Recovering metal(loids) and rare earth elements from closed landfill sites without excavation: leachate recirculation opportunities and challenges

H. Lee[1], F. Coulon[1], D.J. Beriro[2], S.T. Wagland[1*]

[1]School of Water, Energy and Environment, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

[2]Digital Laboratories, British Geological Survey, Nottingham, NG12 5GG, UK

* Corresponding author: s.t.wagland@cranfield.ac.uk

Abstract: Metal(loids) and Rare Earth Elements (REE) ('metals') are naturally scarce and economically high-value. They are used in a wide range of products, with demand continuing to grow. Metal-bearing wastes are a secondary source of raw material that can meet this demand by providing a previously unconsidered low impact supply source. In particular, landfill leachate emerges as a significant potential resource as it contains high concentrations of metalloids, metal ions and RRE. However, realising a profitable return on investment for leachate processing is a tremendous challenge due to a relatively low recovery rate, variation in the multi-element value and the effect of other chemicals (organic and inorganic) in these complex mixtures. There is a need to better understand the mechanisms and potential applicability of investigation and extraction methods for optimising metals recovery from leachate. This paper addresses this need by providing a systematic review of the critical factors and environmental conditions that influence the behaviour of metals within the landfilled waste. The paper provides a synthesis of how these may affect leachate recirculation efficiency for recovery in the context of a range of opportunities and challenges facing circular economy practitioners.

Keywords: circular economy, non-intrusive investigation, organic compounds, mobility, metal recovery

1   Introduction

Metals, metalloids and REE, collectively termed 'metals', are finite natural resources with increasing demand. It is vital to find alternative sources to ensure supplies of these metals, especially for new technologies such as electric vehicles, renewable energy generation and battery storage (Jowitt et al., 2020). Several recent studies reported that a worthwhile amount of valuable secondary raw materials is available within closed landfill sites (Gutiérrez-Gutiérrez et al., 2015; Dino et al., 2017; Krook et al., 2018; Särkkä et al., 2018; Esguerra et al., 2019; Parrodi et al., 2019; Wagland et al., 2019). There are around 21,000 closed landfill sites across England and Wales (DEFRA, 2021; ENDS Report, 2021) and somewhere between 150,000 and 500,000 landfill sites within Europe, with an estimated 90% of them being non-sanitary (Jones et al., 2018). Closed landfills represent a significant opportunity across Europe and the UK to recover value from waste materials as they provide a previously unconsidered localised long-term storage deposit of secondary raw materials similar to traditional metal mineral resources. Enhanced Landfill Mining (ELFM) address the combined and integrated valorisation of distinct landfilled urban waste streams as both materials (Waste-to-Materials, WtM) and energy (Waste-to-Energy, WtE) while meeting the most stringent ecological and social criteria (Jones et al., 2013). ELFM provides an opportunity for combined resource recovery and reclamation of land while mitigating future environmental liabilities and remediation costs through excavation innovative transformation technologies (Jones et al., 2013; Esguerra et al., 2021; Vollprecht et al., 2021). However, existing technologies and good practices are unable to demonstrate the economic viability of such schemes. This is partly because mining processes for recovering material result in high capital costs. There are also important uncertainties about the actual abundance and concentration of suitable waste materials in landfill environments, which need to be known early on in the lifecycle of a metal's recovery project.

50   Two essential by-products of waste disposal by landfills are leachate and landfill gas. The former

51   is formed when rainwater infiltrates and percolates through the degrading waste, the latter by

52   microbial degradation of biodegradable waste materials under anaerobic conditions (Chu, 2008).

53   Effective treatment methods are required as leachate contains trace chemicals, contaminating

54   groundwater, surface water and soil, potentially polluting the environment and harming human

55   health (Brennan et al., 2016). However, ambitions for the landfill management should go beyond

56   protecting human health and the environment, with conservation of energy and recovery of

57   natural resources high on the agenda. Landfill leachate comprises recoverable metals, organics,

58   phosphorus, ammonia, and water (Iskander et al., 2017; Kurinawan et al., 2021). The presence of

59   recoverable metals means that landfill leachate can be of great importance as an alternative to

60   conventional mineral exploration as the sediment of the leachate showed presence of REEs

61   content was more than twice the content in landfilled waste (Gutiérrez-Gutiérrez et al., 2015), but

62   also it can negate the need for full-scale landfill mining.

63   There are four objectives of this review paper: i) to give an overview of the properties and metals

64   content in landfill leachate to gain insight into the opportunities for metal recovery from leachate;

65   ii) to explore the knowledge on various factors affecting metals solubility; iii) to evaluate the

66   efficiency of recirculation for increasing metal recovery rates and; iv) to discuss the opportunities

67   for metal recovery from leachate, analyse the challenges associated with the recovery, and present

68   the perspectives for future research and technology development to maximise the benefits of

69   metals recovery from closed landfill leachate.

70   ## 2   LANDFILL LEACHATE PROPERTIES AND METALS CONTENT

71   Leachate can be formed as a result of chemical and biochemical processes within the landfill. There

72   is nonuniform and intermittent percolation of moisture through the solid waste in the landfill due

73   to leachate generation (Hughes et al., 2013; Edokpayi et al., 2018). Several factors influence

74   leachate composition, such as the age of landfill, depth of the waste in the landfill, location of the

75   site, and weather condition of the landfill site; another critical factor affecting leachate composition

76   is the composition of the waste deposited in the landfill (Jang and Townsend, 2003; Kalčíková et

77   al., 2011; Moody et al., 2017). Generally, the waste composition is categorised as organic (food

78   and garden waste), paper, plastic, glass, metals, etc. Table 1 shows the composition of global waste.

79   **Table 1.** Waste composition range

Component	Range (%)	References
Organic waste	15-58	Tapia, 2009; European Commission, 2016; Abdel-Shafy and Mansour, 2018; Kaza et al., 2018
Paper and cardboard	16-27	
Glass	2-4.5	
Plastic	9-20	
Wood	3-7	
Metal	3-9.2	
Textile	3-9	
Rest	3-18	

80

81   A wide variety of metal contents is collected into the leachate as it drains through the pile of waste

82   in the landfill (Eggen et al., 2010; Edokpayi et al., 2018). Leachate is also rich in ammonia and

83   inorganic components such as iron, chlorine, sulphate, and metals (Öman and Junestedt, 2008).

84   Inorganic compounds may consist of potentially harmful elements such as Pb, Hg, and As in pure

85   form or combined with other elements (Jan et al., 2015). As leachate contains a wide range of

86   metals, it can be considered a great potential for metal recovery. However, there are also challenges

87   associated with the method to meet the need for sustainable leachate management that maximises

88   valuable metal recovery. The key challenge on metal recovery from leachate is the low

89   concentration of metals which is often affected by landfill age and type (Table 2).

90

91 **Table 2.** The concentration range of chemical constituents of landfill leachate determined from
92 available literature

Parameter	Concentration range (mg/l)	Parameter	Concentration range (mg/l)	References
Alkalinity (as $CaCO_3$)	0-20,850	Nitrogen (Ammonia)	0-1,250	Kjeldsen et al., 2002
Aluminium	0-2	Nitrogen (Nitrate)	0-9.8	Kjeldsen et al., 2002
Antimony	0-3.19	Nitrogen (Nitrite)	0-1.46	Christensen et al., 2001
Arsenic	0-0.04	Nitrogen (Organic)	0-1,000	Christensen et al., 2001
Barium	0-2	Nitrogen (Total Kjeldahl)	1-100	Christensen et al., 2001
Beryllium	0-0.36	Nickel	0-7.5	Christensen et al., 2001
BOD_5	0-4,000	Phenol	0.17-6.6	Akinbile et al., 2012
Boron	0.5-10	Phosphorus (Total)	0-234	Kjeldsen et al., 2002
Cadmium	0-0.01	Phosphate	1-10	Christensen et al., 2001
Calcium	100-1,000	pH	4.5-9	Adamcová et al., 2016
Chloride	20-2,500	Potassium	0.16-3,370	Akinbile et al., 2012
Chromium	0-0.05	Selenium	0-1.85	Adamcová et al., 2016
Cobalt	0-7.58	Silicon	0-12	Kjeldsen et al., 2002
COD	150-6,000	Silver	0-1.96	Christensen et al., 2001
Conductivity (μmho/cm)	480-72,500	Sodium	0-8,000	Kjeldsen et al., 2002
Copper	0-9.9	Thallium	0-0.32	Adamcová et al., 2016
Cyanide	0-6	Tin	0-0.16	Adamcová et al., 2016
Fluoride	0.1-1.3	TDS	0-42,300	Akinbile et al., 2012
Hardness (as $CaCO_3$)	400-2,000	Titanium	0-1.5	Christensen et al., 2001
Iron	0-5,500	TSS	140,900	Kjeldsen et al., 2002
Lead	0-5	TOC	335,000	Adamcová et al., 2016
Magnesium	16.5-15,600	TVA (as Acetic acid)	0-19,000	Akinbile et al., 2012
Manganese	0.05-1,400	Turbidity	40-500	Adamcová et al., 2016
Mercury	0-3	Sulphate	0-300	Adamcová et al., 2016
Organic halides	0.32-3.5	Zinc	0-1,000	Christensen et al., 2001
Benzene	0.1-0.6	Phenols	0-4	Christensen et al., 2001
Ethylbenzene	0-4.9	Toluene	0-3.2	Akinbile et al., 2012

93 Note: The grey shaded cell indicates metals and metalloids

94 The leachate produced in young landfills (< 5 years old) contains a substantial number of organic

95 compounds derived from biodegradable organic water materials, which undergoes rapid anaerobic

96 fermentation within confined landfills. As a result, volatile fatty acids (VFAs) are produced, e.g.

97 acetic, propionic, iso-butyric, n-butyric, iso-valeric, and n-valeric acid. It is very well known that

98 organic acids, such as VFAs, may play an essential role in the mobilisation of metals through either

99 the formation of soluble ligand: metal complexes or a decrease of pH (Molaey et al., 2021). Thus,

100 VFAs are considered valuable substrates for metal dissolution, increasing the release of metals in

101 landfill environments. Young leachate is characteristic of its high content of biodegradable organic

102 matter. BOD (Biochemical oxygen demand), COD (Chemical oxygen demand), and BOD/COD

103 ratio act as indicators of microbial activities and organic pollution. BOD/COD describes the

104 biodegradability level of materials by which organic matter containing leachate is readily broken

105 down in the environment (Samudro and Mangkoedihardjo, 2010). Therefore, young leachate shows

106 a high BOD/COD indicator.

107 As landfill age increases, the BOD/COD ratio in leachate decreases (Table 3). This is due to the

108 decomposition of the majority of biodegradable compounds and small quantity changes of less

109 degradable organic matter at the same time that acidic conditions begin neutralise (Talalaj, 2015).

110 As a consequence, the higher pH condition results in decreasing metal release by complexation and

111 precipitation (Zhang et al., 2018). Older leachate from the methanogenic phase is partially

112 characterised by the lower concentration of VFAs. As the content of VFAs and other readily

113 biodegradable organic compounds in the leachate decreases, the organic matter (OM) in the

114 leachate becomes dominated by refractory compounds, such as humic acid (HA) and fulvic acid

115 (FA), which are known to bind metals to their hydroxyl and carboxyl groups, and either mobilise

116 metals or delay their release (Leung and Kimaro, 1997; Bozkurt et al., 2000; Kochany and Smith,

117 2001; Klavinsa et al., 2006; Gutiérrez-Gutiérrez et al., 2015). The humic substances (HS) give a

118 dark colour with increasing pH due to the dissociation of protons (Stevenson, 1994). The decrease

119 in VFAs increases pH; consequently, metals have a relatively low concentration in older landfill

120 leachate as the solubility of metals is decreased with increasing pH.

121 **Table 3.** Selected characteristics of leachate according to landfill age

Parameter	Young	Intermediate	Old	References
Age (years)	<5	5-10	>10	Renou et al., 2008
pH	<6.5	6.5-7.5	>7.5	Bhalla et al., 2013
COD (mg/L)	>10,000	4,000-10,000	<4,000	Bhalla et al., 2013
TOC/COD	<0.3	0.3-0.5	<0.5	Abbas et al., 2009; Zhou et al., 2010

BOD$_5$/COD	>0.3	0.1-0.3	<0.1	Bhalla et al., 2013
Organic compounds	80% VFA	5-30% VFA + humic and fulvic acids	Humic and fulvic acids	Bhalla et al., 2013
Heavy metals (mg/l)	Low medium >2	Low <2	Very low <2	Renou et al., 2008
Molecular size distribution	Over a broad range-high fraction of low molecular weight organics	N/A	Over a narrow range-high fraction of high molecular weight organics	Abbas et al., 2009; Zhou et al., 2010
Biodegradability	Important	Medium	Low	Bhalla et al., 2013

122

3   PHYSICO-CHEMICAL FACTORS AFFECTING METALS SOLUBILITY

Several factors affect metals solubility within solid waste deposits (Fig 1). Important processes

include abiotic redox processes, dissolution/precipitation of minerals, sorption, ion exchange,

organic matter biodegradation, and complexation. The resulting matrix redox changes strongly

influence both the inorganic and organic biogeochemistry of the landfill and therefore influencing

the behaviour and fate of metals within landfills (Christensen et al., 2001). Gaining insights into

the geochemistry of landfill is therefore needed to better understand the solubility of metals and

predict metals recovery.
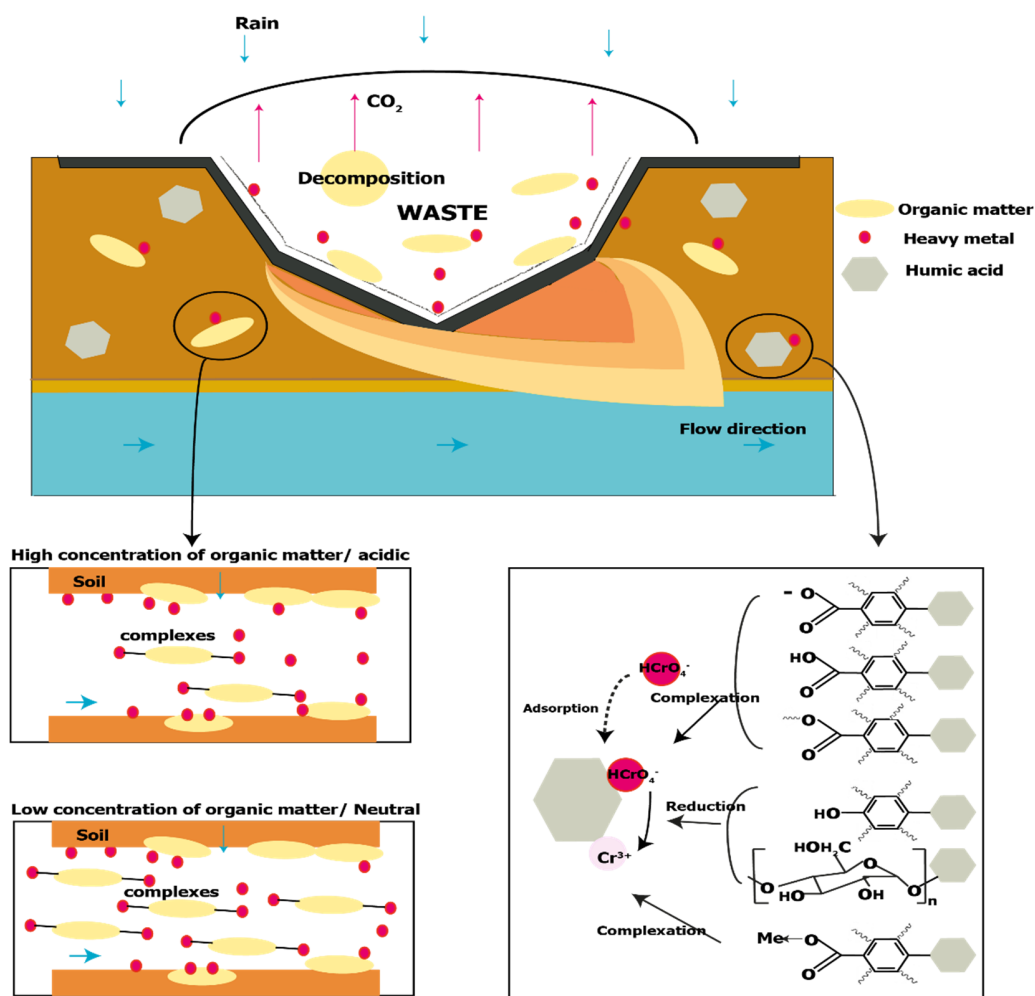
Figure 1. Processes occurring in landfills which affect metal solubility

3.1   Weathering and natural attenuation

The dissolution of metals can occur during natural events, such as weathering and natural attenuation. During weathering processes, a broad range of physical and chemical reactions such as hydrolysis, precipitation, pH neutralisation, oxidation/reduction of metals, sorption, and complexation will change the overall characteristics of metals (Chimenos et al., 2003; Polettini et al., 2004; Saffarzadeh et al., 2011; Takahashi and Shimaoka, 2012). Natural attenuation can be defined as a process by which the concentration of leachates is reduced to an acceptable level by natural processes. It can both mobilise and immobilise metals (Beaven et al., 2013). Based on the

141 definition, *in-situ* natural attenuation mechanisms are identified as physical (diffusion, sorption,

142 dispersion, dilution, and volatilisation), chemical (precipitation, adsorption, ion exchange, redox

143 reaction) and biological (biodegradation) processes. For this reason, it is desirable to be able to

144 predict how the metals in the landfill environment will behave over time when exposed to the

145 weathering effects of infiltrating rainwater and the atmosphere. The effect of weathering on metals

146 solubility is likely to be significant as pH is a dominant parameter in metals solubility and

147 complexation (Stumm and Morgan, 1981). The redissolution of their respective hydroxide mainly

148 causes the release of metals as pH is controlled by the solubility of $Ca(OH)_2$. Therefore, weathering

149 reactions leads to a decrease in pH (Chimenos et al., 2003).

3.1.1 Oxidation

151 Several studies have been shown the formation of Fe/Al-(hydrate) oxides and calcite by weathering.

152 It indicates that metals release may be controlled by sorption processes caused by weathering

153 (Zevenbergen and Comans, 1994; Meima et al., 1997a; Meima and Comans, 1999; Saffarzadeh et

154 al., 2011; Takahashi and Shimaoka, 2012). Saffarzadeh e*t al.* (2011) proposed the following order

155 based on their direct metal uptake capacity: Fe-hydrate > Al-hydrate > calcite. Calcite is not

156 adequate for direct metals sorption; however, they play a crucial role in buffering the system, pH

157 neutralisation; consequently, it minimises metal leaching. Thus, weathering is expected to result in

158 a reduced metal solubility in the long term (Meima and Comans, 1999).

3.1.2 Sorption and precipitation

160 Temporal studies of metal mobility in soils show that mobility decreases over time, suggesting that

161 a high proportion of metals within Municipal solid waste (MSW) which consists of everyday items

162 we use and then throw away, are insoluble (Peters and Shem, 1993; Aucott, 2006). The reasons for

163 the reduced mobility of metals in soil include sorption on soil particles and particularly to HS,

164 precipitation under anaerobic conditions, adsorption, and chelation with inorganic and organic

165   ligands in landfills (Bozkurt et al., 2000). Christensen *et al.* (2001) reported that metals in landfills

166   do not constitute a significant pollution problem due to strong attenuation by sorption and

167   precipitation (Fig 2).
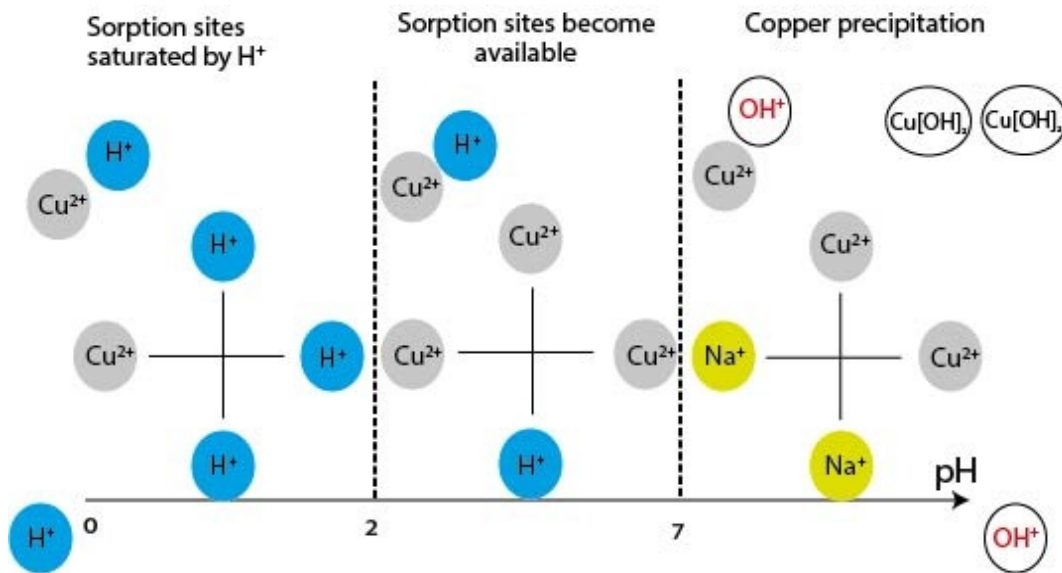
168

169   **Figure 2.** Copper sorption mechanisms (Adapted from Abbar et al., 2017)

170   In general, inorganic content of leachate ranges between 1 and 2000 mg/L. By raising the pH

171   value, metallic hydroxide compounds become insoluble and precipitate from the solution.

172   Alkaline conditions promote metal precipitation and adsorption, depending on the metal

173   speciation (Lukman et al., 2013). Fig. 3 shows the solubility curves of selected metal ions and

174   their respective solubility versus pH. Cu and Ni have a similar curve, albeit that the minimum

175   solubility of Ni occurs at approximately pH 10.5 and the minimum solubility of Cu occurs at pH

176   9. Zn is amphoteric, being soluble in both acid and alkaline conditions. Cu and Zn readily form

177   metallic complexes with ammonia. These metal complexes remain highly soluble at the higher

178   pH values, prohibiting respective metal hydroxide precipitation. Cu sulphide is insoluble, and the

179   presence of sulphide precipitates Cu as it dissociates from the ammoniacal complex. Precipitate

180 in landfill environments strongly relates to organic decomposition and the formation of

181 microorganisms during the process of methanogenesis (Li et al., 2015). According to Fig 3,

182 precipitation is unlikely to occur in strongly acidic conditions except for Fe, Al, Pb and Zn.
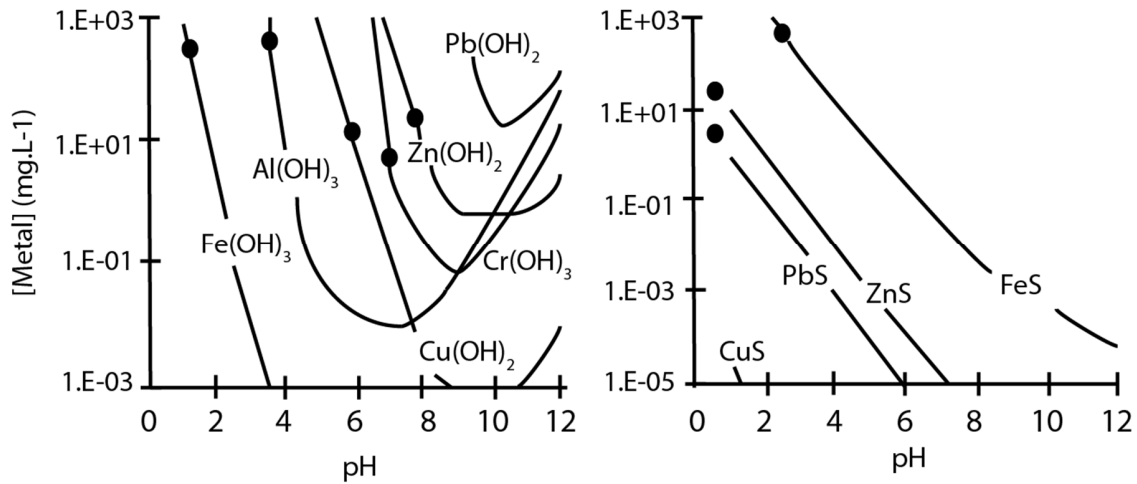
183
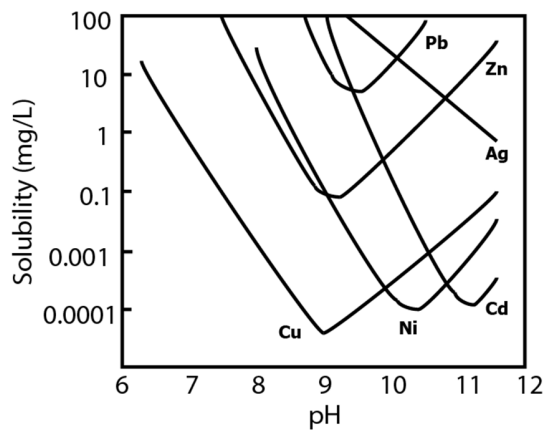
184

185 **Figure 3.** Solubility of metal hydroxides as a function of pH (Marchioretto et al., 2005)

186 Marchioretto *et al.* (2005) reported that when Fe and Al are present in landfill leachate, adsorption

187 and co-precipitation may occur between Cr, Pb, and Zn with Fe(OH)3 and Al(OH)3 as pH increases.

188 The leachability of metals is also influenced by the chemical and physical affinity of metal ions

189 and various waste materials under landfill conditions (Ward et al., 2005). Sulphates in waste are

190 reduced to sulphide that forms insoluble precipitates with most metals or containing amino acids

191 during anaerobic (Christensen et al., 2001). Dissimilatory microbial sulphate reduction is when

192 certain bacteria use sulphate as the electron acceptor in the oxidation of organic matter. However,

193 Cr does not form an insoluble sulphide; it is only precipitated out in the form of hydroxide.

194 Sulphides of the metals are more difficult to dissolve, both in oxidising and reducing environments

195 (Hammack and Edenborn, 1992).

3.1.3 Carbonation and redox

197 Carbonates are also capable of forming precipitates with metals and are abundant in landfill

198 leachate. Nevertheless, the solubility of metal carbonates is generally high (Christensen et al.,

199 2000). Metal precipites of carbonate will dissolve, where the carbonate release will buffer the pH

200 value as the pH decreases, which is called the humic phase (Kjeldsen et al., 2010). As attenuation

201 mechanisms affect metal concentration and stability, it should be considered the metal adsorption

202 and precipitation-pH relationship for recovering metals with high concentration from an economic

203 point of view. The redox potential influences precipitation and should be considered when

204 considering metal solubility. Redox potential is a measure of the propensity of a chemical or

205 biological species to either acquire or lose electrons through ionisation (Lu and Marshall, 2013).

206 Various parameters in landfill leachate can reflect transformations in redox potential. For example,

207 as sulphate is reduced, their concentrations decrease. An increase in redox potential effects on the

208 oxidation of reduced sulphur compounds to SO_4^{2-}. Oxidation of metal sulphides takes place,

209 leading to metals release. The redox conditions in landfill leachate affect metal-organic interactions

210 through the organic ligands, as organics are sensitive to redox conditions (Merian and Clarkson,

211 1991). Abundant OM tends to have low redox potential values. The speciation of metals, which is

212 related to their mobility, is dependent on pH, redox, and organic compounds (Baun and Christensen,

213 2004). Each of the oxidation states has different metal complexation constants, and organic

214 compounds may mobilise it to an extent critically dependent upon the redox conditions (Herbert et

215   al., 1993). For example, Tingzong *et al.* (1997) found that Pb was bound to iron and manganese

216   hydroxide under oxidised conditions. As the landfilled waste shifted to reducing conditions, Pb

217   was leached out. Chuan *et al.* (1996) also reported that the solubility of Pb, Cd and Zn in soils

218   increased when redox potential decreased, and this was due to the dissolution of Fe-Mn ox-

219   hydroxides under reducing conditions resulting in the release of metals. In contrast, Sims and

220   Patrick (1978) found that soluble Zn decreased at low redox potential, which may be caused by

221   different environmental conditions and soil types. Also, Kamon *et al.* (2002) found that low redox

222   potential and alkaline conditions induced by anaerobic respiration in landfill sites tend to prompt

223   immobilization of Zn but a mobilization of Iron. Overall, redox potential strongly affects the

224   behaviour of metals in leachate even though there uncertainty remains regarding to what degree

225   such as different environmental conditions.

226   **3.2   Organic matter decomposition and metal leachability**

227   As landfill age increases, the leachate passes through successive stages of organic substance

228   decomposition, which influences metal leachability. Metal leachability is highest when

229   hydrolysis, fermentation and acetogenesis dominate due to an accumulation of VFA and a pH

230   decrease (Fig 4). The primary acids formed during fermentation are acetic acid (CH_3COOH),

231   propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$) and ethanol (C_2H_5OH).

232   Carboxylic acids act as chelating agents, and there may be an increase in carboxylic functional

233   groups on humic compounds due to the waste being oxidised (Kjeldsen et al., 2010). Qu *et al.*

234   (2008) demonstrated that metals in leachate are bound to organic substances such as fatty acids,

235   FAs and HAs. The fatty acids, FAs, and HAs content in leachates decrease as landfill age

236   increases (Fan et al., 2006; He et al., 2006; Qu et al., 2008). The fatty acids are accumulated

237   during the acid phase of the waste stabilisation (Christensen and Kjeldsen, 1989). FA

238 predominates in young unstable leachates, and its concentration decreases as landfill age

239 increases. The HA-forming processes are dependent on microbial degradation of OM, and the HA

240 increases with the age of leachate, eventually reducing due to the leachate becomes more stable

241 and diluted (Artiola-Fortuny and Fuller, 1982). HA has more carboxylic groups than FA and

242 contains bands of aromatic C=C (Gustafsson and Berggren, 2005; Shirshova et al., 2006). The

243 binding capacities of HS to metals within leachate and solid waste may imply that the solubility

244 of HS strongly influences the mobility of metals (Qu et al., 2008). To the best of our knowledge,

245 no work has been reported on the effects of organic matter decomposition on metal release in

246 landfill environments. It is expected that different metals have different impacts on the

247 decomposition processes of organic matter. Further research is required on the role of organic

248 matter degradation on the release of individual metals.

Age	Leachate pH value
< 5 years	6.5
5 -10 years	6.5-7.5
> 10 years	> 7.5

249
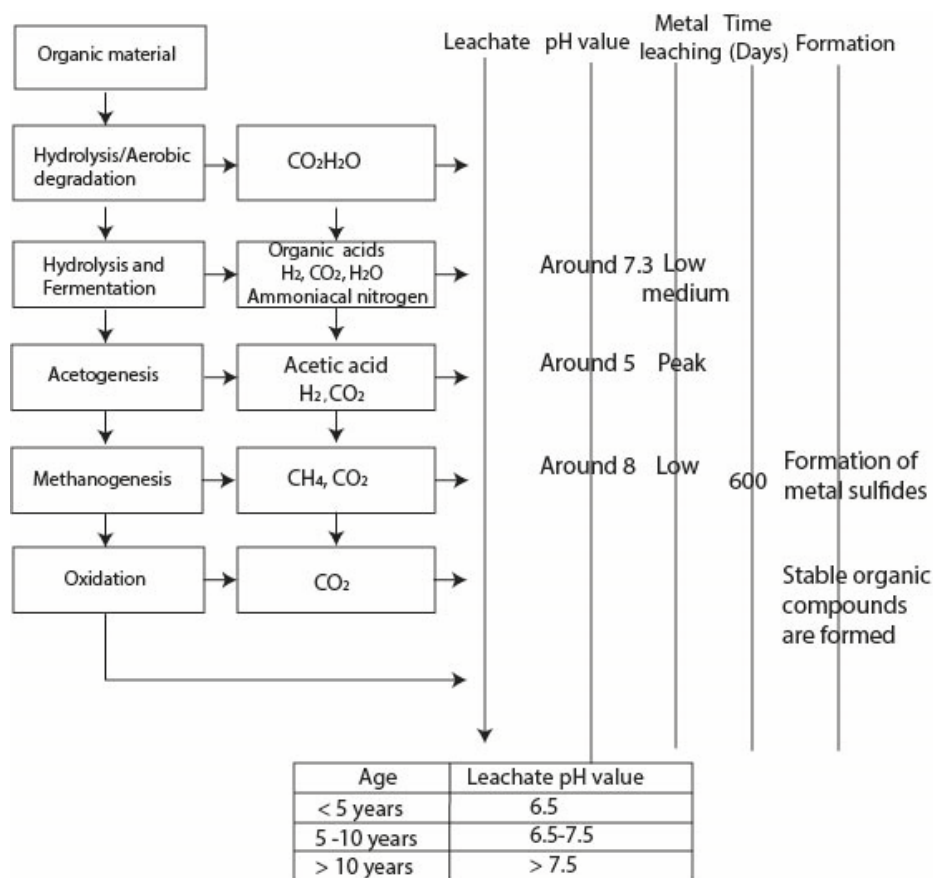
Figure 4. Metal leaching Process in a landfill and leachate pH value (Adapted from Zainol et al., 2012, Adhikari et al., 2014)

3.3 Chelation and complexation with organic substances

Most metal ions bind to neutral molecules in different oxidation states called a ligand, defined as an ion or molecule that binds to a central metal atom to form a complex (both organic; carboxylic acids, amino acids, HAs and inorganic) (Table 4). Ligands lead to the formation of metal complexes and metal chelates (Fig 5). Complexation with organic ligands is known to influence the mobility of metal by either increasing or decreasing its sorption on mineral surfaces. Many organic substances have been commonly identified in leachates worldwide (Details in supplementary data Table 1) (Paxéus, 2000; Staley et al., 2006; Zhang and Zhang, 2009).

260   **Table 4.** Mechanisms of adsorption for organic compounds in soils (adapted from Sposito, 1984)

Mechanisms	Principal organic functional group
Cation exchange protonation	amines, ring NH, heterocyclic N amines, ring NH, Heterocyclic N, carbonyl, carboxylate
Anion exchange water bridging	carboxylate amino, carboxylate, carbonyl alcoholic OH
Cation bridging	carboxylate, amines, carbonyl, alcoholic OH
Ligand exchange hydrogen bonding	carboxylate amines, carbonyl, carboxyl, phenylhydroxyl
Van der waals bonding	uncharged, nonpolar organic functional groups

261

262   Among the organic ligands, HS are the main organic compounds present in landfill leachate (Zhou

263   et al., 2015). HS are the main component of soil OM or humus, most of which combine with the

264   inorganic constituents in the soil (Pettit, 2004). HS have several functional chemical groups

265   (carbonyl, hydroxyl carboxylic acid, phenolic ring, and quinine), which may combine with ions

266   such as Fe^{3+}, Mg^{2+}, and Ca^{2+} and form chelate complexes (Fig 6); thus change the solubility of

267   metals (Tipping et al., 2002). Generally, the potential for complex formation between metals and

268   organics increases with pH alkalisation (Hummel et al., 2000). Farrah and Pickering (1997a)

269   showed that the proportions of metal bound as hydroxyl complexes increase at pH 5 and above

270   although the capacity for complexation shows no dependence on pH (Antelo et al., 2000). Instead

271   the metal-organic interaction depends on the stability of complex formation and metal

272   concentration. Esakku *et al.* (2003) reported higher stability constants for Cu complexes with OM

273   and that these lead to higher Cu content in the organic fraction.

274   Phenolate, amino, and carboxylate groups enhance the formation of metal complexes at high pH,

275   thus become increasingly stable at higher pH levels (Rieuwerts et al., 1998). Carboxylic and

276   hydroxyl functional groups show acid-base behaviour.

277
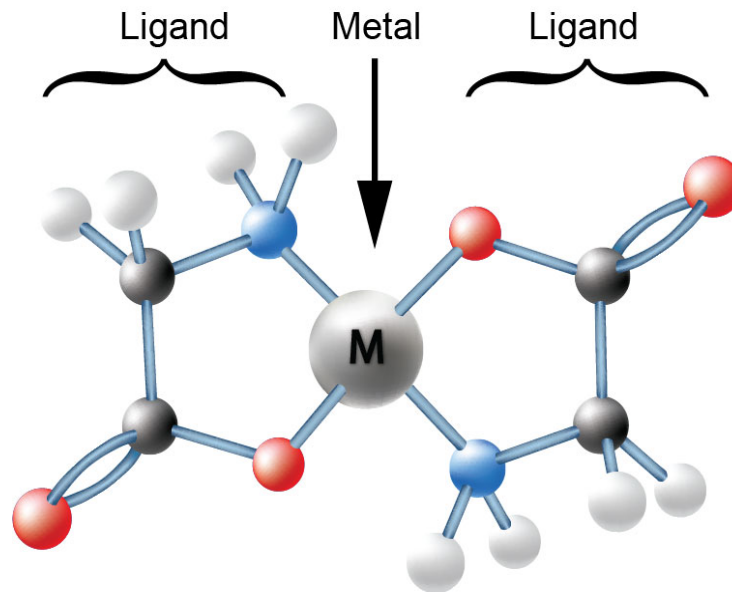
278

279   **Figure 5.** An amino acid chelates (Albion Technology, 2021)

280   At low pH, hydrogen ions compete with the metal ions for these sites, and as pH increases, less

281   hydrogen ions are present and complex site availability for metal ions increases (Scott et al., 2005).

282   There are challenges to understanding the complexation of different metal ions, e.g. i) organic

283   compound functional groups influence the type of reaction it has with metals; and ii) the length of

284   hydrocarbon chain length in carboxylic acid increases its metals adsorption capacity but decreases

285   its stability as complex (Abollino et al., 2003).

286
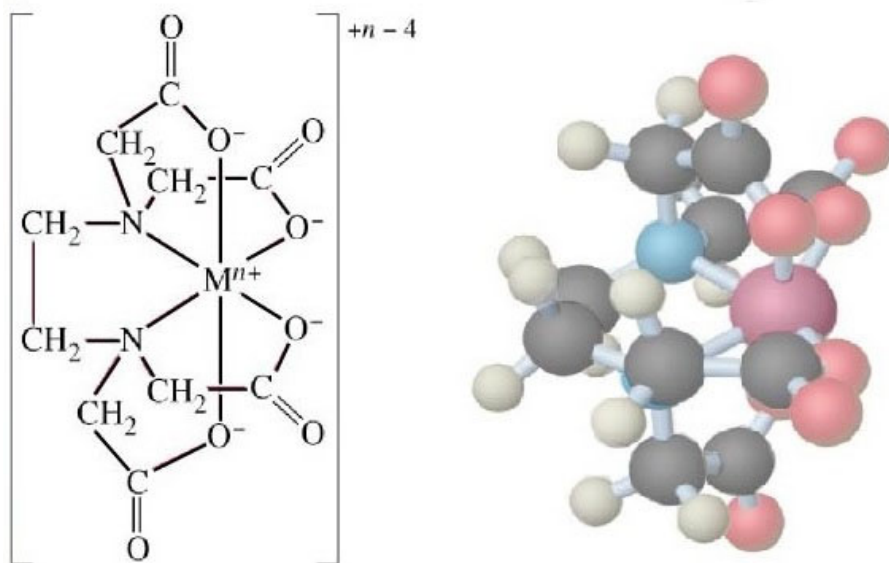
Figure 6. Metal ion complexation and chelate effect (Adapted from Tsezos et al., 2006)

288   Soil organic matter can influence the mobility and speciation of metal, where complexation

289   reactions modify its accumulation potential (Kennou et al., 2015). For example, when organic

290   materials, rich in soluble organic carbon and a large proportion of FAs are applied to soil, metal

291   mobility increases due to the formation of soluble metal-organic complex (Pérez-Esteban et al.,

292   2014). In contrast, when a chelating agent binds to a metal ion in more than one place

293   simultaneously, chelated compounds become more stable (Pohlmeier, 2004). It has long been

294   recognised that complexation may lead to increase metal solubility or decrease adsorption

295   (Cavallaro and McBride, 1978; Bradl, 2004; Güngör and Bekbölet, 2010; Ahmed et al., 2019).

296   Similar observations have been shown to occur within the landfilled waste. A variety of organic

297   compounds can be expected in the leachates, which afford the potential for metal-organic

298   interactions through the organic ligands. Previous studies established that dissolved organic matter

299   (DOM) in MSW has a high affinity for metals, especially for Cu and Pb (Christensen et al., 1996;

18

300　Christensen et al., 2000; Huo et al., 2008). Most insoluble metals are present in their refractory

301　chemical form, i.e. PbSO4. Over time the oxidation/ reduction of these metals to a soluble form

302　through complexation appears likely (Takahashi et al., 2010). If insoluble metal-DOM complexes

303　are formed, the mobility of the metals in question and the DOM to which they are complex

304　decreases. Metal mobility is less clear when soluble complexes are created with DOM (Jansen et

305　al., 2003). On the one hand, it may increase because, i) the mobility of DOM is affected by its

306　functional groups and adsorption to soil particles (Kaiser et al., 1997); ii) binding to DOM prevents

307　immobilisation by precipitation of inorganic metal complexes. On the other hand, the mobility of

308　soluble metal-DOM could decrease complexes when they bind to soil particles through cation

309　bridging (Guggenberger and Zech, 1993).

310　The leachability of metals could be enhanced through ligand complexation where organic acids

311　such as carboxylic acids and phenols, formed during the decomposition of organic compounds,

312　decrease pH. The pH determines the number of acidic functional groups on deprotonated DOM,

313　which increases the availability of sorption sites for binding metals (Stevenson, 1994).

314　Jensen *et al.* (1999b) determined organic complexes of heavy metals in landfill leachate polluted

315　groundwater in the Vejen landfill. They found that organic complexes made up a significant part of

316　the total content of heavy metals: Cd 85%, Ni 27-62%, Zn 16-36%, Cu 59-95%, and Pb 71-91%.

317　Kalis *et al.* (2006) found that the metal-humic acid complexes become the dominant complexed

318　species when humic acid is present. Yu *et al.* (2018) reported that most of the complexes between

319　Cd and the HS would be insoluble, and the complexation could contribute significantly to the

320　reduction in the concentration of Cd in soil solution. Van Ginneken *et al.* (2001) discovered that

321　the stability of chelated metals and noncyclic metal complexes depends on several factors,

322 including pH, metal oxidation state, and ionic strength. Organic-metal complexes are increasingly

323 stable at higher pH levels due to the ionization of functional groups (Jones and Jarvis, 1981;

324 Rieuwerts et al., 1998). Conversely, organic acids present in the dissolved organic carbon (DOC)

325 may act as chelating agents, enhancing the mobilisation of metals (Christensen et al., 1996).

326 Complexing behaviour significantly influences metal attenuation as it affects their mobility and

327 saturation indices (Qu et al., 2019). As metal-organic complexation plays a critical role in the

328 mobility of metals in landfill environments, lab and field experiments would be required to

329 establish the relationship between complexing characteristics and observed metals leaching,

330 performed under varying environmental conditions to optimise metals recovery.

331 **4   LEACHATE RECIRCULATION STRATEGY FOR METAL RECOVERY**

332 Leachate recirculation within landfills has been widely used for a range of purposes since the 1970s,

333 including leachate management, enhanced landfill gas generation or recovery, and improved

334 landfill sustainability (EPA, 2009). Leachate recirculation is a process where leachate is re-

335 introduced into the landfill through an artificial recharge system (White et al., 2011). This technique

336 aims to encourage saturation to stimulate the degradation processes, leading to more rapid

337 stabilisation of the landfill (Scott et al., 2005). However, leachate recirculation can also increase

338 the chloride content. Chloride contents may also be an important controlling factor for metal release.

339 Chloride affects the behaviour of metals by binding the metals on humic acids and the adsorption

340 of metals, such as the adsorption of Cd on iron hydroxides or their desorption mobility (Guevara-

341 Riba et al., 2005; Begeal, 2008; Damikouka and Katsiri, 2020). The ionic forms of Cu and Cd can

342 form metal compounds with the anions such as $CuCl_2$, $CdCl_2$ or $CuSO_4$, leading to chloro-

343 complexation and the formation of dissolved metal-chloride compounds increase the mobility of

metals (Kirkelund et al., 2010; Damikouka and Katsiri, 2020). This implies that leachate recirculation affects metal recovery. Leachate recirculation can significantly influence metal behaviour and fate within waste matrices (Ledakowicz and Kaczorek, 2004). For example, Yao *et al.* (2014) found that leachate recirculation contributed to faster stabilisation of the landfill and reduced leachability of Cu and Zn from the landfill. He *et al.* 2007 have also shown that recirculating leachate, which is by the sequential reactors, in landfills in the early stage allowed methanogenesis to be reached much earlier and that this was accompanied by a reduction of total metals released from landfills. In contrast, Qu *et al.* (2008) demonstrated that the initial stage of leachate recirculation had low leachate pH (5-6) and highly VFA levels (acetate 4500-700 mg/L, propionate 1450-2950 mg/L and butyrate 4500-7200 mg/L) due to the acidification stage, in resulting the concentration of the metals was high at this stage. Bilgili *et al*. (2007) showed that the release of metals can significantly increase at the beginning of leachate recirculation as in the early stages of the waste degradation, pH of the leachate is low contributing to higher solubility of metals and dissolution into leachate (Fig 7).

As stated previously, due to the low concentrations of metals, the way to make it economically viable in recovering metals is to maximise metal concentrations. Recirculating leachates will accentuate the potential for increased metal mobility within and from the landfill when oxidised conditions are introduced. Leachates have been shown to have an increased capability to enhance metal mobility when oxidised (Mårtensson et al., 1999). It implies that leachate recirculation provides higher extractable metals in the initial leaching phase.

364
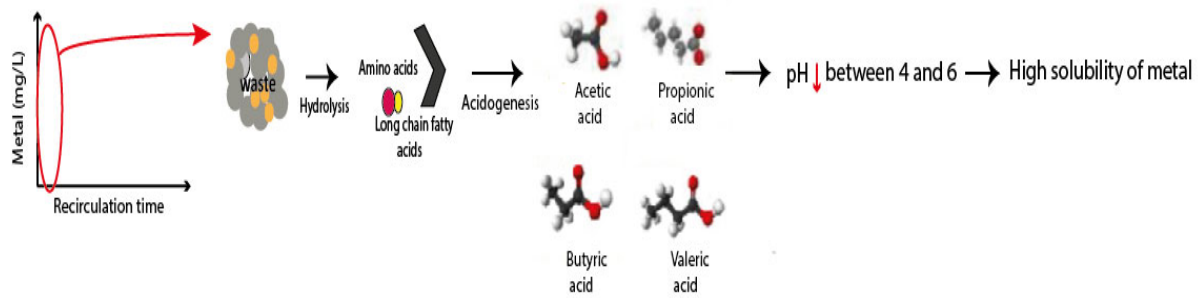
Figure 7. Leachate recirculation strategy for metal recovery

Therefore, regarding the critical challenges in metal recovery in leachate, this suggests that where leachate recirculation is applied with combining organic matter such as HA and pH could increase the economic feasibility.

5 Opportunities for metals recovery from landfill leachate

Leachate contains a wide range of metal such as Cu, Zn, Cr, Cd in addition to REEs (Kjeldsen et al., 2002). Therefore, leachate in landfill sites has a great potential for metal recovery. There are several ways for recovering metals from waste, such as recycling, physico-chemical, thermo-chemical, pyro-metallurgical, hydro-metallurgical, bio-metallurgical, landfill-mining methods (Wang et al., 2017). Due to the lack of economically and operationally feasible primary resources for the production of metals, many countries are forced to depend on recycling metals from secondary sources such as industrial residues and end-of-life products. Table 5 shows various methods to recover metals from waste streams and leachate, suggesting the possibility of recovery metals in landfill leachate. Despite published research works on recovering metals from leachate, studies are scanty in an application towards the recovery of metals from real landfill leachate in the site. The main problem to recover metals from leachate is further compounded for metals that exist

22

381   at low concentrations (Table 2), which can be affected by many factors such as landfill age, type,

382   and chemical and physical mechanism in landfill environments. Also, the strong acidic condition

383   can affect the environment; thus, it may later pose harmful risks to the environment if not managed

384   well. The concentration of metals varies widely, and REEs has a very low concentration (1 or 2

385   µg/g waste), which is limiting the economic viability of the recovery. Relatively, high

386   concentrations of over 1% are needed to approach the cost-effective recovery metals (Umeda et al.,

387   2011). Therefore, process optimisation is important to maximise the concentration of metals or co-

388   extraction of other added-value materials such as nitrogen and phosphorus, improving the process's

389   cost-effectiveness and efficiency. By understanding the processes, including organic-metal

390   interaction in leachate, recovering metal can achieve higher average productivity.

391   Barriers remain in recovering valuable materials present due to the unknown concentrations and

392   distributions of metals in landfills and not meet the reasonable financial level. Metal recovery from

393   leachate has not been investigated before, but prior studies have demonstrated that metals can be

394   recovered from wastewater and aqueous solutions. However, the methods remain limited; for

395   example, physicochemical methods are energy and capital intensive due to the costs of chemicals,

396   oxidants, and membranes; the biological treatment process is limited by treatment effectiveness

397   and energy requirement (Ahn et al., 2002; Kargi and Pamukoglu, 2003).

398

399

400

401

402

403   **Table 5.** Metals recovery from wastewater and liquid solution

Source	Method	Characteristics	Effects	Reference
Leachate from landfill waste	Bioelectrochemical systems (BES)	·BES employs biological and electrochemical reactions to recovery resources from a wide range of substrates.	·The electrical conductivity of leachate makes it favorable for electricity generation, and it contains a high concentration of ammonium nitrogen, which may be recovered for agricultural application. ·Metal also may be recovered by the modified microbial electrolysis cells.	Iskander et al., 2016
Sulfate leachate of cathode scrap of Li-ion batteries	Liquid-liquid extraction	1) The cathode scraps undergo heat treatment to completely liberate the cathodic materials from aluminum foil. 2) Solubilise Co, Li, Fe, Mn, Ni, and Al by leaching the cathodic materials in sulphuric acid in the presence of H_2O_2. 3) Oxidative precipitation of Mn from liquor with $KMnO_4$ and extraction of Al and Fe using D2EHPA. 4) Treat to recover the metals.	·Focuses on selective recovery of Co, Ni, and Li from the sulphate leachate of cathode scarp generated during the manufacture of Li ion batteries. ·High-purity Co in a solution can be recovered by solvent extraction using the sodium salt of PC-88A. ·The metals extraction efficiency and separation factor depend upon the extractant concentration and the equilibrium pH of the aqueous phase.	Nguyen et al., 2014
Solution and leachate derived from electronic scrap	Biogas	·Precipitates metals from solution using the off-gas ·Recovery Au, Pd, and Ag from leachate derived from electronic scarp; safe microbiologically	·Au was recovered from electronic scrap leachate with selectivity against Cu using biogas as they could partially separate Au from Cu. ·In acidic conditions, Au and Cu are removed rapidly and separated from the liquor. ·The solid Pd and Ag will not easily be separated in water via biogas. ·Amines must be avoided for recovering metals using biogas.	Macaskie et al., 2007

End of life electronic wastes	Hydrometallurgical process	·Ferric sulphate concentration range (at 1:10 and 1:5 Cu to sulphide molar ratio 1) filled up by using N2 gas for anaerobic conditions 2) add of 10 ml of $Na_2S \cdot 9H_2O$ solution	·Effect of Fe^{3+} on leaching of Cu and selective recovery of Cu from the polymetallic leachate. ·Lixiviant concentration and pH were the important parameters in $CuSO_4$ precipitation. ·The precipitation mostly occurs in the acidic pH range (0.5 to 1.5). ·$CuSO_4$ can be further pyro/hydrometallurgical processed to produce Cu metal.	Sethurajan and Hullebusch, 2019
Aqueous solutions	Biosorption	·The phosphorylation yeast cells were used in Cu adsorption experiments with 0.1 M HCl, which is strongly influenced by the pH of the solution. ·Recovering metals from aqueous solutions. The biosorption of metals is a complex process affected by the adsorbent, the types, and the concentrations of metals in the solution.	98% of the Cu ions adsorbed to phosphor cells could be recovered by treating the cells with HCl.	Ojima et al., 2019
Sulfuric acid leaching liquor of spent Li-ion batteries	Hydrometallurgical process	·Needs to refine the residues into a purer form such as salts, hydroxides and metals. 1) selective precipitation method by adding dimethylglyoxime (DMG, $C_4H_8N_2O_2$) reagent 2) extraction using cobalt loaded phosphoric acid (D2EHPA) 3) 4Separation and recovery of metal (Ni, Mn, Co, and Li) from sulfuric acid leaching liquor	High purities of Co and Li were recovered as $CoC_2O_4 \cdot 2H_2O$ and Li_2CO_3.	Chen et al., 2015
Acid mine leachate	Sequential precipitation	1) Sequential precipitation; add a sodium hydroxide solution of 5 M 2) Selective dissolution; pre-concentrates of the valuable elements were re-dissolved into solution 3) Oxalic acid precipitation;	·95% of the Cu and Zn were recovered from the residual liquid using Na_2S at pH 2 and 3.	Zhang and Honaker, 2020

		dissolving 8 g oxalic acid dehydrate in 50 ml deionised water using an ultrasonic batch 4) Na_2S precipitation; 1 M Na_2S REEs, Cu, Zn Ni and Co recovery from an acid mining leachate. The sample was collected from a coal preparation plant.	·The optimise the oxalic precipitation for the REE recovery is using a solution pH of 1.2	
Sludge	Precipitation	·Add 3 mol dm^{-3} NaOH, ·The recovery process of heavy metals from polluted sludge leachate with biosurfactant elution by batch and column experiments.	The recovery efficiency of heavy metals (Pb, Ni, and Cr) reached over 90% by the precipitation method with pH 10.9.	Gao et al., 2012
Wastewater	Cementation	·Add Fe, Al, and Zn metallic powders into 250 mL of wastewater ·Stir continuously with a magnetic stirrer	·Cu, Au, and Pd can be recovered by using Fe and Al powder. ·Precious metals can be effectively recovered by combining processes (cementation, neutralisation and reduction)	Umeda et al., 2011
Wastewater	Photoelectrochemical cell	·A stock solution was prepared by dissolving the metal salts into deionised water ·The photoanode and the Pt strip cathode were connected with a commercial Cu wire ·The photoanode was irradiated with a UV lamp	·Heavy metals were recovered by mechanical scratching of the cathode surface.	Wang et al., 2017
Wastewater	Electrochemical reactor	·Prepare solutions using deionised water ·Determining the quality characteristic to be optimised. ·Identification of the noise factors and test conditions. ·Identification of the control parameters.	·The highest efficiencies were obtained for Pb and Cu recovery from diluted solution: 75.8 % and 89.9 %	Kaminari et al., 2007

404

405 Bioelectrochemical systems (BES) is an environmental strategy that employs biological and

406 electrochemical reactions to generate electricity and recovery resources from a wide range of

407 substances. Organic compounds in BES tends to produce electricity and other value-added

408 compounds by oxidising microorganisms. However, a high concentration of metals in landfill

409 leachate can be recovered through BES, and the reduction in leachate volumes can be achieved

410 using osmotic processes integrated with BES. Also, hydrometallurgical processes have gained

411 considerable attention as they show effectiveness in the extraction of metals (Gunarathne et al.,

412 2020). Hydrometallurgical metal recovery is typically performed in three main stages: metal

413 dissolution, concentration and purification, and metal recovery (Gupta,2006). Thus, further

414 research should be studied to take a circular approach, recovering metals from landfill leachate

415 using BES after enhancing metal concentration through leachate recirculation or

416 hydrometallurgical processes using less toxic chemical solvents to be used as leaching agents and

417 assist of acids and pH value.

418 **6   Conclusion**

419 The literature review on landfills has shown a metals recovery opportunities in landfill leachate

420 using factors influencing metal mobility in landfill environments. Landfill leachate is a significant

421 potential resource in landfill as it contains a large variety of dissolved extractable metals. Metal's

422 recovery opportunities may increase by several factors, influencing metal mobility in landfill

423 environments as an excellent challenge for metal recovery from leachate is the low concentration

424 of metals. Younger landfill leachate (>5 years old) has higher organic matter content due to the

425 generation of dissolved and solubilised organic matter, consequently increasing metal release.

426 Therefore, it implies that metal recovery may be effective in younger landfill leachate. Physio-

427 chemical processes affect soluble metal concentration, which is critical to predicting metal recovery

428 as they can govern the mobility of metals. More knowledge is required concerning the complexes

429 in leachate in general and specifically on the importance of the organic matter in leachate, which

430 led to an increase in the metal release rate. This article has also identified the gaps and has indicated

431 that further efforts are required concerning leachate recirculation. It may ensure that maximising

432 the concentration of metals from landfill leachate will be the economic feasible. Although mature

433 technological advances provide opportunities for recovering metals from landfill leachate,

434 significant challenges await us ahead as they can hardly be regarded as economical. Therefore, the

435 chemistry mechanism of landfill environments should be well understood and fundamental and

436 practical barriers of the recovering process in landfill leachate, which will lead us one step closer

437 to resource recovery paradigm for a circular economy in closed landfill.

References

439 Abbar, B., Alem, A., Marcotte, S., Pantet, A., Ahfir, N.D., Bizet, L., Duriatti, D., 2017.
440 Experimental investigation on removal of heavy metals (Cu2+, Pb2+, and Zn2+) from aqueous
441 solution by flax fibres. Process Saf. Environ. Prot. 109, 639–647.

442 Abbas, A.A., Jingsong, G., Ping, L.Z., Ya, P.Y., Al-Rekabi, W.S., 2009. Review on landfill
443 leachate treatments. Am. J. Appl. Sci. 6, 672–684.

444 Abdel-Shafy, H.I., Mansour, M.S.M., 2018. Solid waste issue: Sources, composition, disposal,
445 recycling, and valorisation. Egypt. J. Pet. 27, 1275–1290.

446 Abollino, O., Aceto, M., Malandrino, M., Sarzanini, C., Mentasti, E., 2003. Adsorption of heavy
447 metals on Na-montmorillonite. Effect of pH and organic substances. Water Res. 37, 1619–1627.

448 Adamcová, D., Vaverková, M.D., Bartoň, S., Havlíček, Z., Břoušková, E., 2016. Soil
449 contamination in landfills: A case study of a landfill in Czech Republic. Solid Earth 7, 239–247.

450 Adhikari, B., Dahal, K.R., Khanal, S.N., 2014. A review of factors affecting the composition of
451 municipal solid waste landfill leachate. Int. J. Eng. Sci. Innov. Tech 3, 272–281.

452   Ahmed, H.H., Aglan, H.A., Mabrouk, M., Abd-Rabou, A.A., Beherei, H.H., 2019. Enhanced
453   mesenchymal stem cell proliferation through complexation of selenium/titanium nanocomposites.
454   J. Mater. Sci. Mater. Med. 30. https://doi.org/10.1007/s10856-019-6224-z

455   Akinbile, C.O., Yusoff, M.S., Ahmad Zuki, A.Z., 2012. Landfill leachate treatment using sub-
456   surface flow constructed wetland by Cyperus haspan. Waste Manag. 32, 1387–1393.

457   Albion   ®   Technology,   2021.   https://balchem.com/plant-nutrition/wp-
458   content/uploads/sites/4/2021/03/Plant_newsletter_ChelationAndTheMetalosateProducts.pdf

459   Antelo, J.M., Arce, F., Penedo, F.J., 2000. Effect of pH on the complexation parameters for organic
460   matter   dissolved   in   river   water.   Chem.   Special.   Bioavailab.   12,   9–15.
461   https://doi.org/10.3184/095422900782775580

462   Artiola-Fortuny, J., Fuller, W.H., 1982. Humic substances in landfill leachates: Humic acid
463   extraction and identification. J. Environ. Qual. 11,663-668.

464   Aucott, M., 2006. The fate of heavy metals in landfills: A Review by "Industrial Ecology, Pollution
465   Prevention and the NY-NJ Harbor." Atmos. Environ. 9, 47–53.

466   Baun, D.L., Christensen, T.H., 2004. Speciation of heavy metals in landfill leachate: A review.
467   Waste Manag. Res. 22, 3–23. https://doi.org/10.1177/0734242X04042146

468   Beaven, R.P., Hudson, A.P., Knox, K., Powrie, W., Robinson, J.P., 2013. Clogging of landfill tyre
469   and aggregate drainage layers by methanogenic leachate and implications for practice. Waste
470   Manag. 33, 431–444. https://doi.org/10.1016/J.WASMAN.2012.10.021

471   Begeal, C.J., 2008. The effect of chloride ion concentration on heavy metal partitioning and
472   transport in an urban watershed: Patroon Creek, Albany, NY.

473   Bhalla, B., Saini, M.S., Jha, M.K., 2013. Effect of Age and Seasonal Variations on Leachate
474   Characteristics of Municipal Solid Waste Landfill. Int. J. Res. Eng. Technol. 02, 223–232.
475   https://doi.org/10.15623/ijret.2013.0208037

476   Bilgili, M.S., Demir, A., Özkaya, B., 2007. Influence of leachate recirculation on aerobic and
477   anaerobic   decomposition   of   solid   wastes.   J.   Hazard.   Mater.   143,   177–183.
478   https://doi.org/10.1016/J.JHAZMAT.2006.09.012

479   Borglin, S.E., Hazen, T.C., Oldenburg, C.M., Zawislanski, P.T., 2004. Comparison of Aerobic and
480   Anaerobic Biotreatment of Municipal Solid Waste. J. Air Waste Manage. Assoc. 54, 815–822.
481   https://doi.org/10.1080/10473289.2004.10470951

482   Bozkurt, S.U., Moreno, L., Neretnieks, I., 2000. Long-term processes in waste deposits. Sci. Total
483   Environ. 250, 101–121.Calace, N., Liberatori, A., Petronio, B.M., Pietroletti, M., 2001.
484   Characteristics of different molecular weight fractions of organic matter in landfill leachate and
485   their role in soil sorption of heavy metals. Environ. Pollut. 113, 331–339.

486   Bradl, H.B., 2004. Adsorption of heavy metal ions on soils and soils constituents. J. Colloid
487   Interface Sci. 277, 1–18. https://doi.org/10.1016/J.JCIS.2004.04.005

488   Brennan, R.B., Healy, M.G., Morrison, L., Hynes, S., Norton, D., Clifford, E., 2016. Management
489   of landfill leachate: The legacy of European Union Directives. Waste Manag. 55, 355–363.
490   https://doi.org/10.1016/j.wasman.2015.10.010

491   Cavallaro, N., McBride, M.B., 1978. Copper and cadmium adsorption characteristics of selected
492   acid and calcareous soils. Soil Sci. Soc. Am. J., 42, pp. 550-556

493   Chen, X., Chen, Y., Zhou, T., Liu, D., Hu, H., Fan, S., 2015. Hydrometallurgical recovery of metal
494   values from sulfuric acid leaching liquor of spent lithium-ion batteries. Waste Manag. 38, 349–356.
495   https://doi.org/10.1016/J.WASMAN.2014.12.023

496   Chimenos, J.M., Fernández, A.I., Miralles, L., Segarra, M., Espiell, F., 2003. Short-term natural
497   weathering of MSWI bottom ash as a function of particle size. Waste Manag. 23, 887–895.
498   https://doi.org/10.1016/S0956-053X(03)00074-6

499   Christensen, J.B., Christensen, T.H., 2000. The effect of pH on the complexation of Cd, Ni and Zn
500   by dissolved organic carbon from leachate-polluted groundwater. Water Res. 34, 3743–3754.
501   https://doi.org/10.1016/S0043-1354(00)00127-5

502   Christensen, J.B., Jensen, D.L., Christensen, T.H., 1996. Effect of dissolved organic carbon on the
503   mobility of cadmium, nickel and zinc in leachate polluted groundwater. Water Res. 30, 3037–3049.
504   https://doi.org/10.1016/S0043-1354(96)00091-7

505   Christensen, T.H., Kjeldsen, P., 1989. Basic biochemical processes in landfills. In: Christensen,
506   T.H., Cossu, R., Stegmann, R. (Ed.). Sanitary landfilling: Process, technology and environmental
507   impact, Chapter 2.1. Academic Press, London, 29–49.

508   Christensen, T.H., Kjeldsen, P., Bjerg, P.L., Jensen, D.L., Christensen, J.B., Baun, A., Albrechtsen,
509   H.J., Heron, G., 2001. Biogeochemistry of landfill leachate plumes. Appl. Geochemistry 16, 659–
510   718.

511   Chuan, M.C., Shu, G.Y., Liu, J.C., 1996. Solubility of heavy metals in a contaminated soil: Effects
512   of redox potential and pH. Water Air Soil Pollut. 90, 543–556.

513 Chu. L. M, 2008. Landfills. Elsevier B.V. Encycl. Ecol. 2099–103. doi:10.1016/B978-008045405-
514 4.00345-1.

515 Chung, J., Kim, S., Baek, S., Lee, N.H., Park, S., Lee, J., Lee, H., Bae, W., 2015. Acceleration of
516 aged-landfill stabilization by combining partial nitrification and leachate recirculation: A field-
517 scale study. J. Hazard. Mater. 285, 436–444. https://doi.org/10.1016/J.JHAZMAT.2014.12.013

518 Damikouka, I., Katsiri, A., n.d. Natural attenuation in marine sediments: investigation of the effect
519 of chloride concentration on the mobility of metals. Recent Dev. Innov. Strategy. Environ. Sci. Eur.
520 https://doi.org/10.1007/s11356-020-09852-4

521 DEFRA, BIS, 2012. Resource Security Action Plan: Making the most of valuable materials.
522 London, UK. https://www.gov.uk/government/publications/resource-security-action-plan-making-
523 the-most-of-valuable-materials accessed on 25.08.18.

524 DEFRA, 2021. UK Statistics on Waste. London, UK.
525 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/
526 1002246/UK_stats_on_waste_statistical_notice_July2021_accessible_FINAL.pdf

527 Dino, G.A., Rossetti, P., Biglia, G., Sapino, M.L., Di Mauro, F., Särkkä, H., Coulon, F., Gomes,
528 D., Parejo-Bravo, L., Aranda, P.Z., Lopez, A.L., Lopez, J., Garamvolgy, E., Stojanovic, S., Pizza,
529 A., de la Feld, M., 2017. Smart ground project: A new approach to data accessibility and collection
530 for raw materials and secondary raw materials in Europe. Environ. Eng. Manag. J. 16, 1673–1684.
531 https://doi.org/10.30638/eemj.2017.182

532 Edokpayi JN, Durowoju OS, Odiyo JO (2018) Assessment of heavy metals in landfill leachate: a
533 case study of thohoyandou landfill. Heavy Met, Limpopo Province, South
534 Africa. https://doi.org/10.5772/intechopen.74009

535 Eggen, T., Moeder, M., Arukwe, A., 2010. Municipal landfill leachates: A significant source for
536 new and emerging pollutants. Sci. Total Environ. 408, 5147–5157.
537 https://doi.org/10.1016/J.SCITOTENV.2010.07.049

538 ENDS, 2001. MAPPED: England and Wales' toxic legacy landfills.
539 https://www.endsreport.com/article/1704522/mapped-england-wales-toxic-legacy-landfills

540 Environment Protection Agency (EPA), 2009. A technical assessment of leachate recirculation.
541 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file
542 /291196/scho1109brjc-e-e.pdf

543 Esakku, S., Palanivelu, K., Joseph, K., 2003. Assessment of Heavy Metals in a Municipal Solid
544 Waste Dumpsite. Workshop on Sustainable landfill Management, Chennai, India. 139–145.

545 Esguerra, J.L., Krook, J., Svensson, N., Passel, S. Van, 2019. Assessing the economic potential of
546 landfill mining: review and recommendations. Detritus 8, 125–140.

547 Esguerra, J.L., Laner, D., Svensson, N., Krook, J., 2021. Landfill mining in Europe: Assessing the
548 economic potential of value creation from generated combustibles and fines residue. Waste Manag.
549 126, 221–230. https://doi.org/10.1016/j.wasman.2021.03.013

550 EURELCO., 2017. European Parliament votes YES to include ELFM in the EU landfill directive.
551 https://www.eurelco.org/single-post/2017/03/15/European-Parliament-votes-YES-to-include-
552 Enhanced-Landfill-Mining-in-the-EU-Landfill-Directive accessed on 05.05.18.

553 European Commission, 2016. Directive 2008/98/EC of waste (Waste Framework Directive).
554 http://ec.europa.eu/environment/waste/framework/ accessed on15.05.19.

555 European Commission, 2017. Critical raw material closed loop recovery.
556 https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/critical-raw-material-
557 closed-loop-recovery accessed on 15.05.19.

558 Fan, H. jung, Shu, H.Y., Yang, H.S., Chen, W.C., 2006. Characteristics of landfill leachates in
559 central Taiwan. Sci. Total Environ. 361, 25–37.

560 Fischer, K., Chodura, A., Kotalik, J., Bieniek, D., Kettrup, A., 1997. Analysis of aliphatic
561 carboxylic acids and amino acids in effluents of landfills, composting plants and fermentation
562 plants by ion-exclusion and ion-exchange chromatography. J. Chromatogr. A 770, 229–241.

563 Francois, V., Feuillade, G., Matejka, G., Lagier, T., Skhiri, N., 2007. Leachate recirculation effects
564 on waste degradation: Study on columns. Waste Manag. 27, 1259–1272.
565 https://doi.org/10.1016/J.WASMAN.2006.07.028

566 Frändegård, P., Krook, J., Svensson, N., 2015. Integrating remediation and resource recovery: On
567 the economic conditions of landfill mining. Waste Manag. 42, 137–147.

568 Gao, L., Kano, N., Sato, Y., Li, C., Zhang, S., Imaizumi, H., 2012. Behavior and Distribution of
569 Heavy Metals Including Rare Earth Elements, Thorium, and Uranium in Sludge from Industry
570 Water Treatment Plant and Recovery Method of Metals by Biosurfactants Application. Bioinorg.
571 Chem. Appl. 2012, 11. https://doi.org/10.1155/2012/173819

572 Giannis, A., Makripodis, G., Simantiraki, F., Somara, M., Gidarakos, E., 2008. Monitoring
573 operational and leachate characteristics of an aerobic simulated landfill bioreactor. Waste Manag.
574 28, 1346–1354. https://doi.org/10.1016/J.WASMAN.2007.06.024

575 Guevara-Riba, A., Sahuquillo, A., Rubio, R., Rauret, G., 2005. Effect of chloride on heavy metal
576 mobility of harbour sediments. Anal. Bioanal. Chem. 382, 353–359.
577 https://doi.org/10.1007/s00216-005-3103-x

578 Guggenberger, G., Zech, W., 1993. Dissolved organic carbon control in acid forest soils of the
579 Fichtelgebirge (Germany) as revealed by distribution patterns and structural composition analyses.
580 Geoderma 59, 109–129. https://doi.org/10.1016/0016-7061(93)90065-S

581 Gunarathne, V., Upamali Rajapaksha, A., Vithanage, M., Alessi, D.S., Selvasembian, R., Naushad,
582 M., You, S., Oleszczuk, P., Sik Ok, Y., 2020. Hydrometallurgical processes for heavy metals
583 recovery from industrial sludges. Crit. Rev. Environ. Sci. Technol.
584 https://doi.org/10.1080/10643389.2020.1847949

585 Gungor, E.B.O., let, M., 2010. Zinc release by humic and fulvic acid as influenced by pH,
586 complexation and DOC sorption. Geoderma 159, 131–138.
587 https://doi.org/10.1016/J.GEODERMA.2010.07.004

588 Gupta, C.K., 2004. Chemical Metallurgy Principles and Practice. By Chiranjib Kumar Gupta.,
589 Angewandte Chemie International Edition. https://doi.org/10.1002/anie.200385071

590 Gustafsson, J.P., Kleja, D.B., 2005. Modeling salt-dependent proton binding by organic soils with
591 the NICA-Donnan and Stockholm Humic models. Environ. Sci. Technol. 39, 5372–5377.

592 Gutiérrez-Gutiérrez, S.C., Coulon, F., Jiang, Y., Wagland, S., 2015. Rare earth elements and
593 critical metal content of extracted landfilled material and potential recovery opportunities. Waste
594 Manag. 42, 128–136.

595 Hammack, R.W., Edenborn, H.M., 1992. Applied Micwbiology Biotechnology The removal of
596 nickel from mine waters using bacterial sulfate reduction. Appl Microbiol Biotechnol 37, 674–678.

597 He, J., Kappler, A., 2017. Recovery of precious metals from waste streams. Microb. Biotechnol.
598 10, 1194–1198.

599 He, P.J., Xue, J.F., Shao, L.M., Li, G.J., Lee, D.J., 2006. Dissolved organic matter (DOM) in
600 recycled leachate of bioreactor landfill. Water Res. 40, 1465–1473.

601 He, R., Liu, X. wen, Zhang, Z. jian, Shen, D. sheng, 2007. Characteristics of the bioreactor landfill
602 system using an anaerobic–aerobic process for nitrogen removal. Bioresour. Technol. 98, 2526–
603 2532. https://doi.org/10.1016/J.BIORTECH.2006.09.013

604 Herbert, B.E., Bertsch, P.M., Novak, J.M., 1993. Pyrene Sorption by Water-Soluble Organic
605 Carbon. Environ. Sci. Technol. 27, 398–403. https://doi.org/10.1021/es00039a021

606 Hernández-Berriel, M.C., Mañón-Salas, M.C., Buenrostro-Delgado, O., Sánchez-Yáñez, J.M.,
607 Márquez-Benavides, L., 2014. Landfill leachate recirculation. Part I: Solid waste degradation and
608 biogas production. Environ. Eng. Manag. J. 13, 2687–2695.

609 Hu, L., Long, & Y., 2019. Zinc leaching behavior in semi-aerobic landfill. Environ. Technol. 40,
610 29–36. https://doi.org/10.1080/09593330.2017.1377293

611 Huang, W., Wang, Z., Guo, Q., Wang, H., Zhou, Y., Ng, W.J., 2016. Pilot-scale landfill with
612 leachate recirculation for enhanced stabilization. Biochem. Eng. J. 105, 437–445.
613 https://doi.org/10.1016/J.BEJ.2015.10.013

614 Hughes, S.R., Gibbons, W.R., Moser, B.R. & Rich, J.O. 2013 Sustainable   multipurpose
615 biorefineries for third-generation biofuels and value-added co-products Biofuels - Economy,
616 Environment and Sustainability 2013 245 262 doi: 10.5772/62530

617 Hummel, W., Glaus, M.A., Van Loon, L.R., 2000. Trace metal-humate interactions. II. The
618 "conservative roof" model and its application. Appl. Geochemistry 15, 975–1001.
619 https://doi.org/10.1016/S0883-2927(99)00100-6

620 HUO, S., XI, B., YU, H., HE, L., FAN, S., LIU, H., 2008. Characteristics of dissolved organic
621 matter (DOM) in leachate with different landfill ages. J. Environ. Sci. 20, 492–498.
622 https://doi.org/10.1016/S1001-0742(08)62085-9

623 Iskander, S.M., Brazil, B., Novak, J.T., He, Z., 2016. Resource recovery from landfill leachate
624 using bioelectrochemical systems: Opportunities, challenges, and perspectives. Bioresour. Technol.
625 201, 347–354.

626 Iskander, S.M., Zou, S., Brazil, B., Novak, J.T., He, Z., 2017. Energy consumption by forward
627 osmosis treatment of landfill leachate for water recovery. Waste Manag. 63, 284–291.
628 https://doi.org/10.1016/j.wasman.2017.03.026

629 Jan, T.A., Azam, M., Siddiqui, K., Ali, A., Choi, I., Haq, Q.M.R., 2015. Heavy metals and human
630 health: mechanistic insight into toxicity and counter defense system of antioxidant. Int. J. Mol. Sci.
631 16, 29592-29630.

632 Jang, Y.C., Townsend, T.G., 2003. Effect of waste depth on leachate quality from laboratory
633 construction and demolition debris landfills. Environ. Eng. Sci. 20, 183-196.

634 Jensen, D.L., Ledin, A., Christensen, T.H., 1999. Speciation of heavy metals in landfill-leachate
635 polluted groundwater. Water Res. 33, 2642–2650. https://doi.org/10.1016/S0043-1354(98)00486-
636 2

637 Jiang, J., Yang, G., Deng, Z., Huang, Y., Huang, Z., Feng, X., Zhou, S., Zhang, C., 2007. Pilot-
638 scale experiment on anaerobic bioreactor landfills in China. Waste Manag. 27, 893–901.
639 https://doi.org/10.1016/J.WASMAN.2006.07.008

640 Jones, L.H.P., Jarvis, S.C., 1981. The fate of heavy metals, In D. J. Greenland and M. H. B Hayes
641 (eds.), The Chemistry of Soil Process, John Wiley & Sons, New York, pp. 593-620

642 Jones, P.T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M.,
643 Hoekstra, N., 2013. Enhanced Landfill Mining in view of multiple resource recovery: A critical
644 review. J. Clean. Prod. 55, 45–55.

645 Jones, P.T., Wille, J.E., Krook, J., 2018. 2nd ELFM Seminar in the European Parliament: 5 Lessons
646 Learned Why we need to develop a broad Dynamic Landfill Management strategy and vision for
647 Europe's 500,000 landfills. Policy Brief, EU Training Network for Resource Recovery through
648 Enhanced Landfill [WWW Document]. URL <https://kuleuven.sim2.be/wp-
649 content/uploads/2018/12/NEW-MINE-Policy-Brief-December-2018.pdf> (accessed 12.07.21).

650 Jowitt, S.M., Mudd, G.M., H Thompson, J.F., n.d. Future availability of non-renewable metal
651 resources and the influence of environmental, social, and governance conflicts on metal production.
652 https://doi.org/10.1038/s43247-020-0011-0

653 Kaiser, K., Zech, W., 1997. Competitive Sorption of Dissolved Organic Matter Fractions to Soils
654 and Related Mineral Phases. Soil Sci. Soc. Am. J. 61, 64–69.
655 https://doi.org/10.2136/sssaj1997.03615995006100010011x

656 Kaminari, N.M.S., Schultz, D.R., Ponte, M.J.J.S., Ponte, H.A., Marino, C.E.B., Neto, A.C., 2007.
657 Heavy metals recovery from industrial wastewater using Taguchi method. Chem. Eng. J. 126, 139–
658 146. https://doi.org/10.1016/J.CEJ.2006.08.024

659 Kamon, M., Zhang, H., Katsumi, T., 2002. Redox Effects on Heavy Metal Attenuation in Landfill
660 Clay Liner. Soils Found. 42, 115–126. https://doi.org/10.3208/sandf.42.3_115

661 Kalčíková, G., Vávrová, M., Zagorc-Končan, J., Gotvajn, A.Ž., 2011. Seasonal variations in
662 municipal landfill leachate quality. Manag. Environ. Qual. An Int. J. 22, 612–619.

663 Kalis, E.J.J., Temminghoff, E.J.M., Weng, L., Van Riemsdijk, W.H., 2006. Effects of humic acid
664 and competing cations on metal uptake by Lolium perenne. Environ. Toxicol. Chem. 25, 702–711.
665 https://doi.org/10.1897/04-576R.1

666 Kargi, F., Pamukoglu, M.Y., 2003. Simultaneous adsorption and biological treatment of pre-treated
667 landfill leachate by fed-batch operation. Process Biochem. 38, 1413–1420.
668 https://doi.org/10.1016/S0032-9592(03)00030-X

669 Kaza, Silpa., Yao, Lisa C., Bhada-Tata, Perinaz., Van Woerden, Frank. 2018. What a Waste 2.0:
670 A Global Snapshot of Solid Waste Management to 2050. Urban Development; Washington, DC:
671 World Bank. https://openknowledge.worldbank.org/handle/10986/30317

672 Kennou, B., El Meray, M., Romane, A., Arjouni, Y., 2015. Assessment of heavy metal availability
673 (Pb, Cu, Cr, Cd, Zn) and speciation in contaminated soils and sediment of discharge by sequential
674 extraction. Environ. Earth Sci. 74, 5849–5858. https://doi.org/10.1007/s12665-015-4609-y

675 Kirkelund, G.M., Jensen, P.E., Villumsen, A., Ottosen, L.M., 2010. Test of electrodialytic
676 upgrading of MSWI APC residue in pilot scale: focus on reduced metal and salt leaching.
677 https://doi.org/10.1007/s10800-009-0059-0

678 Kjeldsen, K.U., Jakobsen, T.F., Glastrup, J., Ingvorsen, K., 2010. Desulfosalsimonas propionicica
679 gen. nov., sp. nov., a halophilic, sulfate-reducing member of the family Desulfobacteraceae isolated
680 from a salt-lake sediment. Int. J. Syst. Evol. Microbiol. 60, 1060–1065.

681 Kjeldsen, P., Barlaz, M.A., Rooker, A.P., Baun, A., Ledin, A., Christensen, T.H., 2002. Present and
682 long-term composition of MSW landfill leachate: A review. Crit. Rev. Environ. Sci. Technol. 32,
683 297–336.

684 Klavins, M., Eglite, L., Zicmanis, A., 2006. Immobilized humic substances as sorbents.
685 Chemosphere 62, 1500–1506. https://doi.org/10.1016/J.Chemosphere.2005.06.015

686 Kochany, J., Smith, W., 2001. Application of humic substances in environmental remediation. In:
687 WM'01 Conference.

688 Krook, J., Svensson, N., Van Acker, K., & Van Passel, S., 2018. How to Evaluate (Enhanced)
689 Landfill Mining: A Critical Review of REcent Environmental and Economic Assessments. In P. T.

690 Jansen, B., Nierop, K.G.J., Verstraten, J.M., 2003. Mobility of Fe(II), Fe(III) and Al in acidic forest
691 soils mediated by dissolved organic matter: influence of solution pH and metal/organic carbon
692 ratios. Geoderma 113, 323–340. https://doi.org/10.1016/S0016-7061(02)00368-3

693 Jones & L. Machiels (Eds.), 4th International Symposium on Enhanced Landfill Mining, 317–332.
694 Mechelen, Belgium.

695 Kulikowska, D., Klimiuk, E., 2008. The effect of landfill age on municipal leachate composition.
696 Bioresour. Technol. 99, 5981–5985.

697 Kurniawan, T.A., Singh, D., Avtar, R., Othman, M.H.D., Hwang, G.H., Albadarin, A.B.,
698 Rezakazemi, M., Setiadi, T., Shirazian, S., 2021. Resource recovery from landfill leachate: An

699 experimental investigation and perspectives. Chemosphere 274.
700 https://doi.org/10.1016/j.chemosphere.2021.129986

701 Ledakowicz, S., Kaczorek, K., 2004. Laboratory Simulation of Anaerobic Digestion of Municipal
702 Solid Waste. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 39, 859–871.

703 Leung. W.H., Kimao. A., 1997. Soil amendment with humic acid and phosphate to promote
704 sorption and retard mobility of zinc. Virginia J. Sci. 48, 251-258

705 Li, L., Dunn, J.B., Zhang, X.X., Gaines, L., Chen, R.J., Wu, F., Amine, K., 2013. Recovery of
706 metals from spent lithium-ion batteries with organic acids as leaching reagents and environmental
707 assessment. J. Power Sources 233, 180–189.

708 Li, Z., Xue, Q., Liu, L., Li, J., 2015. Precipitates in landfill leachate mediated by dissolved organic
709 matters. J. Hazard. Mater. 287, 278–286. https://doi.org/10.1016/J.JHAZMAT.2015.01.059

710 Lu Y., Marshall N.M., 2013. Redox Potential. In: Roberts G.C.K. (eds) Encyclopedia of
711 Biophysics. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-16712-6_19

712 Lukman, S., Essa, M.H., Mu'Azu, N.D., Bukhari, A., 2013. Coupled electrokinetics-adsorption
713 technique for simultaneous removal of heavy metals and organics from saline-sodic soil. Sci.
714 World J. 2013. https://doi.org/10.1155/2013/346910

715 Macaskie, L.E., Creamer, N.J., Essa, A.M.M., Brown, N.L., 2007. ARTICLE A New Approach
716 for the Recovery of Precious Metals from Solution and From Leachates Derived From Electronic
717 Scrap. Biotechnol. Bioeng 96, 631–639. https://doi.org/10.1002/bit.21108

718 Marchioretto, M.M., Bruning, H., Rulkens, W., 2005. Heavy metals precipitation in sewage sludge.
719 Sep. Sci. Technol. 40, 3393–3405.

720 Mårtensson, A.M., Aulin, C., Wahlberg, O., Ågren, S., 1999. Effect of humic substances on the
721 mobility of toxic metals in a mature landfill. Waste Manag. Res. 17, 296–304.

722 Meima, J.A., Comans, R.N.J., 1997. Geochemical modeling of weathering reactions in municipal
723 solid waste incinerator bottom ash. Environ. Sci. Technol. 31, 1269–1276.
724 https://doi.org/10.1021/es9603158

725 Meima, J.A., Comans, R.N.J., 1999. The leaching of trace elements from municipal solid waste
726 incinerator bottom ash at different stages of weathering. Appl. Geochemistry 14, 159–171.
727 https://doi.org/10.1016/S0883-2927(98)00047-X

728 Merian E., Clarkson TW., 1991. Metals and their compounds in the environment. VCH, Weinheim

729 Molaey, R., Yesil, H., Calli, B., Tugtas, A.E., 2021. Influence of volatile fatty acids in anaerobic
730 bioleaching of potentially toxic metals. J. Environ. Manage. 285, 112118.
731 https://doi.org/10.1016/J.JENVMAN.2021.112118

732 Moody, C.M., Townsend, T.G., 2017. A comparison of landfill leachates based on waste
733 composition. Waste Manag. 63, 267–274.

734 Nguyen, V.T., Lee, J.C., Jeong, J., Kim, B.S., Pandey, B.D., 2014. Selective recovery of cobalt,
735 nickel and lithium from sulfate leachate of cathode scrap of Li-ion batteries using liquid-liquid
736 extraction. Met. Mater. Int. 20, 357–365. https://doi.org/10.1007/s12540-014-1016-y

737 Ojima, Y., Kosako, S., Kihara, M., Miyoshi, N., Igarashi, K., Azuma, M., n.d. Recovering metals
738 from aqueous solutions by biosorption onto phosphorylated dry baker's yeast OPEN.
739 https://doi.org/10.1038/s41598-018-36306-2

740 Öman, C.B., Junestedt, C., 2008. Chemical characterisation of landfill leachates - 400 parameters
741 and compounds. Waste Manag. 28, 1876–1891.

742 Parrodi, J.C.H., López, C.G., Küppers, B., Raulf, K., Vollprecht, D., Pretz, T., Pomberger, R., 2019.
743 Case study on enhanced landfill mining at mont-saintguibert landfill in Belgium: Characterization
744 and potential of fine fractions. Detritus 8, 47–61. https://doi.org/10.31025/2611-4135/2019.13877

745 Paxéus, N., 2000. Organic compounds in municipal landfill leachates. Water Sci. Technol. 42, 323–
746 333.

747 Pérez-Esteban, J., Escolástico, C., Masaguer, A., Vargas, C., Moliner, A., 2014. Soluble organic
748 carbon and pH of organic amendments affect metal mobility and chemical speciation in mine soils.
749 Chemosphere 103, 164–171.

750 Peters, R.W., Shem, L., 1993. Separation of Heavy metals: Removal from Industrial Wastewaters
751 and Contaminated Soil. No. ANL/ES/CP-78514; CONF-9303107-1, Argonne National Lab:
752 Lemont, IL, USA.

753 Pettit, R.E., 2004. Organic matter, humus, humate, humic acid, fulvic acid and humin: Their
754 importance in soil fertility and plant health. CTI Research.
755 http://www.humates.com/pdf/ORGANICMATTERPettit.pdf accessed on 16.09.19.

756 Pohlmeier, A, 2004. Metal speciation, chelation and complexing ligands in plants. M.N.V. Prasad,
757 J. Hagemeyer (Eds.), Heavy metal stress in plants: from biomolecules to ecosystem. Springer, New
758 Delhi

759 Polettini, A., Pomi, R., Valente, M., 2004. Remediation of a Heavy Metal-Contaminated Soil by
760 Means of Agglomeration. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 39,
761 999–1010. https://doi.org/10.1081/ESE-120028409

762 Qu, C., Chen, W., Hu, X., Cai, P., Chen, C., Yu, X.Y., Huang, Q., 2019. Heavy metal behaviour at
763 mineral-organo interfaces: Mechanisms, modelling and influence factors. Environ. Int. 131,
764 104995. https://doi.org/10.1016/J.ENVINT.2019.104995

765 Qu, X., He, P.J., Shao, L.M., Lee, D.J., 2008. Heavy metals mobility in full-scale bioreactor landfill:
766 Initial stage. Chemosphere 70, 769–777.

767 Renou, S., Givaudan, J.G., Poulain, S., Dirassouyan, F., Moulin, P., 2008. Landfill leachate
768 treatment: Review   and   opportunity.   J.   Hazard.   Mater.   150,   468–493.
769 https://doi.org/10.1016/J.JHAZMAT.2007.09.077

770 Rieuwerts, J.S., Thornton, I., Farago, M.E., Ashmore, M.R., 1998. Factors influencing metal
771 bioavailability in soils: Preliminary investigations for the development of a critical loads approach
772 for metals. Chem. Special. Bioavailab. 10, 61–75. https://doi.org/10.3184/095422998782775835

773 Rivas, E., Ángeles Martín-Lara, M., Blázquez, G., Pérez, A., Calero, M., n.d. Column Leaching
774 Tests to Valorize a Solid Waste from the Decommissioning of Coal-Fired Power Plants.
775 https://doi.org/10.3390/en12091684

776 Saffarzadeh, A., Shimaoka, T., Wei, Y., Gardner, K.H., Musselman, C.N., 2011. Impacts of natural
777 weathering on the transformation/neoformation processes in landfilled MSWI bottom ash: A
778 geoenvironmental   perspective.   Waste   Manag.   31,   2440–2454.
779 https://doi.org/10.1016/J.WASMAN.2011.07.017

780 Samudro, G., Mangkoedihardjo, S., 2010. Review on Bod , Cod and Bod / Cod Ratio : a Triangle
781 Zone for Toxic , Biodegradable and Stable Levels 2, 235–239.

782 Šan, I., Onay, T.T., 2001. Impact of various leachate recirculation regimes on municipal solid waste
783 degradation. J. Hazard. Mater. 87, 259–271. https://doi.org/10.1016/S0304-3894(01)00290-4

784 Särkkä H., Kaartinen T., Hannus E., Hirvonen S., Valjus T., Lerssi J., Dino GA., Rossetti P.,
785 Griffiths Z., Wagland S.T., Coulon F. 2018. Investigation of municipal solid waste (MSW) and
786 industrial landfills as a potential source of secondary materials. Detritus. 01: 83-90.

787 Scott, J., Beydoun, D., Amal, R., Low, G., Cattle, J., 2005. Landfill management, leachate
788 generation, and leach testing of solid wastes in Australia and overseas. Crit. Rev. Environ. Sci.
789 Technol. 35, 239–332. https://doi.org/10.1080/10643380590917969

790 Sethurajan, M., Van Hullebusch, E.D., n.d. metals Leaching and Selective Recovery of Cu from
791 Printed Circuit Boards. https://doi.org/10.3390/met9101034

792 Shirshova, L.T., Ghabbour, E.A., Davies, G., 2006. Spectroscopic characterisation of humic acid
793 fractions isolated from soil using different extraction procedures. Geoderma 133, 204–216.

794 Sims, J. L., & Patrick, W. H. (1978). The distribution of micronutrient cations in soil under
795 conditions of varying redox potential and pH. Soil Science Society of America Journal, 42, 258–
796 262.

797 Sponza, D.T., Ağdağ, O.N., 2004. Impact of leachate recirculation and recirculation volume on
798 stabilization of municipal solid wastes in simulated anaerobic bioreactors. Process Biochem. 39,
799 2157–2165. https://doi.org/10.1016/J.PROCBIO.2003.11.012

800 Sposito, G., The Surface Chemistry of Soils, 234 pp., Oxford Univ. Press, New York.

801 Staley, B.F., Xu, F., Cowie, S.J., Barlaz, M.A., Hater, G.R., 2006. Release of trace organic
802 compounds during the decomposition of municipal solid waste components. Environ. Sci. Technol.
803 40, 5984–5991.

804 Stevenson, F.J, 1994. Humus Chemistry. Genesis, Composition, Reactions, second ed., Wiley, New
805 York.

806 Stumm W, Morgan J, 1981. Aquatic chemistry, 2nd edn. Wiley Interscience, New York, 780 pp

807 Takahashi, F., Etoh, J., Shimaoka, T., 2010. Metal mobilization from municipal solid waste
808 incineration bottom ash through metal complexation with organic and inorganic ligands. J. Mater.
809 Cycles Waste Manag. 12, 1–9. https://doi.org/10.1007/s10163-009-0266-0

810 Takahashi, F., Shimaoka, T., 2012. The weathering of municipal solid waste incineration bottom
811 ash evaluated by some weathering indices for natural rock. Waste Manag. 32, 2294–2305.
812 https://doi.org/10.1016/J.WASMAN.2012.06.009

813 Talalaj, I.A., 2015. Mineral and organic compounds in leachate from landfill with concentrate
814 recirculation. Environ. Sci. Pollut. Res. 22, 2622–2633. https://doi.org/10.1007/s11356-014-3533-
815 0

816 Tapia, A.D.A, 2009. Required Framework and Policy Conditions for energy and waste management
817 towards sustainable development in Ecuador. Master thesis, Asia Pacific University.
818 https://www.researchgate.net/profile/Angel_Avadi/publication/235784990_Required_framework
819 _and_policy_conditions_for_energy_and_waste_management_towards_sustainable_development
820 _in_Ecuador/links/0912f51380aae78ab6000000/Required-framework-and-policy-conditions-for-

energy-and-waste-management-towards-sustainable-development-in-Ecuador.pdf Tingzong, G., DeLaune, R.D., Patrick, W.H., 1997. The influence of sediment redox chemistry on chemically active forms of arsenic, cadmium, chromium, and zinc in estuarine sediment. Environ. Int. 23, 305–316. https://doi.org/10.1016/S0160-4120(97)00033-0

Tipping, E., Rey-Castro, C., Bryan, S.E., Hamilton-Taylor, J., 2002. Al(III) and Fe(III) binding by humic substances in freshwaters, and implications for trace metal speciation. Geochim. Cosmochim. Acta 66, 3211–3224. https://doi.org/10.1016/S0016-7037(02)00930-4

Tsezos, M., Remoudaki, E., Hatzikioseyian, A., 2006. Biosorption - Principles and applications for metal immobilization from wastewater streams. Work. clean Prod. nano Technol. pp.23–33. Seoul, Korea

Umeda, H., Sasaki, A., Takahashi, K., Haga, K., Takasaki, Y., Shibayama, A., 2011. Recovery and Concentration of Precious Metals from Strong Acidic Wastewater. Mater. Trans. 52, 1462–1470. https://doi.org/10.2320/matertrans.M2010432

Van der Sloot, H.A., van Zomeren, A., Meeussen, J.C.L., Seignette, P., Bleijerveld, R., 2007. Test method selection, validation against field data, and predictive modelling for impact evaluation of stabilised waste disposal. J. Hazard. Mater. 141, 354–369.

Van Ginneken, L., Bervoets, L., Blust, R., 2001. Bioavailability of Cd to the common carp, Cyprinus carpio, in the presence of humic acid. Aquat. Toxicol. 52, 13–27. https://doi.org/10.1016/S0166-445X(00)00134-X

Vollprecht, D., Machiels, L., Jones, P.T., 2021. The eu training network for resource recovery through enhanced landfill mining—a review. Processes 9, 1–20. https://doi.org/10.3390/pr9020394

Wagland, S.T., Tyrrel, S.F., 2010. Test methods to aid in the evaluation of the diversion of biodegradable municipal waste (BMW) from landfill. Waste Manag. 30, 934–935.

Wagland, S.T., Coulon, F., Canopoli, L., 2019. Developing the case for enhanced landfill mining in the UK. Detritus, 5, 105-110.

Wang, D., Li, Y., Li Puma, G., Lianos, P., Wang, C., Wang, P., 2017. Photoelectrochemical cell for simultaneous electricity generation and heavy metals recovery from wastewater. J. Hazard. Mater. 323, 681–689. https://doi.org/10.1016/J.JHAZMAT.2016.10.037

Wang, H., Zhang, S., Li, B., Pan, D., Wu, Y., Zuo, T., 2017. Recovery of waste printed circuit boards through pyrometallurgical processing: A review. Resour. Conserv. Recycl. 126, 209–218.

852   Ward, M.L., Bitton, G., Townsend, T., 2005. Heavy metal binding capacity (HMBC) of municipal
853   solid waste landfill leachates. Chemosphere 60, 206–215.

854   White, J.K., Beaven, R.P., Powrie, W., Knox, K., 2011. Leachate recirculation in a landfill: Some
855   insights obtained from the development of a simple 1-D model. Waste Manag. 31, 1210–1221.

856   Yao, J., Kong, Q., Li, W., Zhu, H., Shen, D.S., 2014. Effect of leachate recirculation on the
857   migration of copper and zinc in municipal solid waste and municipal solid waste incineration
858   bottom ash co-disposed landfill. J. Mater. Cycles Waste Manag. 16, 775–783.

859   Yao, J., Qiu, Z., Kong, Q., Chen, L., Zhu, H., Long, Y., Shen, D., 2017. Migration of Cu, Zn and
860   Cr through municipal solid waste incinerator bottom ash layer in the simulated landfill. Ecol. Eng.
861   102, 577–582.

862   Yu, Y., Wan, Y., Camara, A.Y., Li, H., 2018. Effects of the addition and aging of humic acid-based
863   amendments on the solubility of Cd in soil solution and its accumulation in rice. Chemosphere 196,
864   303–310. https://doi.org/10.1016/J.CHEMOSPHERE.2018.01.002

865   Zainol, N.A., Aziz, H.A., Yusoff, M.S., 2012. Characterisation of Leachate from Kuala Sepetang
866   and Kulim Landfills: A Comparative Study. Energy Environ. Res. 2, 45-52.

867   Zevenbergen, C., Comans, R.N.J., 1994. Geochemical factors controlling the mobilization of major
868   elements during weathering of MSWI bottom ash. Stud. Environ. Sci. 60, 179–194.
869   https://doi.org/10.1016/S0166-1116(08)71455-9

870   Zhang, W., Honaker, R., 2020. Process development for the recovery of rare earth elements and
871   critical metals from an acid mine leachate. Miner. Eng. 153, 106382.
872   https://doi.org/10.1016/J.MINENG.2020.106382

873   Zhang, W.Y., Zhang, H.Z., 2009. Analysis of organic components in landfill leachate by SPME
874   coupled with GC-MS. 3rd Int. Conf. Bioinforma. Biomed. Eng. iCBBE 2009 1–4.
875   https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5162352

876   Zhang, Y., Zhang, H., Zhang, Z., Liu, C., Sun, C., Zhang, W., Marhaba, T., 2018. pH Effect on
877   Heavy Metal Release from a Polluted Sediment. https://doi.org/10.1155/2018/7597640

878   Zhou, Z., Hu, D., Ren, W., Zhao, Y., Jiang, L.M., Wang, L., 2015. Effect of humic substances on
879   phosphorus removal by struvite precipitation. Chemosphere 141, 94–99.
880   https://doi.org/10.1016/J.CHEMOSPHERE.2015.06.089

881   Zhou, Q., Li, W., Hua, T., 2010. Removal of organic matter from landfill leachate by advanced
882   oxidation processes: A review. Int. J. Chem. Eng, 10, 47-56.