



# Alkaline tailings as novel soil forming substrates: Reframing perspectives on mining and refining wastes

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## ABSTRACT

Historically, tailings management plans have focused largely on confinement and containment, with little regard to long term alteration of the chemical, physical, and biological properties of tailings materials. Management strategies are now moving towards *in situ* remediation of tailings to mitigate environmental risks associated with long term storage, and return occupied land areas to an alternative, productive land use. Creating a stable, sustainable ecosystem in tailings storage areas requires shifting our perspective to think of tailings as a novel soil forming material rather than as a waste. This review presents a conceptual model of soil formation (pedogenesis) in alkaline tailings and mineral processing residues, which can be used to guide rehabilitation efforts and identifies key knowledge gaps for future research. Although tailings and mine wastes exhibit chemical, physical, and biological properties greatly different to those of bedrock-derived parent materials, they experience the same drivers of soil formation (climate, organisms, relief, time) as bedrock parent materials, and understanding how these drivers interact is of importance in accelerating natural processes of soil formation and attainment of a desired ecosystem endpoint. Individual processes (desiccation, mineral precipitation) early in pedogenesis in alkaline wastes are relatively well understood; however, the interactions between these processes (particularly between abiotic and biotic processes) in guiding and controlling the rates of soil development in alkaline tailings remain a priority for future research.

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## 1. Introduction

### 1.1. Global production of (alkaline) tailings and mine wastes and challenges for remediation

Approximately 7 Gt of tailings are produced worldwide every year as byproducts of mineral extraction and refining activities (Mudd and Boger, 2013). Assuming an average bulk density of  $1.5 \text{ t m}^{-3}$  (Sarsby, 2000) and a stack height of 20 m, tailings facilities are currently expanding globally by 23,750 ha per year, occupying otherwise productive land. Tailings production is likely to increase in future as a result of increasing global demand and decreasing ore grades (Bogich and Matos, 2008; Maier et al., 2014; Menzie et al., 2004; Mudd and Boger, 2013), generating an ever increasing burden for environmental management in the minerals industry. It is crucial to the sustainability of the minerals industry that effective, low-cost, rapid strategies for tailings management are implemented to minimize the impact of increased demand for metals on the environment. Although some industries are beginning to explore reuse options for tailings, including as concrete and cement

fillers (Celik et al., 2006; Das et al., 2007; Klauber et al., 2011; Pontikes and Angelopoulos, 2013; Shi and Kan, 2009), road base materials (Klauber et al., 2011; Sorlini et al., 2012), pigments (Dengxin et al., 2008; Klauber et al., 2011; Pontikes and Angelopoulos, 2013), and catalysts for various industrial processes (Klauber et al., 2011; Pontikes and Angelopoulos, 2013; Zhang et al., 2012), these are in their infancy and therefore the need for effective remediation strategies to deal with tailings persists.

Acidic, sulfide-bearing tailings have been well-studied for the past seven decades, with various authors focussing on the geochemistry (Hoffert, 1947; Neel et al., 2003; Singer and Stumm, 1970), microbiology (Baker and Banfield, 2003; Ehrlich, 1963; Tyson et al., 2004), mineralogy (Dold and Fontbote, 2002; Nordstrom and Alpers, 1999), and physical properties of these tailings (Blowes et al., 1991; Hunter and Whiteman, 1975) as well as their impacts on surrounding environments and animal and human health (Bonilla-Valverde et al., 2004; Hayes et al., 2012; Ramirez-Andreotta et al., 2013). In comparison, alkaline tailings and mine wastes are poorly studied, despite undergoing similarly rapid processes of geochemical weathering and ecosystem development (Bondici et al., 2013; Mains et al., 2006). Major types of alkaline tailings and mine wastes include gold refining tailings, bauxite residue (alumina refining tailings), chromite ore processing residue, uranium mill tailings, and steel slag, creating a total of 1.70 Gt of alkaline

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**Table 1**

Properties of selected alkaline tailings as produced, without amendment or weathering. Displayed values those reported in the literature for tailings from individual refineries (may be averaged from multiple references) or averaged values from multiple refineries as previously determined by other authors. In both cases the number of samples from which the average was generated is indicated in brackets. Where values were given as ranges by authors, the midpoint was taken as the representative value (i.e. 'pH 3–5' would be recorded as pH 4). A dash (–) indicates that no data was found in the published literature. Numbered references are listed below the table.

Property	Tailings type					References
	Bauxite residue	Chromite ore processing residue	Gold tailings	Uranium mill tailings	Steel slag	
Volume produced globally (Gt/year)	0.12	0.0006	1.27	0.061	0.17–0.25	1–4
Total volume in storage globally (Gt)	3	–	–	1.6	–	1, 5
Mineralogical Residual minerals from parent ore	Hematite, goethite, quartz, rutile, anatase, gibbsite, boehmite	Chromite, quartz	Pyrite, pyrrhotite, quartz, coesite, kaolinite, muscovite, chlorite, mica, amphibole, feldspar, albite	Quartz, feldspar (potassium and plagioclase), micas, pyrite, sphalerite, galena, zircon, apatite, monazite, tourmaline, hematite, goethite	N/A – generated from metal precursor	1, 5, 6–15
Minerals precipitated or added during ore processing	Calcite, tricalcium aluminate, sodalite, cancrinite, perovskite	Brownmillerite, larnite, periclase, portlandite	Calcite, dolomite	Gypsum, barite, fluorite, dolomite, calcite, iron sulfates and oxyhydroxides	Portlandite, larnite, calcite, dolomite, lime, periclase, pentahydrate, monticellite, merwinite, magnesite, wollastonite, hematite, srebrodol'skite, mayenite, uvarovite	1, 6–17
Physical Texture (% sand/silt/clay)	–	18/45/37 (n = 4) <sup>a,b</sup>	28/69/3 (n = 1)	40/–/– (n = 1)	–	9, 18, 19
Bulk density (g cm <sup>-3</sup> )	2.5 (n = 13)	2.8 (n = 4) <sup>a</sup>	–	1.8 (n = 3)	2.8 (n = 3)	1, 9, 20–24
Specific surface area (m <sup>2</sup> g <sup>-1</sup> )	32.7 (n = 30)	–	–	–	3.9 (n = 2)	1, 23, 25
Chemical pH	11.3 (n = 44)	11.8 (n = 3)	8.6 (n = 6)	9.1 (n = 3)	12.7 (n = 63)	1, 14, 18, 22, 26–34
EC (mS cm <sup>-1</sup> )	7 (n = 46)	–	4 (n = 4)	37 (n = 40) <sup>c</sup>	5 (n = 63)	1, 14, 29–31, 34
ESP (%)	70 (n = 10)	–	57 (n = 3)	–	–	1, 29–31
Exchangeable Na <sup>+</sup> (mmol <sub>c</sub> kg <sup>-1</sup> )	101 (n = 9)	–	14 (n = 1)	–	–	1, 29
Exchangeable K <sup>+</sup> (mmol <sub>c</sub> kg <sup>-1</sup> )	2 (n = 8)	–	3 (n = 1)	–	–	27, 29
Exchangeable Ca <sup>2+</sup> (mmol <sub>c</sub> kg <sup>-1</sup> )	158 (n = 8)	–	63 (n = 1)	–	3 (n = 1)	23, 27, 29
Exchangeable Mg <sup>2+</sup> (mmol <sub>c</sub> kg <sup>-1</sup> )	4 (n = 8)	–	4 (n = 1)	–	–	27, 29
Organic C (%)	0.30 (n = 5)	–	0.38 (n = 1)	–	–	11, 35–39
Total N (%)	0.13 (n = 7)	–	–	–	–	27
Extractable NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	9 (n = 4)	–	–	–	–	27
Extractable NO <sub>3</sub> <sup>-</sup> (mg kg <sup>-1</sup> )	0.75 (n = 4)	–	1 (n = 1)	–	–	27, 29
Available P (mg kg <sup>-1</sup> )	7 (n = 4)	–	7 (n = 1)	20 (n = 1)	–	27, 29, 32
Biological Dominant bacterial phyla	Proteobacteria, Actinobacteria, Bacteroidetes, Firmicutes	Proteobacteria, Firmicutes, Actinobacteria, Tenericutes	–	Proteobacteria, Actinobacteria, Firmicutes, Bacteroidetes	Proteobacteria	33, 40–42
Dominant fungal phyla	Ascomycota, Basidiomycota	–	–	–	–	40
Dominant archaeal phyla	–	–	–	–	–	

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