureau of Land Management contained 25,281 sites and 65,976 features as of 31 December 2009 (www.geocommunicator.gov). About 20 % of these sites have either been remediated, or have reclamation actions planned or are underway or do not require further action, whereas the remaining 80 % require further investigation and/or remediation. As per the estimates of US EPA, the surface coal mining practices ever since 1992 buried almost 1200 miles of Appalachian streams including deforestation leading to algal bloom (Stoner 2011). The Iberian Pyrite Belt (IPB) is an extensive mining district that represents the largest concentration of known massive sulfides on the Earth. The IPB comprises more than 80 mines in southern Spain and Portugal, including important historical sites such as Rio Tinto, Tharsis, La Zarza, Sotiel and Aznalcóllar in Spain, and Aljustrel, Loussal and Neves-Corvo in Portugal (Edmondson 1989). The mineralization is dominated by pyrite (>90 % in volume), with variable amounts of sphalerite (ZnS), chalcopyrite ($CuFeS_2$) and galena (PbS). The earlier mining activities resulted in a total of 57 abandoned waste piles (with a total volume of 107 Hm^3) and 10 tailing dumps (42 Hm^3) in the province of Huelva alone, which represents one of the largest accumulations of pyritic mine wastes in the world (Rowe et al. 2007). Canada alone has an estimated 10,000 abandoned mines. A few examples include: Giant gold mine, Britannia copper mine, Kam Kotia copper and zinc mine and Gunnar uranium mine and mill site (http://www.miningfacts.org/Environment/What-are-abandoned-mines/).

It is important to note that, to date, no reliable statistics about the total number of AMLs exist, although their predominance is confirmed in some of the nations like Australia, Canada, UK, US and South Africa (Wolkersdorfer 2008). In addition, what is missing in many of these statistics is the scope of pollution emanating from small-scale mining when large-scale mines have been abandoned. The question is therefore, whether small-scale mines have also been abandoned in the above nations, if so, what is their numbers? This information is not available to the best of our knowledge.

3 Ecological impacts of AMLs

There has been a global 30 years record of high increase in surface mining which is thought to be a prime cause of immediate sign of ecological losses, downstream impacts and a long-term pollution problems (Palmer et al. 2010). Minerals associated with six types of functions, viz., energy minerals, precious metals, ferrous metals, non-ferrous metals, specialty metals and industrial metals (Cooke and Johnson 2002), are involved in indirect impact to pollution (Table 2). Ferrous metals followed by non-ferrous metals are generated as a result of tremendous destruction to the landscape releasing tons of toxic materials into water bodies and atmosphere. Even though the precious metal in itself is a least pollutant in nature, the production of such metals is indeed a high energy-consuming and polluting process with negative ecological effects. Certainly, a wedding ring is expected to produce 20 tons of waste, and the monetary value equals to wedding ring would not be sufficient to remediate a site containing such a waste dump over several years. Likewise, there is a substantial financial burden to overcome pollution (Stuurman 2015) besides environmental issues, and unfortunately lack of effective and augmentative implementation of programs of remediation.

3.1 Potential impacts of AMLs on human health

According to Lee et al. (2005a, 2005b), the cancer and non-cancer toxic hazard indices of metals such as As, Cd, Cu, etc. for the exposed individuals through soils and stream (drinking) waters of the abandoned Songeheon Au–Ag mine site of Korea are significantly greater. Maramba et al. (2006) reported a continued Hg exposure to residents via different pathways including soil, water, air and fish in the vicinity of abandoned Hg mine in Philippines. Elevated levels of Hg/MeHg exceeding the recommended levels have been reported in fish, sediment and blood of residents in addition to several unusual health effects (anaemia, elevated liver function, gingivitis, mercury lines, gum bleeding and neurologic effects such as numbness, weakness, tremors and incoordination). Consumption of food crops grown in the mined areas is considered as one of the major contributing factors for human and animal exposure to toxic metals resulting in adverse health impacts. In a study that was conducted in the abandoned Myungbong Au–Ag mine area in Korea, Lee et al. (2008) concluded that the daily intake of rice by the local residents from the abandoned mine area

Table 2 Major industrial minerals implicated in pollution (Cooke and Johnson 2002)

Mineral type	Main minerals involved
Energy minerals	Uranium, coal and petroleum
Precious metals and minerals	Gold, silver, platinum group, diamonds
Ferrous (steel industry) metals	Iron, manganese, nickel, chromium, cobalt, molybdenum
Major non-ferrous metals	Aluminum, lead, zinc, copper, tin
Specialty metals	Titanium, cadmium
Industrial metals	Asbestos, barites, gypsum, phosphate, potash, kaolin, vermiculite salt, perlite, fluorspar, graphite, sulphur

can pose a potential health threat (cancer risk) due to the long-term toxic metal exposure influenced by past mining activities in the AML.

Surface soils with severe contamination of metals and high levels of Cd in blood of residents near abandoned Cu mine in Korea has also been reported (Kim et al. 2008). In a recent study, Ji et al. (2013) studied the potential health impacts of toxic metals contamination (Cd, Cu, As. Pb and Zn) on the residents near abandoned Cu mines located in Goseong, Gyeongsangnam-do, a southern coast city in Korea. Contamination of Cu, Zn and As in these soils exceeded the soil quality guidelines. Also, the levels of Cu, Pb, Cd and Zn were higher in the crop plants from these soils compared to reference sites. Some rice samples exceeded Cd levels than permissible levels and consumption of rice has been attributed as the major contributing factor for higher daily intake of Cd by residents in that area. The maximum acceptable range of toxic metals for humans in soil is generally 10–700 mg kg^{-1} Pb and 0.1–97 mg kg^{-1} As (Brattin and Ruby 1999), neglecting the significance of health and diversity of microbial and plant dwelling on that soil. A recent review of Basu et al. (2015), focusing on the human health effect of artisanal and small-scale gold mining in Ghana, South Africa, clearly documented that more than a million people live in AMLs, all of them are exposed to relatively high levels of toxic metals such as Hg, and have become sensitive to chemical exposures in the long-run. To our knowledge, there exist no data on cancer rates at the AMLs, and more work is needed in this research area.

3.2 Impact of AMLs on soil health

A healthy soil is an integration of physical, chemical and biological components which benefits environment and ecological productivity including microbial biomass (Hibma 2013; Pankhurst et al. 1997). Soil health can be determined by measure of absolute bioavailability, also called Oral Absorption Fraction (OAF), and relative bioavailability as Relative Absorption Factor (RAF), available to the animals dwelling around AMLs (Brattin and Ruby 1999). Corresponding to the nature of soil, the activity of Plant Growth-Promoting Rhizobacteria (PGPR), P-solubilizing bacteria, mycorrhizal-helping bacteria, and Arbuscular Mycorrhizal Fungi (AMF) also increases in the soil (Khan 2005). Grasses like *Andropogon gerardii* and *Festuca arundinaceae* were found to be highly dependent on the soil microbial activity to survive over the heavy metal contaminated soils (Shetty et al. 1994). Some of the important factors to determine soil health include toxicity or deficiency of heavy metal in soil (Table 3) or bioavailability in plant, adsorption into soil as pH and redox potential are involved in adsorption (Alloway 2013; Mohee and Mudhoo 2012; Mudhoo and Mohee 2012). During surface mining, land is found to be damaged from 2 to 11

Table 3 Soil indication based on metal deficiency (Alloway 2013)

Metal deficient in soil	Indication in soil/soil health
B, Co, Cu, Fe, Mn, Mo, Ni, Se, Zn	Sandy texture
B, Co, Cu, Fe, Mn, Mo, Ni, Se, Zn	Heavily weathered tropical soil
B, Co, Cu, Fe (Calcareous) Mn, Se	High organic matter content
B, Cu, Zn	Low organic matter content
B, Co, Cu, Se, Zn	Flooded soil (Paddy field)
B, Co, Cu, Fe, Mn, Ni, Zn	Free $CaCO_3$
Co, Fe, Mo, Se, Zn	High Fe, Mn, Al oxides
Cu, Mn, Zn	Clay-rich soils (liable to waterlogging)
Co, Cu, Fe, Mn, Ni, Zn	High pH
Cu, Mn, Mo, Se, Zn	Low pH
Cu, Fe, Mn, Zn	High salt content
Fe, Zn	High HCO_3^-
Mo	Free drainage
Cu, Fe, Zn	High P status
Cu, Zn	High N Status

times more when compared to underground mining. The direct effects of mining activities can be a disturbed landscape, loss of cultivated land, forest and pasture land, and the overall loss of land productivity (Copeland 2007) and the indirect effects being soil erosion, air and water pollution, toxicity, loss of biodiversity, and ultimately loss of economic wealth (Wong 2003).

The ecotoxicology impacts on soil organisms and plants are directly related to soil health which is determined by critical limit concentration (CLC) of metals, a maximum threshold limit often calculated in terms of their concentration in food items for human consumption. Effects of AMLs on soil microbial community and its associated functions have been reported by Pereira et al. (2006). Based on a previous eco-toxicological evaluation conducted at the abandoned Cunha Baixa uranium mine site, Portugal, soils in the AMLs are confirmed to be hazardous for soil invertebrates (Pereira et al. 2009). A recent study on assessment of metal toxicity and bioavailability in metallophyte leaf litters and metalliferous soils from abandoned copper mine using earthworm *E. fetida* showed both mine leaf litter and contaminated soil significantly contributed to metal bioavailability to earthworm which severely affected its reproduction (Nirola et al. 2016a). The diversity, abundance and species richness of faunal community containing nematodes were shown by Park et al. (2011) to be reduced in soils contaminated with drainage from AMLs. Results of a study by Moreno-Jiménez et al. (2011a, 2011b) indicated that ecological impacts of AMLs are relatively high with risk, affecting potential receptors as soil micro-organisms, flora and fauna. According to these authors, remedial actions are necessary in AMLs to combat its negative impacts on the ecosystem. According to the study of Mummey et al. (2002), reclaimed soil had more grasses than forbes; however, the sites having trees with clay-loam soil had higher EC and NH_4^+ concentration. Clearly, the soil health in their study showed marked improvement of its properties to reflect that reclamation site matures with time.

3.3 Impact of AMLs on aquatic ecosystem

There is only little information on the impacts of AMLs on water quality. Leaching is one of the main means by which metals from AMLs find their way and contaminate the underground water bodies (Lange et al. 2010). Water draining from active and abandoned coal and base metal mines generally contains sulfuric acid and heavy metals at high levels which could contaminate streams and agricultural land. Entry of AMLs-originated contaminants into the aquatic ecosystem may also occur during heavy rainfall events that cause over-bank flooding (Ochieng et al. 2010). Elevated concentrations of toxic chemicals in the aquatic ecosystems mediated by AMLs in turn result in enhanced toxic chemical uptake by plants and humans posing serious threat. In fact, Africa has significant AMLs-water related challenges (Naicker et al. 2003). Post-closure decant from defunct coal mines is estimated at 62 ml/d, and in the order of 50 ml/d of acid mine water discharges into the Olifants river catchment (Maree et al. 2004). It is clear, therefore, that significant volumes of polluted water need to be managed on a continuous basis for decades to come. Gunduz et al. (2010) reported As pollution in the groundwater of Simav Plain, Turkey mediated by AMLs. Currently, there is a global need to safeguard the purity of water against contamination from AMLs. It is also necessary to ensure that the best pollution prevention strategies are employed, especially in case where the environmental risks can be managed (www.miningwatch.org/emcbc/publications/amd-water.htm).

3.4 Effects of AMLs on biodiversity—a conservative focus

According to the United Nations Convention on Biological Diversity (UN CBD), biodiversity is defined as "The variability among living organisms from all sources including *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems". Water, Energy, Health, Agriculture and Biodiversity (WEHAB) Working Group (2002) states in their document that at a macro-level, the atmospheric gases are balanced through photosynthesis and carbon sequestration in presence of biodiversity with 40 % of global economy based on biological products and processes. Biodiversity is, therefore, a key element to sustain life on the Earth as its unflinching role of supporting the biogeochemical cycling, provisioning, regulating and beautifying the environment makes this planet habitable (Fig. 1).

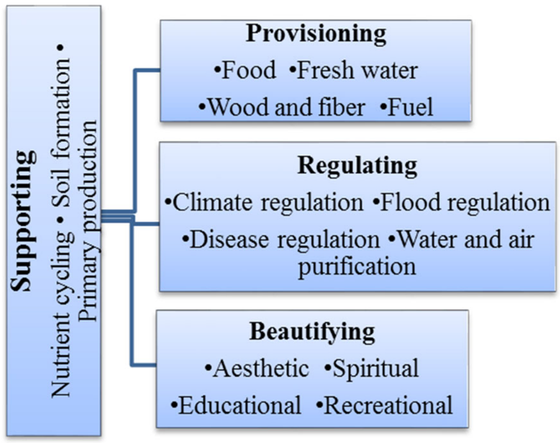


Fig. 1 Ecosystem services (Millennium Ecosystem Assessment, UNEP 2010)

In the case of mining industries, effective biodiversity conservation will bring about an increased confidence of investors, communities, partners and NGOs, and reduces risks and liabilities (Tropek et al. 2012). In an important historical event towards the direction of biodiversity conservation by mining giant, Rio Tinto, a Strategic Response to Biodiversity Conservation and Management was launched in November 2004 at the World Conservation Forum in Bangkok. This strategy was developed in consultations with the organizations such as Bird Life International, Earth Watch Institute, Fauna and Flora International, and the Royal Botanic Gardens, Kew which included a detailed survey of the level of awareness and management of biodiversity issues (Starke 2006). Moreover, the 2008 report of Rio Tinto on biodiversity states that "Rio Tinto is committed to sustainable development not just because it is the responsible and ethical approach to managing the Earth's natural resources, but also because it makes sound business sense" (Tinto 2008). Biodiversity will be incomplete if either phytodiversity or zoodiversity is missing or detached from each other. In this context, the avian diversity was almost 90 % successfully restored in a reclaimed mined land whereas the non-avian faunal vertebrates were found to be slow to restore. To tackle this problem, there are number of measures in place like fox baiting, corridor construction and breeding habitat construction to restore non-avian fauna. A 30 years of research had indicated a possibility of restoring faunal diversity by improving the restoration practices as in the case of Alcoa mine area of southwest Australia (Nichols and Grant 2007). Batty (2005) opined that AMLs are ideal places for harboring some of the rare and threatened species even from major taxonomical orders. Indeed, given a changed physico-chemical nature of the habitat, the endemism could give way to evolution pertaining to the local climatic adaptation. It was observed that in ancient Lead mine at Peak, UK, some of the metallophyte species such as *Minuartia verna, Thlaspi caerulescens, Cochlearia pyrenaica* and *Viola lutea,* invertebrates like *Leptarthrus brevirostris* and *Carabus monilis*, and uniquely adapted diverse microorganism are found safe and healthy (Batty 2005). In fact, the reputation of a mining company rests on the management of post-mined lands in terms of biodiversity conservation.

4 Reclamation of AMLs

Reclamation of a land is a method used to revive a polluted or disturbed land into its original state so that the normal process of interaction between biotic and abiotic factors of the ecosystem takes place (Sheoran et al. 2010). To determine quality of a land, an AML requires mineralogical analysis, physico-chemical analysis, checking extremes of pH, sodicity and salinity, checking erodibility, analysis of plant nutrients, and biological health (Sheoran and Sheoran 2009). Presence or absence of biodiversity plays a major role in determining land quality while considering indicators of reclamation such as nutrient cycling, soil formation and primary production (Fig. 1). In case of operational mine sites, progressive reclamation can be implemented, whereas in AMLs the cost burden is high as a result of abrupt attempt for reclaiming (Stuurman 2015). In 2006, the Congressional testimony concluded that it would take nearly $72 billion to cleanup just the abandoned hard rock mines that produce heavy minerals like silver, gold, uranium and other metals, located largely in the western United States (Clark 2010). Monitoring and maintenance of soil nitrogen level, and containing soil erosion are some of the important areas of priority during the process of AMLs reclamation (Ghose 2001).

4.1 Challenges and objectives of AMLs reclamation

Reclamation, Rehabilitation, and Remediation (RRR) of AMLs cannot be achieved by merely removing human-made structures, but by restoring the lost natural property called biodiversity (Tropek et al. 2012). Restoration is still misunderstood as decommissioning phase of a mine, placing pressure on managers to revegetate or renew within few years, which should actually take at least a decade for that place to start shaping up as a reformed ecosystem. Moreover, an ideal view on restoration is thought to be achieved by inclusion of aesthetic, cultural, moral, historical, political and social aspects besides others. An adaptive management of AMLs gives a scientific approach to remediate and restore with abundant scope for monitoring and research in future (Wassenaar et al. 2013). Abandoned mine sites present a number of inherent challenges (Cao 2007) that are different from other land restoration programs which include: (a) absence of any planning for rehabilitation during the original operation like Environment Impact Assessment (EIA), lack of documentation of pre-mining local flora and fauna; (b) degraded state of the sites—early miners did not conserve topsoil and sites are often completely bear with denuded expanses of regolith, bedrock and tailings emplacements, presenting hostile environments for revegetation; (c) inadequate documentation of the operation presents accidental hazards, including unmarked workings, unstable embankments, and unexpected chemical contamination; (d) acidic water coupled with the uncertain extent of working seals entry and exit routes of water channels making difficult and sometimes impossible to assess the impact, and remaining soils are often contaminated and become acidic after long-term exposure to site pollution; (e) mining and processing methods often spread the impact of activities beyond the precincts of the original site affecting a larger area; (f) needs proper considerations of heritage and scientific significance as most sites are isolated from major settlements, and in many cases cost recovery through subsequent sale of remediated land is not generally feasible; (g) sites may have become the habitat for native fauna and relict populations of native flora, and sometimes as a direct result of mine disturbance can complicate restoration (Batty 2005); and (h) documentation and management about the presence of exotic noxious plants and weeds to encourage native flora and fauna.

Furthermore, the actual surface at the derelict site needs proper restoration even after the site has been levelled, regarded or filled (Bradshaw and Chadwick 1980). The soil fertility must be restored so that the land can be grassed and trees planted by laying of topsoil (where applicable) or substitute materials, application of fertilizers and seeding (frequently by hydraulic methods) (Li et al. 2006). Adequate subsoil drainage will also need to be installed. As recreation plays a major role in the life of a community, derelict areas have frequently been reclaimed for such a purpose (Mishra et al. 2012). Parklands, playing fields and other sporting facilities, marinas, etc. often have arisen from areas of former derelict sites. If buildings are to be erected at an abandoned site, the ground requires adequate compaction and/or reinforcement so that the structures are not subjected to risky settlement. Industrial estates are also often located on restored land, may be as new housing estates. A post-rehabilitation audit of the derelict Conrad base metal mine in eastern Australia, indicates ongoing environmental hazard of acid mine drainage and increase in concentrations of arsenic and lead to 3 % in soil and sediment (Gore et al. 2007). In order to rehabilitate remote contaminated sites effectively, on-site analyses should be carried out to ensure that the materials used to rehabilitate the site are not contaminant-bearing. Understanding the geomorphic setting of the rehabilitated areas is also important in understanding where, and for what period, contaminated materials might be stored in fluvial systems downstream of mine workings (Duque et al. 1998). Thus, chemical and geomorphic audits should form a fundamental part of all rehabilitation works to ensure favorable environmental outcomes (Gore et al. 2007).

Management of mine dumps is a real necessity if water quality around these sites is to be protected from further deterioration. There are a wide variety of technologies, introduced by many mining companies that can mitigate metal releases from active mine dumps. These include constructed wetlands (Lupankwa et al. 2004a, b), grouting (Ravengai et al. 2004), anoxic limestone drains, bactericides, run-off diversion, and the introduction of sulphate-reducing bacteria. Some of the features that complicate rehabilitation projects are due to lack of extensive and detailed planning (Cao 2007); however, the aims for effective reclamation of a mined site include: (a) removing risks potentially posed upon health and safety of humans and animals; (b) stabilizing the site and reduce or remove the impact of erosion and mass movement; (c) maintaining or increasing the biological diversity of species in the vicinity; (d) removing or ameliorating sources of site contamination by monitoring and documentation; (e) removing features limiting the beneficial use of the site and its surroundings; and (f) improving the visual amenity of the site and its surroundings. In many instances, the mined site may also require complementary off-site works to protect rehabilitation (www.environment.gov.au/system/files/resources/…0e70…/ir624.docx). It may also be necessary to limit the types of activities permitted on sites either for a short- or long-term to safeguard the integrity of rehabilitation (http://www.mrt.tas.gov.au/portal/rehabilitation-trust-fund).

4.2 Reclamation approaches for AMLs

As per the available records, there is an increase in the mining activity in proportionate with increasing population in the last four decades. The non-digital age of seventies and digitalized turn of the millennia brought about awareness in terms of health risk and environmental pollution (Lee et al. 2005a, 2005b; Bempah 2016). Yet, there is no control to the exploitation of natural resource as evident in copper production doubling proportionately with population despite the slogans of "reduce, reuse and recycle". For instance, the 1973 world copper production was 7,116,900 tons that was more than doubled to 16,200,000 tons in 2010 (Alloway 2013) which corresponds to 1973 global population of 3,924,667,649 doubling to 6,895,889,018 in 2010 as reported in Population Division, United Nations 2011. However, there is no documentation on subsequent increase of land rehabilitation corresponding to the level of mining growth and per-capita metal consumption. Therefore, if population increase is a threat to natural resources, irresponsible mining is a curse to humanity (https://www.hrw.org/report/2005/06/01/curse-gold) when a massive patch of land is left dry and barren after the extraction is over. Reclaiming a contaminated land is necessary to make it ecologically viable as it is carried out using available technology based upon the nature and severity of pollution. Available technologies for the reclamation of AMLs can be categorised into existing and emerging approaches as detailed below.

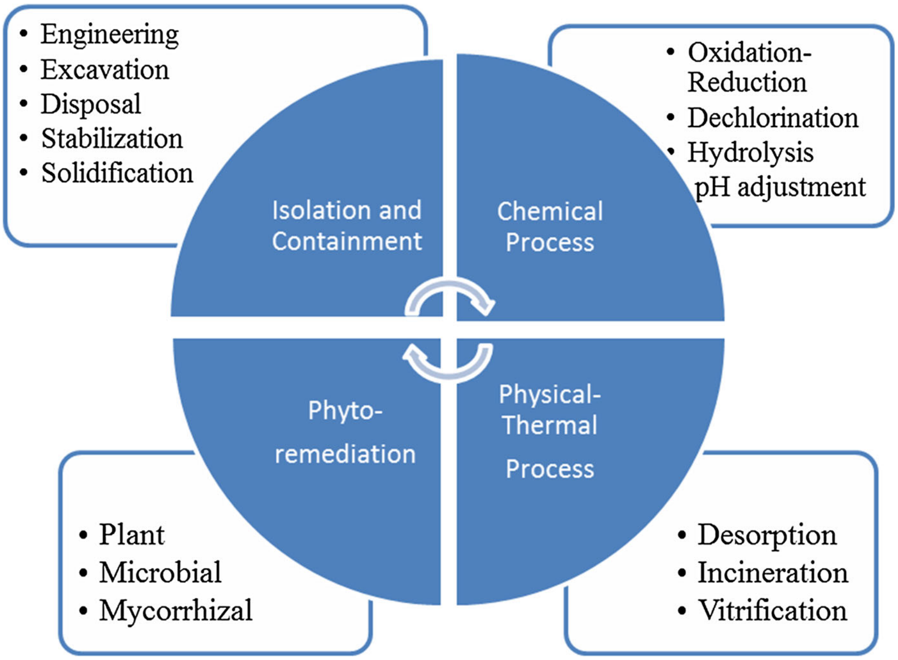
4.2.1 Existing approaches for reclamation of AMLs

Reclamation is open to options like engineering by excavation and disposal, and process-based techniques with an objective to destroy or remove contaminant or modify into a less toxic compound or even isolate the contaminant (Tordoff et al. 2000). In a process-based technique, there is an involvement of physical, biological and chemical processes including stabilization and thermal process (Wood 1997). Depending upon the cases involved during reclamation process, either all or some of the methods of reclamation are applicable, but commonly and ultimately phytoremediation is applicable everywhere to stabilize the toxic substances if the area is large and extended (Fig. 2) (Sheoran et al. 2010). However, for cases with lesser volume and area, showing negligible impact of contamination, the process involving isolation and containment, chemical or thermal is enough to deal with the pollutant (Lottermoser 2010). There are other remediation techniques already practiced to reclaim a contaminated land by the use of permeable treatment walls, pyrometallurgical separation including in situ treatments like soil washing or chemical leaching (Mulligan et al. 2001).

4.2.1.1 In-situ stabilization of AMLs using amendments A disturbed or polluted land has an upset soil profile and characters, therefore, allowing a reclamation method of soil amendment technique involving different biological and chemical substances for implementation (Sydnor and Redente 2002; Yang et al. 2006). Particularly, as a recipe, the soil amendments like phosphorous materials show good efficiency for decreasing lead pollution (Hettiarachchi et al. 2001) together with promotion of revegetation (Mendez and Maier 2008). Moreover, for zinc, amendments like clays and alkaline materials are ideal choice, whereas oxides of iron and organic matters are suitable for treating chromium contamination. To mend arsenic contaminated soils, oxides of iron and manganese are highly preferred along with implementation of revegetation programs (Kumpiene et al. 2008). However, there are negative effects of phosphorous and alkaline materials on arsenic contaminated soils and oxides of manganese and alkaline materials on chromium-contaminated soils (Kim and Dixon 2002; Rai et al. 2004). Recently, it has been reported that chelating agents like citric acid (40 mmol kg^{-1}) boosts the efficiency of phytoaccumulation in maize and vetiver grass, resulting in a 14-fold increase of Pb uptake, in particular, by maize shoot (Freitas et al. 2013).

Primarily, the amendments such as Begingite are used to immobilize metals at the sites contaminated

Fig. 2 Overall reclamation method based upon nature and severity of pollution



with Zn and Cd in America, Europe and other parts of the world (Lelie et al. 2001). The contaminants in soils can be ameliorated or stabilized by adsorption, complexation or precipitation using lime, phosphates and organic matter, but these methods alone are not ideal for agricultural land unless phytoremediation is also promoted side-by-side (Adriano et al. 2004). Indeed, the use of soil amendments together with growth of plants was the success in Sudbury, Canada where after liming and fertilizing contaminated soil, a 30 km^2 of AML was recovered by phytostabilization of the contaminants in a complete revegetation program (Winterhalder 1996). Indeed, long-term effectiveness of organic amendments on the reclamation of AMLs had been confirmed by Pichtel et al. (1994) at field-scale, where, paper-mill sludge and sewage sludge amendments successfully reclaimed AMLs containing pyritic spoil. The use of large quantities of neutral coal fly ash facilitated by co-application with lime-stabilized biosolid also offered an additional opportunity for the reclamation of abandoned acid mine spoil (Abbott et al. 2001). Larney et al. (2003) witnessed positive responses to one-time application of organic amendments (compost, green manures) in the short-term (4 years), and advocated their use in soil reclamation of AMLs, despite a lingering question about the longevity of their beneficial effects. Fellet et al. (2011) proposed that biochar could be used as potential amendment for the reclamation of abandoned dumping sites of mining areas. Very recently, Oh and Yoon (2016) also reported that soils near the abandoned mines can be reclaimed through biochar amendment owing to the potential of the biochar to reduce the leachability of toxic contaminants such as nitro explosives and metals from the mine tailings. Also, the review by Brown and Chaney (2016) highlights the possible use of combination of mixtures, typically consisting of a material with high metal binding capacity (cyclone ashes, municipal biosolids or materials rich in Al, Fe or Mn oxides), materials to adjust pH (sugar beet lime, dolomitic limestone, cement kiln dust), and an organic residue to provide better soil structure and nutrients (compost, animal manures, municipal solid waste) for the successful reclamation of abandoned mine impacted sites. Full evaluation of the benefits of the use of amendments, however, is still being developed.

4.2.1.2 Revegetation of AMLs following phytoremediation Revegetation is a process of planting a suitable plant species using a correct method in a right time so that the plants survive the odds of all ecological factors and grow as fast as they can to establish well on time (Sheoran et al. 2010). Revegetation of AMLs is ideally suited for species of drought tolerant and fast-growing, with their ability to form good canopy and deeper root growth (Tordoff et al. 2000). Usually, grasses having C4 system of photosynthesis are adapted to grow well in AMLs as a pioneer vegetation (Sheoran and Sheoran 2009). Contextually, the AMLs are surrounded by native flora that provides information on the response of native fauna and a spontaneous biodiversity response as a whole. Usually, the adaptation of fauna goes well along with old trees providing shelter, food and assurance, but the birds are found equally well adapted in young forest with sufficient understorey (Lindenmayer and Salt 2008). Technically, revegetation at a mined site is phytoremediation; hence, some of the aspects of phytoremediation concerning revegetation are reviewed in the following sections.

Phytostabilization—a preferred option in phytoremediation of AMLs Phytoremediation, an aesthetically-pleasing, passive and solar energy-driven technique, is cost-effective as very large volumes of contaminated soil could be treated in situ where excavation is not required (Mench et al. 2010). Over the last 10 years, the potential use of trees as a suitable vegetation cover for contaminated sites received increasing attention (US EPA 2012). In spite of its potential for wider use, application of phytoremediation has several limitations (Tordoff et al. 2000). The contaminated site to be remediated must have feasible conditions to suitably support the plant growth. As the plant roots go so deep, phytoremediation is generally applicable only at shallow depths. Phytoremediation is not suitable for rapid treatments since establishment of plants in the remedial sites takes longer times. Over all, to reduce the treatment time in phytoremediation denser root mass is required (Gerhardt et al. 2009). Another demerit is the possible bioaccumulation of the contaminant in the food chain when herbivores eat the phytoaccumulators (Noret et al. 2007). In view of this, ‘phytomining’ is presently practised where plants are harvested and disposed or destroyed after the extraction of reusable metals from it (Chaney et al. 2007). Phytoextraction, under the wider umbrella of phytoremediation, is a slow process of remediation with a problem of metal exposure and successive risk of improper disposal of biomass from a contaminated area (Van Nevel et al. 2007). Similarly, phytovolatilization makes the metals pass into the fruit, timber, grains or vegetables. Rhizofiltration, a water remediation technique, is a costly affair as it requires continuous pH monitoring and an elaborate bioractor establishment (Gratão et al. 2005). Besides, there is an anomaly about the kind of plant species to be introduced over polluted land because of the issues of genetic erosion, allelopathy and species extinction. Continuous monitoring is required to assess the fate of contaminants at the sites undergoing phytoremediation (Lai and Chen 2009). How many years more for people to get back to Chernobyl in Ukraine when phytoremediation in the area is already in full swing for the last two decades is a question to be answered (Anspaugh 2008).

The ‘*Green remediation’* employs those species of plants native to metalliferous soils with a capacity to bioaccumulate metals such as zinc and nickel to concentrations ≤ 2 % in the aerial plant dry matter (hyperaccumulators). Growing such plants under intensive crop conditions and harvesting the dry matter is proposed as a possible method of metal removal and for ‘polishing’ contaminated agricultural soils down to metal concentrations below statutory limits. Plants like *Alyssum montanum*, *Alyssum bertolonii* were tested hydroponically to show cadmium tolerance and accumulation capacity revealing that metallicolous plants which are least represented and diverse are also suitable for phytoremediation of metals (Barzanti et al. 2011). Dhankar et al. (2012) reported that *Thalaspica erulescens* and *Arabidopsis halleri* have phytoextraction ability to uptake Zn up to 40,000 mg kg^{-1} in the aerial plant body. An interesting fact is that some families of plants showing signs of Cation Diffusion Facilitator (CDF) and Zinc-Iron-regulated transporter-like Protein characters (ZIP) have been understood to be zinc phytoextractors. Since phytoextraction is an agronomic approach of phytoremediation, it can only be used to remediate contaminated sites with the aim of harvesting the metal-rich plant tissue, followed by treatment to contain the metals off-site (Cunnigham et al. 1995; Huang et al. 1997). A drawback is that the total amount of metal present in the soil may far exceed the capacity of the plants to accumulate that metal, even over an extended time period (Ernst 1996). Moreover, phytoextraction can only remove metals available in the root zone of the plant, and not in the greater depths.

An alternative to phytoextraction and the best option in phytoremediation is phytostabilisation where a constructed ecosystem based on metal tolerant or accumulating plants may be effective in reducing the mobility of heavy metals within the soil (Dahmani-Muller et al. 2000; Gupta et al. 2000). Phytostabilization has been used successfully to revegetate mine spoils and areas around smelters (Vangronsveld et al. 1995). It also assists in soil enrichment to initiate organic matter cycling (Baker et al. 1994). Thus, the growth of plants with an ability to tolerate adverse conditions found on derelict mine sites increases soil organic matter, which plays an important role in immobilizing heavy metals, improving soil structure, increasing soil fertility and reducing erosion (Mendez and Maier 2008). This process may also include the use of nontoxic metal-immobilizing or fertilizing soil amendments to improve plant growth (Vangronsveld and Cunningham 1998; Sellers 1999). Among four native shrubs (*Myrtus communis*, *Retama sphaerocarpa*, *Rosmarinus officinalis* and *Tamarix gallica*) field-trialed over a 2-year period for phytoremediation of toxic metals (As, Al, Zn, Cu, Cd) in a pyritic waste contaminated soil, *R. sphaerocarpa* showed highest survival and depletion of available metals with low metal transfer to shoot under prevailing conditions. Based on this, *R. sphaerocarpa* was identified as a promising plant for phytostabilisation of metals and rhizospheric processes such as metal chelation by plant exudates and metal immobilisation by rhizosphere bacteria are thought to be responsible for metal stabilisation (Moreno-Jiménez et al. 2011a, 2011b). Species like *Cynodon dactylon, Juncus usitatus*, *Lomandra longifolia* were identified as potential species for use in phytostabilization programs due to their tolerance in acid soils and tolerance to significantly higher concentrations of Pb and Cd than other plant species present on the derelict Silver Peak mine near Yerranderie in the Blue Mountains, NSW, Australia (Archer and Caldwell 2004). However, it is necessary to identify phytostabilizers among the native metallophytes for revegetation of an abandoned mine site recovering from pollution and degradation (Claveria et al. 2010). In this direction, *Acacia pycnantha*, the Australian legume, growing around a derelict copper mine at Kapunda, South Australia has been found suitable for revegetation of mined areas polluted with copper, zinc, cadmium and lead (Nirola et al. 2015, 2016b).

Reclamation and revegetation of AMLs with various revegetation models utilizing the mycorrhizal technology was suggested as an effective tool by Kumar et al. (2010). *Ricinus communis* L. (castor bean) growing naturally on heavily contaminated mine tailing heaps containing Cu, Zn, Pb, Mn and Cd in Zimapan region of Hidalgo state in Mexico has been shown to stabilise toxic metals and at the same time useful for the production of energy (Olivares et al. 2013). However, the role of mycorrhiza in the stabilisation of metals by this plant has yet to be established. Thus, the dual use of this plant as a metal stabiliser with low metal translocation factors and energy crop makes it very attractive in terms of cost-benefit and lowering the human health hazards. Since toxicity of a pollutant to biota is regarded as a direct measure of its bioavailability (Ronday et al. 1997) and a reduction in toxicity is a necessary characteristic of bioremediation process, metal monitoring and toxicity testing should be an integral part of the phytoremediation programs. Zipper et al. (2011) developed a forestry reclamation approach (FRA) that can be employed by abandoned coal mining firms to restore vegetation. Reclamation of AMLs using FRA could restore these lands' capabilities to provide forest-based ecosystem services such as wood production, atmospheric carbon sequestration, wildlife habitat, watershed protection and water quality protection to a greater extent than conventional reclamation practices. In fact, microbially-assisted phytoremediation (Sprocati et al. 2014) could be one among the suitable approaches to reclaim AMLs; however, studies are not available to the best of our knowledge in this aspect.

4.2.1.3 Other approaches for reclamation of AMLs Heat could be effectively used to reclaim AMLs. Navarro et al. (2014) confirmed the effectiveness of thermal desorption for the removal of Hg (removal efficiency = 99 %) from a soil collected from abandoned mining area of Iberian Peninsula. Solar thermal desorption could be an innovative AMLs treatment option; however, future studies are warranted in this direction. Among the approaches suited for the reclamation of AMLs, soil washing processes are also feasible. Yang et al. (2009) suggested that HCl and NaOH could be used to effectively extract all toxic metals from mine tailings of abandoned Songcheon Au–Ag mine. Naftz et al. (1999) demonstrated the use of permeable reactive barriers (PRBs) in field to control radionuclide and trace element contamination in groundwater from AMLs. PRB is one of the most effective in situ remediation technology for contaminated groundwater associated with AMLs in Korea (Brebbia and Kungolos 2007). While the above approaches have proven to be efficient to remediate a wide range of contaminants worldwide, only a limited number of investigations reported their performance for the reclamation of AMLs.

4.2.2 Emerging reclamation approaches for AMLs

Some of the emerging strategies towards the reclamation of AMLs are the use of transgenic plants for the removal of toxins from AMLs (Seth 2012), thereby mitigating its risk followed by the use of nanomaterials as amendments for abandoned mine soil reclamation (Liu and Lal 2012). Though these approaches are at their developing stage, still several studies are warranted in the future to confirm their field-scale adaptability in the reclamation of AMLs. Further, there are greater scopes for the use of several other emerging technologies such as microbially-assisted phytoremediation by employing phytoremediating plant + novel bacterial and/or algal consortium (Kuppusamy et al. 2016a) for the reclamation of AMLs, which is so far unexplored. Development of such novel AMLs reclamation strategies is both reliable and sustainable.

4.2.2.1 Transgenic plants for metal removal from AMLs Over and above the Earth's edaphosphere, the rhizosphere consists of various mixtures of soil types with unique blend of properties differing from one place to another. One of the reasons for Earth's species diversity and richness is its growth, distribution and adaptation based upon the soil property and climate. With a good approach on molecular and cellular mechanisms of a suitable plant species, genetic engineering can be attempted to further enhance its ability to remediate the contaminants (Kärenlampi et al. 2000). Thus, transgenic plants carrying heavy metal-resistant genes are preferred over the normal plants in phytoremediation (Eapen and D'souza 2005). The use of transgenic/genetically modified plants is, therefore, emerging as a promising technology for remediating the mined sites (Bennett et al. 2003). Plants containing transgenes are responsible for increased accumulation of metals so that the pollutant-accumulated plants could be removed and destroyed which ultimately prevent the contaminant migration to sites where they pose a threat to the human health (Seth 2012). However, the contaminant metal, nature of recipient metallophyte, target genes, source of transgenes and final result of transformation are the critical components of a transgenic system (Rotteveel et al. 2006).

There are examples of using heterologous genes from microorganisms, plants and even animals to improve the efficiency of transgenic plants to deal with pollutants. Poplar plant showed enhanced growth, lesser toxicity symptoms with higher phytoextraction capacity when heavy metal resistant gene, *ScYCF1*, of yeast was introduced (Shim et al. 2013). With the use of plant tissue culture, a plant genome can be vitalized by incorporating a foreign genome of a better choice, to produce clones with better characters (Doran 2009). It has come to light that genetically engineered plants are efficient in bioaccumulation and degradation of pollutants (Kumar and Baul 2010) besides their inclusion for the task of phytosensing. Dhankher et al. (2002) tested a transgenic system in *Arabidopsis thaliana* for arsenate removal by inserting two genes, arsenate reductase C (*arsC*) and glutamylcysteine synthetase (GCS) from *E. coli*, and observed a 2- to 3-fold increase in accumulation of As. Similarly, Boominathan and Doran (2003) and Freeman et al. (2004) demonstrated tolerance towards cadmium (Cd) and nickel due to antioxidative defense and antioxidants such as glutathione in transgenic *Arabidopsis thlaspi*. An increase in accumulation and volatilization of selenium (Se) by *Arabidopsis* and Indian mustard was observed when a gene encoding the enzyme SMT was cloned from a Se-hyperaccumulator, *Astragalus bisulcatus,* to the two test plants (LeDuc et al. 2004). Rhizoremediation of heavy metals using engineered plant–microbe symbiosis was demonstrated by Wu et al. (2006). Significant enhancement in phytoextraction of lead, Cd, Cu, As and Se was reported in transgenic plants (Kotrba et al. 2009). Very recently, Zhou et al. (2013) used transgenic hairy roots developed by *Agrobacterium rhizogenes* in phytoremediation of heavy metals and organic pollutants. Although legislative barriers block the release of genetically-modified organisms into the natural ecosystem, the use of plants rather than microorganisms as 'engineered environmental biosystems' help to overcome these barriers (Kuppusamy et al. 2016a).

4.2.2.2 Nanotechnology for reclamation of AMLs Nanotechnology is an advanced modern approach that could be promising for the reclamation of metal polluted sites (Otto et al. 2008). It is because nanotechnology provides new types of materials which offer the unique (easier delivery of the small-sized particles into the contaminated media; higher reactivity due to smaller particle size and higher specific surface area) and important solutions to the limitations of other conventional amendments used for the reclamation of contaminated sites. According to Liu and Lal (2012), nanomaterials with large potentials for mine soil reclamation include zeolites, zero-valent iron nanoparticles, iron sulfide nanoparticles and C nanotubes. They proposed a practical and economical approach to apply the above materials for AMLs. However, still this idea has not been convincingly proved. Notably, future research could be directed in this direction.

4.3 Risk-based remediation of AMLs—a sustainable approach

There is likelihood of an unknown species already evolving, present or adapted in nature to carry out remediation process naturally but unknown to the scientific world. If *Crotalaria cobalticola* is seen growing over an unknown soil-status area, should we agree that the soil in that place has more cobalt concentration? What would happen if sunflower (*Helianthus annus*) growing over uranium-contaminated soil reaches a human or animal food chain? (Al-Saad et al. 2012). We need scientific basis to answer the queries given the fact that phytoremediation is a slow process and a juvenile science compared to other disciplines (Van Nevel et al. 2007). There are agronomic plants like *Zea mays* and *Vicia faba* which are found to remove toxic chemical like TNT and RDX from soil (Lal and Srivastava 2010), again toxic to humans if consumed directly or indirectly (Lee et al. 2008). Transgenic plants pose risk of interbreeding (Andow and Zwahlen 2006) with native and wild population raising the concern about mutation and genetic erosion. There is also a risk of transformation of metals into more bioavailable forms or more toxic in nature (Gratão et al. 2005). Using various types of soil amendments such as metal inactivating additives (coal, fly ash or zeolites) there has been a good progress to remediate metal contaminated soils. However, the use of synthetic chelators are found to be creating detrimental effect by leaching underground, and are also found to be unfriendly to the microbial action to carry out symbiotic association with plants (Lelie et al. 2001).

As the process of remediation is implemented, there are unforeseen risks and hazards needing advance cautioning. One of the major objectives of the mine site remediation is to mitigate the long-term negative impacts to the ecosystem and preferably bring back the land to a beneficial use post mining remediation (Wassenaar et al. 2013). The remedial objectives depend on the intended land use as agreed upon by all the stakeholders including the industry, regulators and community. The future land use could be a stable landscape, agriculture, grazing, housing or cultural and recreational (Mishra et al. 2012). Any remedial efforts should be directed towards removing the risk rather than the contaminant (Reinikainen and Sorvari 2016). The traditional methods of remediation are based on excavation and subsequent disposal of the contaminated soil which is not only very expensive but does not eliminate the contaminant since it is only transferred to another site (Kuppusamy et al. 2016b). Further, for any contaminant to pose risk it has to be in a bioavailable form, therefore, contaminant bioavailability plays a central role in any risk assessment (Van den Brink et al. 2016). Generally, elevated concentrations of toxic metals as determined by aggressive extraction techniques are recorded in the abandoned mining sites (van Veen et al. 2016). However, these metal concentrations represent the total metal concentrations and major portion of this metal may not be naturally bioavailable due to ageing in which bioavailability of the metal decreases over a long period of time due to physiochemical or biological processes such as weathering, sequestration etc. Therefore, risk based remediation that considers social, economic and environmental factors and directed towards eliminating or minimising risk to human and environmental health as a cost effective approach has been recently gaining more recognition for remediation of contaminated sites worldwide (Reinikainen and Sorvari 2016). This approach considers contaminant bioavailability therefore its exposure and risk to biota as central rather than total contaminant which saves the industry substantial costs from unnecessary remediation (Latawiec et al. 2010).

4.4 Current policies for regulation of mined land pollution

When mining was initiated commercially in human civilization, it was highly rampant, unplanned and least managed. In course of time, environmental problems like water and soil contamination, health and hygiene deterioration, disturbed settlement, unplanned township came up leading to behavioral problems like attitude change of miners leaving them fatigue, boring and least motivated (Kitula 2006). The declining living condition and environmental negligence must have triggered law and order problem, ultimately harming their family life as well as their profession indirectly impacting on labor quality and commitment, forcing mine to shut down due to business loss. A planned mine site would have a recreational facility, a planned settlement, a tranquil community motivated to business and committed to collective goal of peace and prosperity. A 30 years mine closure data of around 1000 mines reveal that 75 % of premature mine closure was due to business loss and lack of efficient operation. It also revealed that a sustainable mining practice would have prolonged the mining life involving the environment management, community engagement, safety and resource efficiency (Laurence 2011).

Since AMLs, on one hand, would require effective remediation strategies, the currently operational mining industries specifically need a scientific assessment model or framework to operate in an environment friendly way (Burchart-Korol et al. 2016). One of the standards tested recently in China is a model named 'pressure-state-response' which is adopted to grade the land-use standard (or level of exploitation or pollution), an assessment of land-use level measured by indexing system (Lei and Hui 2011). In WA, a leading federal state of Australia for mining activities, in its mining act of 1978 mining operation was defined as 'merely extraction of ores, removal of overburden and processing, forgetting the remediation part'. However, part IV of the Environmental Protection Act 1986 in WA compulsorily stresses on the need to have a memorandum of understanding (MOU) between the Department of Mining and Petroleum (DMP) and Environmental Protection Authority (EPA) in terms of environmental protection and rejuvenation in the pre- and post-mining stages. The area of interest included in the MOU is mining impact, location of the mine site, ecological status, social and cultural heritage sensitivity, mining significance and economic viability. As per the Introduction to Mining Law Fact Sheet 36 of 2011, a mining proposal guidelines set by DMP must include the parameters like site description, expert consultation, technical details of geology and hydrology, floral and faunal description of sites, Environmental Impact Assessment (EIA), transport corridors, mine closure and rehabilitation information. Moreover, the guidelines for mines closure plans (www.slp.wa.gov.au) have been jointly prepared by DMP and EPA which now primarily focuses on DMP executing the closing procedures with no assessment requirement of EPA unless there is a high risk foreseen on the environmental damage. In the Appendix K, page 76 of the examples of mine closure completion criteria, it underlines the objectives like vegetation rehabilitation status and quantitative vegetation monitoring to be met as per the set guidelines. According to Australian Northern Territory media release of Lesley Major on 20/03/2013 (http://www.ntepa.nt.gov.au/news/2013/legacy-mining-issues-at-redbank), there is a water contamination issue due to acid release in Red Bank Mine site near the Queensland border caused due to inadequate closure of the mine site. As a solution to this, NT EPA is preparing an 'Environment Quality Report' under part 3 of the EPA Act. Such positive indications are stepping stones towards building up strong legally binding actions for the protection of pre- and post-mining environment.

In the USA, problems of Mountain Top Removal mining as in Appalachian region by dumping on the lowlands and destroying large patches of forest for the sake of non-renewable resource like metals and minerals is posing a big problem. To deal urgently, a direct political intervention is necessary if the course of law takes long time to contain the immediate environmental losses. In such situations, the use of executive power has proven rightly to tackle complex issues of environment pollution concerning general public. In one such incidence, Bush administration took direct initiative in USA to deal with issues of grazing policy, natural gas, and national forest regulation to work promptly for positive cause (Davis and Duffy 2009).

The Mining Minerals and Sustainable Development (MMDS) project stresses on the ethical business practices, upholding of human rights and respecting of cultures, implementing risk management strategies, and contribute to social, economic and institutional development of communities. In such a scenario, an awareness of sustainable mining is apparently grasping the business even in the third world countries in recent years. Asian Nation Laos in its Sepon Gold-

Copper mine is practicing all the modern approaches and standards from EIA to occupational health and safety regulations to achieve sustainable mining which has been employing around 7000 people is surely a positive beginning (Laurence 2011; Ji et al. 2011).

5 Conclusions

A perusal of literature indicates that there exists no consolidated information on the global occurrence of AMLs. This review presents a detailed account on the current scenario of major AMLs worldwide, indicating the nature of predominant pollutant metals in each case. The AMLs require attention through multiple angles of remediation strategies considering soil-health status, biodiversity build-up perspective (BBP), probability of use or disuse of soil amendments, and the scope of using transgenic plants. It is evident that the traditional land rehabilitation technology alone cannot cope with pace, extent and severity of environmental pollution with persistent problems of climate change and global warming. In the midst of snowballing problems of mine site reclamation like budget constraint, ignorance of pollution consciousness and missing priority of AML remediation, the pinch of economic recession and carbon trade policy is haunting from the other side. While there seems an urgency to implement revegetation technology for multitude of long-term benefits on one hand, challenges remain to finding an immediate, easy and effective way-out for faster result to achieve remediation on the other hand. In this context, strict monitoring of the currently operational mining sites by concerned agencies with rigorous implementation of proven scientific programmers of reclamation with continuous research and development in the field is advised. Considering the complexity of AMLs in terms of exposure and pollution, a rapid building of knowledge towards genetic engineering and plant taxonomy is necessary to avoid unforeseen blunders of "toxicity making rather than toxicity breaking". In this scenario, developing transgenic plants which are well tested, safe and efficient is necessary and urgent, besides using the traditional species called metallophytes. The blending up of science of remediation with mining policies and regulations is an ideal choice which when implemented practically can balance economic development and environmental destruction for safer future.

Acknowledgments KV thanks the Government of Australia (Department of Education, Employment and Workplace Relations) for the Endeavour Executive Award, and RN acknowledges UniSA, Adelaide for providing APA scholarship.

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