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Review

Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge

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A B S T R A C T

The oxidative dissolution of sulfidic minerals releases the extremely acidic leachate, sulfate and potentially toxic elements e.g., As, Ag, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Th, U, Zn, etc. from different mine tailings and waste dumps. For the sustainable rehabilitation and disposal of mining waste, the sources and mechanisms of contaminant generation, fate and transport of contaminants should be clearly understood. Therefore, this study has provided a critical review on (1) recent insights in mechanisms of oxidation of sulfidic minerals, (2) environmental contamination by mining waste, and (3) remediation and rehabilitation techniques, and (4) then developed the GEMTEC conceptual model/guide [(bio)-geochemistry-mine type–mineralogy- geological texture-ore extraction process-climatic knowledge)] to provide the new scientific approach and knowledge for remediation of mining wastes and acid mine drainage. This study has suggested the pre-mining geological, geochemical, mineralogical and microtextural characterization of different mineral deposits, and post-mining studies of ore extraction processes, physical, geochemical, mineralogical and microbial reactions, natural attenuation and effect of climate change for sustainable rehabilitation of mining waste. All components of this model should be considered for effective and integrated management of mining waste and acid mine drainage.

1. Introduction

1.1. Environmental contamination by mining waste and acid mine drainage

Intensive mining activities have produced a vast amount of hazardous wastes throughout the world, which are commonly associated with high content of acid generating sulfide minerals, and potentially toxic metals and metalloids (PTMs) e.g., As, Sb, Cu, Pb, Cd, Zn, Hg, Ag, Sn, Fe, Al, Mn, Tl, U, Th and W (Ashley et al., 2003, 2004; Bhattacharya et al., 2006; Jung, 2008; Modabberi et al., 2013). The erosion, dispersal, leaching, and atmospheric transport of tailings may spread these elements in a natural aquatic and terrestrial system (Paktunc et al., 2003; Anawar et al., 2011a). The disposal practices of mining waste, burial (Juillot et al., 1999), pedogenesis (Courtin-Nomade et al., 2005), chemical weathering of sulfide minerals and subsequent formation of secondary Fe, Mn and Al oxyhydroxide minerals control the fractionation of these PTMs and acid mine drainage (AMD) in the waste deposit, residential/agricultural lands and aquatic ecosystems. Thus, mining activities cause the massive environmental degradation, water and soil contamination and biodiversity loss (Bhattacharya et al., 2006; Luptakova et al., 2012). The extension of agricultural fields and suburban development has encroached many mining affected sites worldwide creating a health risk to residents living there (Hamilton, 2000; Anawar et al., 2006; Zhuang et al., 2009).

Climate change directly influences hydrology, contaminant generation from mining waste and transport in aquatic ecosystems (Nordstrom, 2009; Anawar, 2013). The transport and fate of contaminants in water, soil and sediment environments can be understood using knowledge of isotopic tracer and reactive transport modeling. Fractionation of stable Fe, Cu and Zn isotopes controls the cycling of Fe, Cu and Zn in metal-rich AMD, river water and soils, where the fractionation of Cu isotopes is greater than that for Zn isotopes (Borrok et al., 2009).

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1.2. Reactive transport modeling

Many reactive transport models have been developed to interpret the oxygen diffusion in the soil/mining waste, kinetic pyrite oxidation, AMD generation, advective–dispersive transport of the aqueous components, mineral–water reactions, chemical equilibrium, geochemical reactions, acid neutralization in the spoil pile, water quality and post-mining environmental impacts (Gerke et al., 1998; Kruse and Younger, 2009; Anawar, 2013). As for example, PHREEQC is a geochemical equilibrium model that can determine aqueous chemical speciation, mineral saturation and other above mentioned activities (Eary et al., 2003). A few more advanced reactive transport models have been developed such as probabilistic LaSAR (Lagrangian Stochastic Advective Reactive)-PHREEQC model (Malmstrom et al., 2008); MIN3P, a multicomponent reactive transport model (Ouangrawa et al., 2009); and RETRASO, a latest model formulated in a multiphase perspective (Saaltink et al., 2004).

1.3. Objectives of this study

The literature review shows that many research articles have been published studying AMD and toxic elements generation from different mining waste and tailings, and mitigation measures throughout the world. They studied the geological, geochemical, mineralogical, and geophysical characterization of these hazardous wastes (Table 2 and Appendix Tables 1–6), while some studies designed the remediation options using different amendments and engineering techniques (Table 1). The Global Acid Rock Drainage (GARD) guide consolidated the technical and management practices from the published research articles, and consultancy reports into a guide that helped the mining industries and government agencies for the management of AMD, environmental protection and regulation of mining (see http://www.gardguide.com/index.php?title=Main_Page; Verburg et al., 2009). The GARD guide contains many conceptual models, graphs and flowcharts providing a broad, but not specific, understanding of AMD management technology.

Despite some common characteristics, the GARD guide did not present clear ideas about pre-mining and post-mining practices considering (bio)-geochemistry, mine type, mineralogy, geological texture, ore extraction and climate influence for mining waste management. The present study has provided some specific and new scientific approach regarding these aspects in a concise and single model for ease of access by the authors. A few review articles have been published focusing on the mechanisms for oxidation of

Table 1
Different remediation options for mining wastes and AMD, and their advantages and disadvantages.

Remediation options	Advantage	Disadvantage	Reference
Zero-valent iron Barriers	Effective clean up of acidic leachates and contaminants; low cost	Reduced iron reactivity by contamination coating, silica or OM	Bartzas et al., 2006
Desulphurization by H_2O_2 (alone) or with cemented paste backfill	Ground support in underground mines; less tailings at the surface	Cost and labor intensive; difficult to manage AMD	Benzaazoua et al., 2008
Phytostabilization (aided) by mining, municipal, garden, and sewage waste	Commercially available sorbents; more realistic and cost-effective	Low microbial and enzymatic activity due to metal toxicity	Ciccu et al., 2003; Alvarenga et al., 2009
Store-release cover design	Geomechanical stability; in-situ remediation; highly sustainable	Susceptible to climate hazard	Gatzweiler et al., 2001
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Electrodialytic remediation	Fast removal; effective	Expensive; labourous; not sustainable; damage to soil	Rojo et al., 2010
Sediment basedecological treatment	Sustainable; Realistic; cost effective; ecological restoration	Affected by climate change and hydrology	Kalin et al., 2006
Passive treatments by carbonate, lime, marble, fly ash	Realistic; moderately cost effective	Overdose may mobilize contaminants; need care	Pérez-López et al., 2009; Zornoza et al., 2013
Washing remediation of soil	Permanent solution; ex situ process	Expensive; labourous	Moutsatsou et al., 2006
Solar thermal desorption and vitrification	Ex situ process; more safety; low pollution	High capital cost; less effective; air pollution	Navarro et al., 2009
Lead precipitation by phosphate in soil	In situ treatment; long- term stable; efficient	Medium cost; less adverse effects	Tang and Yang, 2012
Soil development by vegetation cover on mine tailings	Realistic; long-term stable: ecologically safe	Slow and takes long time	Valente et al., 2012
Placing pyrite-rich mining waste under water level	Low cost	Not suitable for long- term/water shortage	Changul et al., 2010
Compacted soil covering over coal waste dumps and vegetation	Cost-effective; low spontaneous combustion; low pyrite oxidation	Reductive dissolution and mobility of contaminants	Querol et al., 2011
Treating tailings with Fe(II) sulfate	Fe oxyhydroxide; reduced As bioavailability	No significant adverse effect	Seidel et al., 2005
Metal-binding hydrogel particle amendment	Increased moisture; lowered soluble metal; high germination of seed	Expensive	Guterres et al., 2013
Metal recovery from mine water by polymers	Selected metal recovery; generating purified water	Difficult to dispose used magpie polymers	McCloskey et al., 2010
Lower oxidation of pyrite by glycerol	Effective	Uncertainty in long- term performance; expensive	Behrooz and Borden, 2010
AMD treatment by nanoparticle lime	Higher efficiency than conventional use of lime; very fast and effective	Expensive	Roy and Bhattacharya, 2010
U recovery from waste by algal/microbial biomass	Long-term means to remove U/radionuclides	No significant adverse effect	Kalin et al., 2005
Suppression of pyrite oxidation by carrier microencapsulation	Very effective; even in acidic pH and presence of iron oxidizing bacteria	Need special technique and some cost	Evangelou, 2001; Satur et al., 2007; Thakur Jha et al., 2011, 2012
Biochar-aided rehabilitation	Sustainable; effective for revegetation and phytostabilization	No significant disadvantage; little cost	Fellet et al., 2011
Preventing pyrite oxidation by biochar	Very effective	No significant disadvantage; little cost	Jain et al., 2014
AMD treatment by biochar	Neutralization of acidity; decrease in metal toxicity	No significant disadvantage	Kim et al., 2014