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Charles D. Spellman Jr.

Travis L. Tasker

Joseph E. Goodwill

William H.J. Strosnider

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1 **Potential Implications of Acid Mine Drainage and Wastewater Co-treatment on Solids**
2 **Handling: A Review**

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4 Charles D. Spellman Jr¹, Travis L. Tasker Ph.D.², Joseph E. Goodwill Ph.D. P.E.³, William H.J.
5 Strosnider Ph.D.⁴

6
7 ¹ *Dept. of Civil and Environmental Engineering, University of Rhode Island, Kingston, RI,*
8 *02881. Email: cspellman@uri.edu*

9 ² *Dept. of Environmental Engineering, Saint Francis University, Loretto, PA 15940. Email:*
10 *ttasker@francis.edu*

11 ³ *Dept. of Civil and Environmental Engineering, University of Rhode Island, Kingston, RI, 02881*
12 *(Corresponding author). Email: goodwill@uri.edu*

13 ⁴ *Belle W. Baruch Marine Field Laboratory, University of South Carolina, Georgetown, SC*
14 *29440. Email: bill@baruch.sc.edu*
15

16 **Abstract**

17 Acid mine drainage (AMD) is a persistent and extensive source of water pollution and ecological
18 degradation. Co-treating municipal wastewater (MWW) with AMD using existing infrastructure
19 at conventional wastewater treatment plants (WWTPs) may serve as a potential option for AMD
20 abatement. However, commonly elevated iron and aluminum concentrations and low pH of
21 AMD could negatively impact various processes at a WWTP. The focus of this mini-review was
22 to determine how co-treating MWW with AMD could impact the solids handling processes at a
23 WWTP. While no studies have explored the solids that could be generated during co-treatment in
24 a WWTP, there are numerous articles that separately discuss the solids generated during AMD or
25 MWW treatment. Reviewing this literature revealed that iron and aluminum, common metals in
26 AMD, are already present in MWW sludge and typically benefit most solids handling processes.
27 The addition of AMD would elevate iron and aluminum concentration but would likely result in
28 improved sludge dewatering, removal of odor-causing compounds during processing, and a
29 decreased bioavailability of trace metals and water-soluble P in land applications. This review
30 concludes that co-treating MWW with moderate-to-low volumes (< 50%) of AMD within
31 WWTPs will have minimal impact, and likely improve, solids handling processes.
32

33 Keywords: Acid Mine Drainage; Wastewater treatment; Co-treatment; Iron; Waste management;
34 Sewage Sludge.

35 **Introduction**

36 Global industrialization has brought about a plethora of legacy pollution issues, including
37 acid mine drainage (AMD). AMD is created when sulfide-containing minerals, such as pyrite
38 (FeS_2), are exposed to oxygen and water after mining or other types of land disturbance
39 (Younger et al. 2002). The resulting discharges often have elevated acidity (some coal drainages
40 may be net neutral), elevated sulfate and iron (Fe) concentrations from the oxidation of sulfide
41 rock, and a variety of trace metals [e.g., aluminum (Al), manganese (Mn), copper (Cu), zinc
42 (Zn), arsenic (As), and lead (Pb)] from low pH driven dissolution of surrounding rocks
43 (Evangelou and Zhang 1995; Jacobs et al. 2014; Strosnider et al. 2011; Younger et al. 2002).

44 AMD abatement can be obtained by both passive (e.g. limestone dissolution, engineered
45 wetlands) and active (e.g., chemical addition) treatment approaches (Hedin et al. 1994; Johnson
46 and Hallberg 2005; Watzlaf et al. 2004). However, additional approaches can include co-treating
47 AMD with other wastes such as organic solid waste substrates, agricultural slurry, fracking
48 flowback water, or municipal wastewater (MWW) (Chang et al. 2000; He et al. 2016; Hughes
49 and Gray 2013a; McDevitt et al. 2020). Benefits of co-treating AMD with other wastewaters
50 includes providing low cost AMD abatement, improving effluent quality from treatment systems,
51 and mitigating AMD impacts on receiving bodies.

52 Co-treating MWW with AMD could enhance conventional waste water treatment plant
53 (WWTP) processes, including improved colloid destabilization (i.e. coagulation) during metal
54 hydrolysis (Metcalf & Eddy et al. 2013), precipitative removal of biochemical oxygen demand
55 (i.e. “enhanced coagulation”, Edzwald and Tobiasson 1999), increased nutrient removal by
56 phosphate adsorption onto metal hydroxides (Ruihua et al. 2011), and enhanced inactivation of
57 fecal coliforms (Winfrey et al. 2010). Co-treatment may also offer opportunities for bioelectricity

58 generation (Vélez-Pérez et al. 2020). Although successful co-treatment with AMD and MWW
59 has been noted primarily in passive systems (e.g. Johnson and Younger 2006; McCullough et al.
60 2008; Strosnider and Nairn 2010), effective co-treatment has also been demonstrated in more
61 conventional MWW treatment scenarios (Deng and Lin 2013; Ruihua et al. 2011; Wei et al.
62 2008). In a comprehensive bench scale examination of AMD and MWW co-treatment, Hughes
63 and Gray (2012, 2013a; b) demonstrated improved phosphate adsorption, metal (e.g., Fe and Al)
64 removal, decreased effluent chemical oxygen demand (COD) concentrations, and concluded that
65 co-treatment should not degrade activated sludge system performance. Although the literature
66 suggests that co-treating AMD and MWW within the existing infrastructure of WWTPs is
67 feasible, there are substantial research gaps prohibiting full-scale adaptation. One overlooked
68 factor is the impacts of AMD addition on a MWW facility's waste solids handling and
69 subsequent disposal processes.

70 Nearly all WWTP processes generate physical byproducts classified as “solids” that
71 require separate treatment and disposal. Solids, generalized as “sludge”, encompasses pre-
72 treatment grit, sludge from primary sedimentation, wasted activated sludge, and filtration
73 backwash solids (Carnes and Eller 1972). Larger objects removed by screening (e.g. “rags”)
74 which are typically directly landfilled will not be classified as solids in the scope of this review.
75 Solids treatment and disposal (i.e. “solids handling”) is equally as intricate and important as
76 liquid-phase treatment. Solids may require pre-treatment such as chemical-conditioning,
77 thickening, and/or digestion which is traditionally followed by mechanical dewatering (filter
78 pressing, centrifugation, etc.) (Carnes and Eller 1972). Treated solids can either be landfilled,
79 incinerated, or conditioned for beneficial reuse. Conditioned solids for the purpose of land
80 application are defined as “biosolids.”

81 AMD strength (acidity, pH, metal concentrations, etc.) can vary greatly with mine type
82 (coal versus hard rock drainage) and geographic location, meaning no two drainages are alike.
83 However, the authors suggest that co-treating MWW with AMD, in general, could result in
84 elevated concentrations of Fe and Al (found in most mine drainages) in solids generated during
85 MWW treatment. These elevated metal concentrations may impact facilities solids handling
86 processes. The primary objective of this review is to identify how certain AMD metals (i.e.,
87 elevated Fe and Al loads) from co-treatment with MWW may influence traditional WWTP solids
88 handling processes.

89 **Review Methodology**

90 This review identified relevant peer-reviewed research that highlight the impact of Al and
91 Fe on MWW solids handling processes. Relevant literature was identified through Google
92 Scholar searches and was extracted from bibliography sections in relevant textbooks. Keywords
93 that were used alone and in various combinations to find literature included “activated sludge”,
94 “trace metals”, “acid mine drainage”, “iron”, “aluminum”, “metal hydroxides”, and “sludge
95 handling.” There was no bias towards certain publications and all works were reviewed equally.
96 The authors acknowledge the limited number of articles published within the last ten years, with
97 the majority being published prior to 2010. However, all cited studies were screened via the
98 Elsevier Scopus citation database (www.scopus.com) to ensure the cited information was the
99 most recent and relevant.

100 **Review Results**

101 It is not uncommon for metals, especially Fe, to appear in MWW solids in substantial
102 amounts. Typical concentrations of Fe range from 1 to 300 g per dry kilogram of MWW solids,

103 with little information on Al or Mn (Environmental Protection Agency 2009). These metals are
104 of little concern for WWTPs as they are relatively unregulated as sludge constituents. Neither Fe
105 nor Al in solids is currently regulated as a pollutant for land application or landfilling (per U.S.
106 Code of Federal Regulations Title 40, Part 503); Fe and Al are not mentioned in any of these
107 regulations (as of March. 27, 2020) nor regulations for other countries (per European Union
108 Directive 86/278/EEC). Generally, increasing Fe and Al concentrations in a facility's secondary
109 treatment processes may have overall benefits for the WWTP. Elevated Fe and Al concentrations
110 in sludge have been correlated with lower COD concentrations in plant final effluents, likely by
111 coagulation mechanisms (Park et al. 2006). Improved effluent water quality is the primary aim
112 for a WWTP, but Al and Fe addition by co-treatment will likely benefit other MWW treatment
113 processes, such as solids handling. The benefits that could be provided by MWW co-treatment
114 with AMD are summarized in Table 1 and discussed in depth in the following text.

115

116 ***Conditioning and Dewatering***

117 Introduction of increased Fe and Al concentrations from AMD could improve sludge
118 dewatering during co-treatment of MWW. Al and Fe salts that undergo hydrolysis are often used
119 for sludge conditioning and to improve coagulation of suspended particles (Davis and Edwards
120 2014; Novak 2006). The addition of these metal salts decreases raw sludge specific resistance to
121 filtration (SRF) and lowers the percent of “bound water” within the sludge, thus reducing the
122 time needed for dewatering (Katsiris and Kouzeli-Katsiri 1987). Yu *et al.* (2016) demonstrated a
123 negative curvilinear correlation between Fe(III) and sludge water (Fig. 1).

124 In comparison between Fe and Al coagulants, ferric Fe [Fe(III)] based coagulants remove
125 approximately double the bound water compared to those treated with Al [82% vs only 48%

126 removal, respectively] (Katsiris and Kouzeli-Katsiri 1987). The decrease in bound water leads to
127 more efficient and cost-effective sludge dewatering. Therefore, increasing Fe(III) concentrations
128 by co-treating MWW and AMD may improve sludge settling and dewatering. It is also not
129 uncommon for drinking water utilities that use metal coagulants to send their Fe/Al-rich sludge
130 to a WWTP for disposal as an alternative to landfilling, as many drinking water facilities do not
131 operate an on-site sludge handling system. WWTPs accepting these sludges have generally
132 experienced no negative impacts on their treatment processes (Asada et al. 2010; Marguti et al.
133 2018).

134 The presence of Al in secondary MWW waste sludge has benefits that are similar to
135 those provided by Fe. $\text{Al}(\text{OH})_3$ concentration was demonstrated to be inversely proportional to
136 the SRF, implying Al also improves sludge dewaterability (Hsu and Pipes 1973). Furthermore,
137 anaerobic digestion of Al-rich sludge before dewatering further improved dewaterability by
138 nearly two orders of magnitude. The Al particles act as “skeleton builders”, significantly
139 strengthening the solids bulk structure and improving water movement out of the sludge (Lai and
140 Liu 2004). However, certain Al species or complexes can lead to variability in dewatering
141 performance. For example, polymerized forms (mixed with polymer) of hydrolyzed Al improve
142 sludge dewatering by allowing higher resistance to compression (Cao et al. 2016). This,
143 however, only holds implications for co-treatment scenarios where polymers are also added
144 during dewatering.

145 Co-treating MWW with AMD may also serve as a low-cost alternative to implementation
146 of an advanced oxidation process (AOP). AOP is a technique that can be used at WWTPs to
147 generate numerous radicals that improve oxidation processes and sludge conditioning (Glaze et
148 al. 1987; Neyens and Baeyens 2003). AOP can occur by mixing ferrous Fe [Fe(II)] with

149 hydrogen peroxide, facilitating a Fenton reaction that generates hydroxyl radicals and Fe(III).
150 Co-treatment with Fe-rich AMD could replace a Fenton AOP and retain comparable dewatering
151 efficiency. Yu *et al.* (2016) directly compared sludge dewatering characteristics with addition of
152 Fe in the form of either Fe(II), Fe(III), or a variation of the Fenton AOP process. The
153 experiments mixed sludge and Fe (always 48 mg Fe/g sludge) in a conditioning tank followed by
154 pumping the mixture to a pressure-controlled feed tank, and then dewatering the mixture via a
155 laboratory diaphragm filter press. The addition of Fe improved dewatering to some degree in all
156 cases when compared to control raw sludge (Fig. 2).

157 Although Yu *et al.* noted that Fenton reactions achieved the best performance, Fe(III)-
158 alone without an AOP still significantly improved sludge water content. Increased Fe(III) content
159 decreases the sludge cake water content by up to 15% compared to raw sludge (RS), suggesting
160 that adding AMD through co-treatment could improve sludge processing. Conversely, Fe(II)
161 yielded little to no improvement over the RS. An AMD discharge with an increased Fe(II)
162 fraction would require significant oxidation for enhanced sludge processing. Although the Fe(II)
163 results are noteworthy, it is of minimal concern for co-treatment adaptability as it will be rapidly
164 oxidized to Fe(III) in a WWTPs aeration basin. However, this could be of concern for WWTPs
165 co-treating MWW with AMD that store sludge in an anaerobic system with long detention times
166 where Fe reduction would likely occur (Rasmussen et al. 1994). The stability of Al in the +3
167 oxidation state could be more suitable during anaerobic storage and processing (Park et al. 2006).

168 Co-treating MWW with AMD will also impact the pH of sludge and further influence the
169 performance of the solids handling system. Sludge pH is inversely proportional to its
170 dewaterability, with an optimum dewatering pH of 2.5 for both centrifugal or filtration
171 dewatering (Chen et al. 2001). However, operating at extremely acidic pH values is likely not

172 feasible due to elevated corrosion risks and slower oxidation rates of odor-causing compounds
173 (Nielsen et al. 2006). Yet sludge flocs have been shown to still maintain structural stability over
174 a pH range of 4.5 to 9.5 (Liao et al. 2002) while also maintaining SRF between pH 3 and 7, with
175 less desirable SRF at higher pH values (Raynaud et al. 2012). Over a pH range of 3.2 to 9.1,
176 lower pH values also correlated with a lower sludge shear sensitivity (i.e. stronger flocs)
177 (Mikkelsen et al. 1996). The improved sludge dewaterability over a lower pH range is attributed
178 to positively charged ions from acid compounds (e.g. H^+ , Fe^{+3} , etc.) neutralizing the sludge
179 particles surface charges. The neutralization leads to improved aggregation and a particle size
180 distribution more conducive to dewatering (Karr and Keinath 1978). At a higher pH, the size
181 distribution shifts to high concentrations of smaller particles that fill voids, trap water, and clog
182 filtration pores reducing overall bound water movement (Raynaud et al. 2012). Although lower
183 pH may improve dewaterability, dewatered sludge will require amendments (i.e., lime, etc.) to
184 obtain the pH necessary for post-dewatering processes [e.g., minimum pH for biosolids land
185 application is 12 (Doyle 1967)].

186

187 ***Odor Control and Anaerobic Processes***

188 Managing odor is a common nuisance and cost burden at many WWTPs (Dague 1972).
189 Fe from co-treatment may help mitigate odor at WWTPs and could present positive economic
190 benefits for the immediate community by increasing surrounding property values by up to 15%
191 (Lebrero et al. 2011). Divalent metal species in AMD, including unoxidized Fe(II), can scavenge
192 and react with the primary odor-causing compound H_2S to form insoluble metal sulfide
193 complexes which are non-odorous (Johnson and Hallberg 2005). This suggests that the addition
194 of Fe(II) in mostly anaerobic settings (e.g. AMD added after aeration) would assist in decreasing

195 odor causing compounds during solids processing. Oxidized Fe in aerobic co-treatment systems
196 will also enhance odor reduction. The addition of zero-valent Fe (Fe⁰) nanoparticles at various
197 doses to MWW sludge demonstrated improved oxidation of H₂S to form Fe sulfides and
198 increased the final biosolids nutrient bioaccessibility (Li et al. 2007). The resultant Fe-sulfides
199 further reacted with H₂S to form Fe polysulfides without the need for additional Fe input.
200 Although the aforementioned study utilized Fe⁰, only the core of the nanoparticles contained Fe⁰
201 while the shell was oxidized and consisted of hydroxides/oxyhydroxides. These hydrolyzed Fe
202 compounds are similar to those that would form after oxidation of AMD Fe.

203 Al addition also improves the overall anaerobic sludge digestion processes. Biogas often
204 contains volatile sulfur compounds (e.g. H₂S, CH₃SH, CS₂) that cause nuisance odors and
205 corrosion issues. Dosing Al can remove high percentages of these dangerous sulfur compounds
206 from biogas while maintaining consistent digester performance (Akgul et al. 2017). Additionally,
207 the total volume of biogas generated would be expected to decrease (Hsu and Pipes 1973) likely
208 resulting from significant removal of volatile compounds. Furthermore, the same study showed a
209 noticeable decrease in digester coliform counts as well as improved dewaterability after
210 digestion. All of the aforementioned improvements could equate to significant cost savings for a
211 WWTP, in addition to benefits from reduced odors. These results suggest that co-treatment with
212 Al-rich AMD (which is relatively rare) would be most advantageous at a WWTP operating an
213 anaerobic digestion system, due to the valance-stability of Al.

214

215 ***Biosolids Composition and Land Application***

216 Although MWW solids may contain 1 to 300 g of Fe per dry kilogram of solids
217 (Environmental Protection Agency 2009), only a handful of studies have examined the

218 relationship between Fe and Al content in water and resulting biosolids Fe and Al content. As
219 previously discussed, there are minimal regulatory standards for common AMD metals in
220 biosolids. However, trace metals and metalloids (e.g. Pb, Hg, and As) in biosolids can have
221 environmental and human health implications if they bioaccumulate or leach after land
222 application (Arulrajah et al. 2011). Both As and Hg have frequently been investigated for their
223 role in biosolids toxicity during land use. AMD from the eastern part of the United States rarely
224 has As and Hg concentrations above drinking water standards (Herlihy et al. 1990), but elevated
225 concentrations of various metals and metalloids of concern (e.g., As, Cd, Pb) can be found in
226 other geographic locations which would have negative implications for co-treatment feasibility
227 (Cheng et al. 2009; Rytuba 2000; Strosnider et al. 2011). Decreasing the bioavailability of trace
228 metals and metalloids in soil is important when considering if biosolids can be applied to land.
229 Fig. 3 demonstrates the difference in bioavailability of Pb during a field study when 99% Fe-
230 powder was added to biosolids compost (109 g Fe/kg) and mixed with soil (Brown et al. 2012).
231 Experimental analysis showed that 75% of the Fe in the amended biosolids was Fe(III), similar
232 to what might be expected of co-treatment biosolids.

233 Although Fe amended biosolids decreased the bioavailability of Pb (Fig. 3) there was
234 significantly less impact on As bioavailability (Brown et al., 2012). The increased retention of
235 toxic compounds by elevated-Fe biosolids during soil application renders amended biosolids
236 marketable not just as compost, but also as remediation substrate for sequestering trace metals
237 (e.g. Pb) in soils (Farfel et al. 2005). It is important to note that the substantial concentration of
238 Fe added (>80 g/kg) in the Brown *et al.* experiment would only be expected under co-treatment
239 with a high ratio of Fe-rich AMD. This Fe concentration is likely orders of magnitude higher
240 than what a typical AMD discharge [AMD Fe varies 1 µg/L to > 600 mg/L (Johnson 2003;

241 Strosnider et al. 2011; Younger et al. 2002) and 0.2-70 mg/L Fe for coal mine drainage
242 (Strosnider et al. 2020)] might contribute in a co-treatment system. In these situations, solids
243 trace metal bioavailability would likely not be improved as demonstrated in the Brown *et al.* low
244 Fe (5 g Fe/kg) experiments. These results imply that decreased toxic compound concentrations
245 could only be expected during co-treatment on a case by case basis as a function of AMD and
246 MWW influent Fe concentrations and system Fe removal capabilities.

247 Both Fe and Al may benefit agricultural land application of biosolids. AMD metals have
248 demonstrated potential related to improving soil phosphorus (P) availability. Adler and Sibrell
249 (2003) showed that additions of neutralized AMD “flocs” to high-P soil (20 g floc / kg soil)
250 could sequester roughly 70% of water-extractable P. A similar result was noted in a larger scale
251 study, where application of manure mixed with AMD treatment residuals to a large parcel of
252 farmland decreased the water-soluble P content (Sibrell et al. 2015). Similarly, mixing biosolids
253 with Al-rich water treatment alum sludge improved agricultural crop yields in traditional potting
254 soil by retaining higher concentrations of P at both laboratory (60 days) and greenhouse (105
255 days) scales (Mahdy et al. 2009). Furthermore, the application of Al-hydroxides (1 to 4% w/w)
256 in the aforementioned study also decreased the total nutrient loading in greenhouse runoff. The
257 reduction of soluble P in biosolids amended with Al-rich water treatment sludge is caused by the
258 formation and precipitation of Al/Fe-P complexes or P adsorption unto hydroxides (Huang et al.
259 2007). Commercially available Fe(III)-rich biosolids have varying results on agricultural use,
260 demonstrating improved growth size of oranges but no impact on pear growth (Pérez-Sanz et al.
261 2002). However, most studies examining agricultural Fe-rich biosolids applications
262 demonstrated non-negative yet neutral impacts on fruit growth. There is a strong potential for
263 AMD co-treatment biosolids to support localized agriculture. Co-treatment could reduce

264 demands for artificial fertilizers and potentially decrease nutrient loading on waterways without
265 negatively impacting agriculture processes.

266

267 *Incineration Considerations*

268 Co-treatment has the potential to impact sludge incineration operations. The
269 aforementioned inverse relationship between Al and Fe content and sludge bound water would
270 also improve the combustibility of the dewatered sludge, reducing stress on incinerator
271 processes. Furthermore, the resulting ash would have increased amounts of extractable P (Farfel
272 et al. 2005). Ash generated by incinerating sludge from co-treated MWW with AMD could
273 improve nutrient recovery and be viewed as a beneficial reuse product. Due to increasing global
274 stress on P demand, WWTP processes have long been a point of focus as a source of potential P
275 recovery and recycling (Farfel et al. 2005; Ottosen et al. 2013). Ash product produced from a co-
276 treating incineration facility with a high extractable P could alleviate local P demand. Incinerated
277 sludge ash can contain up to 10% P by mass (Donatello and Cheeseman 2013) and the amount of
278 P that is recoverable is directly proportional to ash value. Sludge ash can successfully be applied
279 to land as a fertilizer (Bierman and Rosen 1994). Therefore, this beneficial use ash also carries
280 economic incentives, as it is now a product to boost revenue rather than a waste. Furthermore,
281 the extractable P-rich ash is significantly less dense than a dried and stabilized sludge making it
282 more economically viable to transport.

283 There are also disadvantages to be considered for incineration facilities. Depending on
284 the water chemistry of the AMD, the ash could contain higher weight-percentages of toxic trace
285 metals (e.g. As and Pb). Ash containing > 100 mg/kg of Pb would be considered a hazardous
286 waste and could not be disposed of in a traditional municipal landfill. Pb concentrations in

287 municipal landfills can be indirectly associated with a variety of health issues for neighboring
288 communities (Kim and Williams 2017), and remains a liability for the generator. Furthermore,
289 As is a primary contaminant in landfill leachates (Pinel-Raffaitin et al. 2006), and a landfill
290 would likely not accept As-containing wastes due to the potential costs required for As treatment
291 after leaching.

292 **Conclusions**

293 From a solids handling perspective, co-treating MWW with AMD could provide
294 numerous benefits for a WWTP. The metals common to AMD (e.g., Fe, Al) are already present
295 in conventional MWW sludges, and additional loads from co-treatment would not result in
296 concentrations above those seen in some facilities. Current regulations indicate that sludges with
297 high concentrations of these metals can be easily disposed in landfills or land applied. When Fe
298 and Al concentrations are elevated, they may provide additional benefits that could make co-
299 treating MWW with AMD more economically viable. For example, elevated Fe and Al can
300 improve sludge dewatering, potentially lowering operating costs. The Al in these sludges can
301 also decrease concentrations of odor causing compounds that are often challenging to control at
302 WWTPs. Other opportunities might exist to use the biosolids or incinerated sludges (i.e., ash)
303 from co-treating MWW with AMD for soil remediation or agricultural amendments (e.g.
304 immobilizing trace metals in contaminated soils). While the findings of this review suggest that
305 there are potential benefits from co-treating MWW with AMD, many questions remain to be
306 answered before full-scale implementation. Further research into potential impacts from other
307 common AMD metals (Cu, Mn, Zn, etc.) is needed. Future work should also include laboratory
308 scale studies to investigate the outcomes of this review in various co-treatment scenarios (e.g.
309 dewatering, digestion systems, incineration, and land application).

310

311 **Data Availability Statement**

312 No data, models, or code were generated or used during the study

313

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320

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510 **Table 1.** Summary of key improvements on solids handling from co-treatment.

Potential benefits of co-treating MWW with AMD	Relevant Citation
AMD addition would elevate iron concentrations above a facility's current levels, but resulting concentrations would likely not exceed those already commonly observed in typical MWW sludges (1 to 300 g Fe per dry kg)	EPA, 2009
Iron and aluminum concentrations are correlated with a decrease in COD concentrations	Park et al., 2006
Increases in iron concentration generally reduces sludge water content	Katsiris and Kouzeli-Katsiri, 1987; Yu et al. (2016)
Aluminum decreases sludge specific resistance to filtration	Hsu and Pipes, 1973
WWTPs co-treating MWW with AMD containing high iron concentrations have ability to easily adapt to a Fenton AOP	Yu et al. (2016)
Decrease in pH improves dewaterability	Raynaud et al 2012; Karr and Keinath 1978
AMD metals may precipitate nuisance odor-causing compounds	Johnson and Hallberg, 2005
Aluminum addition is advantageous for WWTPs with anaerobic digestion	Akgul et al., 2017; Hsu & Pipes, 1973
Iron can decrease bioavailability and mobility of trace metals in land application	Farfel et al., 2005; Brown et al. 2012
Iron-rich biosolids decrease water-soluble phosphorus content when added to fertilizer	Adler and Sibrell 2003; Farfel et al., 2005; Sibrell et al., 2015
Incinerated sludge may be rich in phosphorus and used for land application	Farfel et al., 2005; Donatello & Cheeseman, 2013