Proceedings of the West Virginia Academy of Science

Original Research Paper

Evaluation of the use of AMD sludge as soil amendment

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Article history
Received: 7 October 2022
Revised: 9 December 2022
Accepted: 12 December 2022

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Abstract: The treatment of acid mine drainage (AMD) involves chemical additives to raise pH and precipitate solubilized metals. The byproduct of this process is an AMD sludge precipitate, and its management and disposal are a continuous environmental legacy. This study evaluated the application of AMD sludge as a soil amendment to support vegetation establishment. A small-scale growth study was completed with six treatments composed of different proportions of topsoil and AMD sludge as follows: i) 100% topsoil, ii) 10% sludge, and 90% topsoil, iii) 20% sludge and 80% topsoil, iv) 30% sludge and 70% topsoil), v) 40% sludge and 60% topsoil), and vi) 50% sludge and 50% topsoil. Four replications of each treatment were considered. Ground cover was monitored weekly for nine weeks (September 29, 2021 – December 2, 2021). Stem length and biomass were measured. Groundcover varied from 14.6% to 70.1% among all treatments throughout the study; all treatments were determined as statistically similar to the 100% topsoil treatment. Biomass ranged from 1.41 to 6.22 g, and average stem length varied from 3.6 to 4.6 cm. Toxicity did not exceed minimum levels for one representative sludge sample. This preliminary study provides support for the further advancing AMD sludge as a soil amendment.

Keywords: Acid mine drainage; sludge, land application, by-products, alternative disposal

Introduction

Mining activities expose sulfide minerals in rocks that, when in contact with oxidizing conditions (oxygen and water), produce sulfate-rich drainage known as acid mine drainage (AMD) (Skousen *et al.* 2019). AMD is characterized by low pH and solubilized metals that are toxic to water bodies, negatively impacting the environment and making water not safe for use (Skousen *et al.* 2017; Amanda and Moersidik 2019).

Mining effluents are standardized and controlled by laws and regulations established by federal and state regulatory programs since the 1970s. Once mine operators are required to meet land reclamation and water standards, the AMD is treated prior to discharge by a range of techniques that vary according to environmental and mine conditions. These treatments include raising the pH to neutralize acidity and precipitation of metal ions. (*Skousen et al.* 1998; Zinck and Griffith 2013; Skousen *et al.* 2017).

The treatment of AMD can be done by passive and active methods. Passive methods - such as wetlands, bioreactors, limestone leach beds, and open limestone channels - rely on biological, geochemical, and physical processes that occur naturally and do not need human assistance in their operation (Skousen *et al.* 2017). The effectiveness of the passive methods is associated with the AMD composition, and they are applied when the contaminates are not significantly critical. Alternatively, active treatments use alkaline chemicals (e.g., $Ca(OH)_2$, CaO, NaOH, Na_2CO_3, and

NH_3) to neutralize acidity and are applied when there are high amounts of pollutants. Once the neutral condition is achieved, the solubilized metals precipitate form a metal hydroxide sludge, here referred to as AMD sludge (Skousen *et al.* 2017; Amanda and Moersidik 2019; Skousen *et al*. 2019).

Sludge production is a problem on its own because of the amount of sludge produced by AMD active treatments. Additionally, the sludge possesses high water contents with low total solids percentage and exhibits difficulties in dewatering; these factors increase the costs of its disposal and management (Tolonen *et al.* 2014). Sludge is commonly disposed of in ponds, into deep mines, in active coal mine refuse areas, and onsite burial (Ackman 1982).

U.S. Environmental Protection Agency suggests the application of Pollution Prevention principles when dealing with industrial waste. The Pollution Prevention Act of 1990 establishes the following waste hierarchy: 1) source reduction, 2) reuse/recycle, and 3) disposal. According to these principles, the adoption of an alternative means of use for AMD sludge can reduce the volume of sludge and its environmental impacts, reduce costs with management, and avoid future problems (USEPA n.d.).

AMD sludge has been studied for a range of applications such as adsorptive pollution control, microbially facilitated ferric reduction, and catalytic degradation of wastes (Anwar *et al*. 2021). Land application has also been studied as an option for sludge application (Skousen *et al.* 1998; Adler and Sibrel 2003; Sibrel *et al*. 2009). This study analyzed the application of AMD sludge as a soil amendment for supporting vegetation as an alternative means of reuse of this material.

Materials and Methods

Acid mine drainage (AMD) sludge source

The AMD sludge used for this study was sourced from the OMEGA impoundment (39º31′57.9′ N, 79º56′21.0″ W), a treatment station located south of Morgantown, West Virginia, operated by the West Virginia Department of Environmental Protection (WVDEP). The raw AMD treated on this site is a product of multiple underground mines. The treatment consists of the use of calcium hydroxide (hydrated lime) to raise pH from 3.2 to 6.7 (clarification) and precipitate solids. The supernatant is settled in a series of ponds before its discharge into the environment through a National Pollutant Discharge Elimination System (NPDES). The precipitated sludge underflow is treated with polymers to create flocks that are dewatered through geobags (Dalen 2021). The sludge used for this study was collected from an old sludge pond located on the site.

Test set-up

A small-scale growth study was completed to evaluate the establishment and cover capacity of different media composed by topsoil and AMD sludge. The treatments consisted of six volume-based mixtures of topsoil and sludge: (i) 100% topsoil, (ii) 10% sludge and 90% topsoil, (iii) 20% sludge and 80% topsoil, (iv) 30% sludge and 70% topsoil, (v) 40% sludge and 60% topsoil, and (vi) 50% sludge and 50% topsoil.

There were four replications of each mixture, resulting in twenty-four samples. The mixtures were put in pots of 20 cm diameter and 18 cm height. The pots were filled with the mixtures to the height of 15 cm. The bulk density of the medias ranged between 0.29 g/cm^3 (100% topsoil) and 0.50 g/cm^3 (50% topsoil and 50% sludge) (Table 1).

Table 1. Bulk density, ρ_b, of the treatment media mixtures

Treatment	ρ_b (g/cm^3)
100% topsoil (100T)	0.29
10% sludge and 90% topsoil (10S90T)	0.29
20% sludge and 80% topsoil (20S80T)	0.37
30% sludge and 70% topsoil (30S70T)	0.37
40% sludge and 60% topsoil (40S60T)	0.46
50% sludge and 50% topsoil (50S50T)	0.50

The samples were seeded with 2 g of Kentucky 31 tall fescue grass seed (*Festuca arundinacea*; Pennington Seed, Greenfield, MO), a tolerant species (USDA Plants Database 2022). Seeding methods followed four steps, as recommended by manufacture: 1) the top layer was loosed and smoothed, 2) the seeds were spread by hand, 3) the surface was slightly tapped to guarantee the seeds were in contact with the soil, and 4) the samples were watered with 250 ml of water each (Fig.1).

The pots were randomly arranged in four plastic storage containers (96.5-cm deep, 56-cm wide, and 41-cm tall) – one of each treatment per container. The containers were labeled as “A”, “B”, “C”, and “D”, and the pots were labeled according to the treatment and the container orientation (Fig. 2).

Figure 1. Progression of study preparation (from left to right: topsoil and sludge mixing, seeding, watering, straw layer, and final setup).

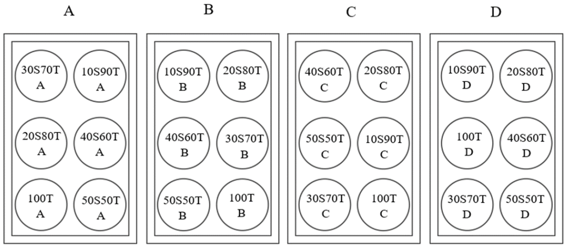

Figure 2. Organization of mixtures per container and container position in the research area. (S: sludge, T: topsoil)

Drainage holes were added to the bottom of the containers, and the samples were placed over a 15-cm thick topsoil layer. A layer of seeding straw with tackifier (Pennington Seed, Madison, GA) was added to protect the seeds. The straw layer was substantially removed after the seed germination to facilitate ground cover measurements. The containers were surrounded and covered by a 1.2-m tall green garden fence, to prevent animal intervention (TENAX®) (Fig. 3).

The initial watering schedule was 250 mL daily during the first week of germination. Then, the watering schedule was reduced to 2-3 times a week. The watering schedule varied due to precipitation and frost (Fig. 4).

Figure 3. Final setup of containers A, B, C, and D (from left to right)

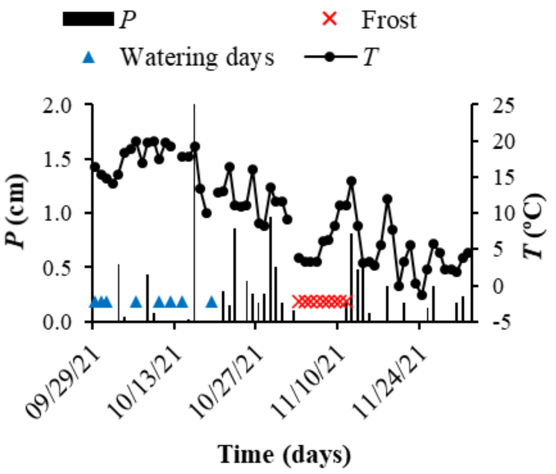

Figure 4. Watering schedule with mean daily temperature, *T*, and total daily precipitation, *P*, and days frost was observed.

Data collection

Samples of approximately 500 g of each soil mixture were collected for analysis at near beginning (24 September 2021) and end (9 December 2021) the growth season. The samples were analyzed by the WVU Soil Test Laboratory (Morgantown, WV) for pH (1:1 – soil: water), P, K, Ca, Mg (extraction using Mehlich 3), organic matter (OM) (Loss on ignition), and electric conductivity (EC).

Photographs were recorded weekly to monitor the ground cover during the nine weeks of study (29 September 2021 – 2 December 2021). The photographs were analyzed for ground cover by area, using Adobe Photoshop 2022. Stem sizes were measured for a minimum of 10 random live stems from each sample at week 5 (November 1). At the end of the study, total live above-ground biomass was collected and weighted following guidance by Franks and Goings (1997).

Total waste analysis was completed on the sludge by Pace Analytical (Greensburg, PA). Concentrations of arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver were determined following standard methods (i.e., EPA 6010D, EPA 7471B, SM 2540G-2015).

Statistical methods

Comparisons of ground cover, stem height, and biomass were made among treatments. The data were tested for normal distribution using the Shapiro-Wilk test and Anderson Darling tests. Then, the data were analyzed using analysis of variance (one-way

ANOVA) when normally distributed, or Wilcoxon/ Kruskal-Wallis non-parametric analysis when not normally distributed (Ott and Longnecker 2001). Statistical analysis was completed using JMP 16 software.

Results

Groundcover

Groundcover varied from 14.6% to 70.1% among all treatments. The samples composed of 100% topsoil (100T) consistently resulted in the highest weekly mean ground cover during the study period. There was one exception during week 2 when the treatment 30S70T had the highest ground cover on average (= 29.46%) (Fig. 5A).

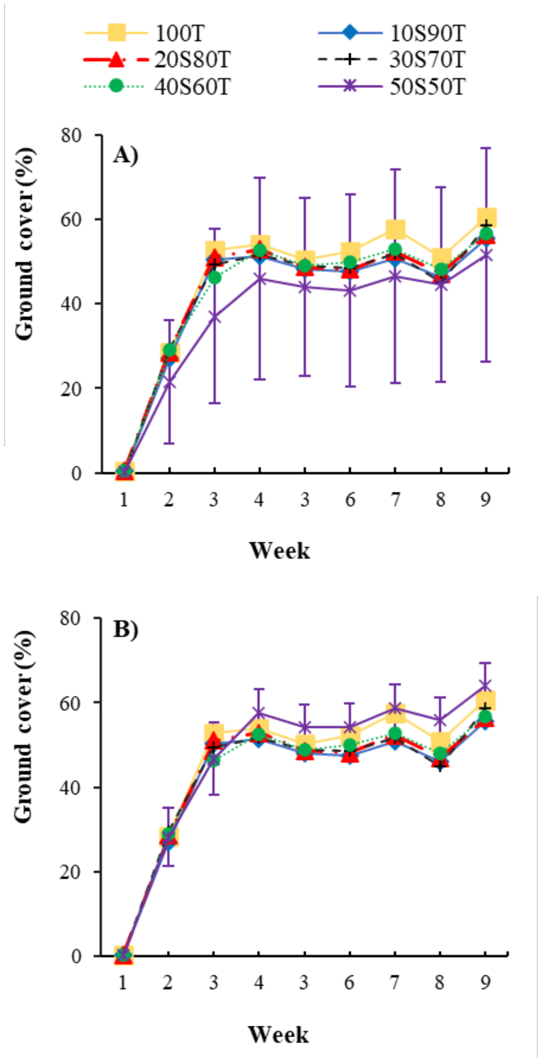

Figure 5. Mean ground cover: A) all samples, B) outlier 50S50T sample removed; error bars denote standard deviation

Differences were observed in one of the 50% sludge samples (50S50T D) from week one, potentially due to errors in the mixing process. This container was saturated with low permeability throughout the study. By observation, the water remained pooled after watering for more time than the other samples. This constantly submerged sample had a ground cover value 78% less than the other 50% sludge samples, on average, by the end of the study.

This outlier lowered the mean ground cover of the 50S50T mixtures, resulting in the lowest mean ground cover during the study. However, if the sample 50S50T D was removed, the mixtures with 50% sludge would show the greatest mean ground cover, exceeding all mixtures for weeks 4 to 9 (Fig. 5B); however, these differences were not all statistically significant (e.g., Fig. 6).

The ground cover data for week 9 tested as normally distributed when the results for treatment 50S50T D were excluded. While 50% sludge treatment was significantly greater than some of the other treatments with sludge (when the outlier was removed), all treatments containing sludge were determined statistically similar to the topsoil control (100T) (Fig. 6).

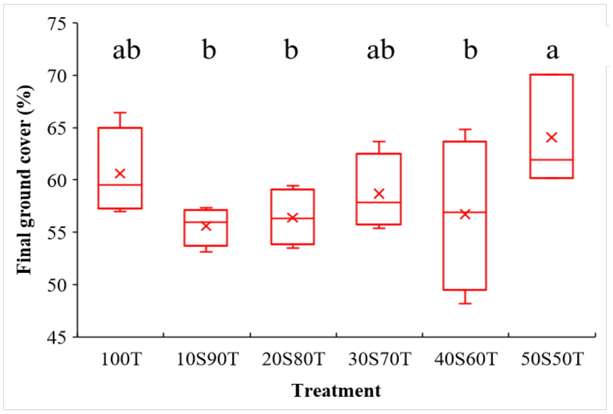

Figure 6. Comparison of final ground cover (week 9) by treatment. Summary values for the tenth percentile, first quartile, median, third quartile, and ninetieth percentile; x denotes the mean. Letters denote statistical significance; outlier removed from the 50S50T treatment.

Biomass

Total biomass ranged from 1.41 g to 6.22 g. Biomass ranged from 4.86 g to 5.62 g for the 100% topsoil treatment. The 50% sludge treatment had the two largest biomass values among all mixtures: 6.22 g (50S50T C) and 6.12 g (50S50T A) (Fig. 7).

As previously discussed, 50S50T D had the lowest live biomass (1.41 g) due to excessive water content. This outlier was removed from statistical analysis. The biomass data tested as normally distributed when the outlier was removed. All treatments with up to 30% sludge had biomass values significantly less than the control (100% topsoil). The 50% sludge treatment had biomass significantly greater than the 100% topsoil treatment (Fig. 7).

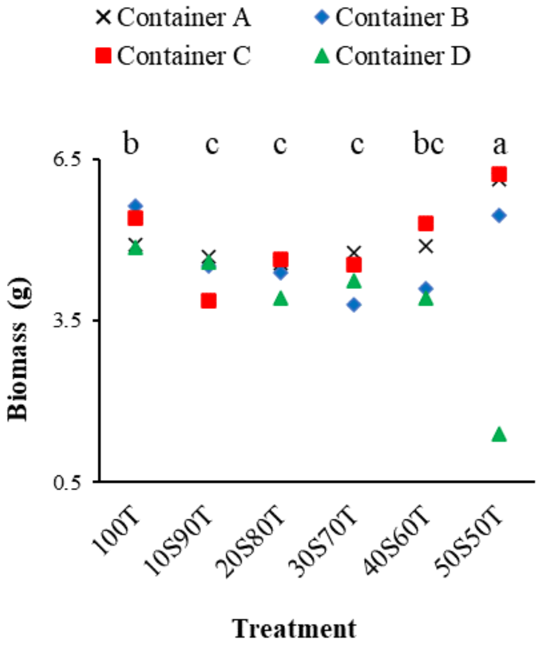

Figure 7 Biomass. Letters above plots denote statistical significance; outlier removed from statistical analysis shown.

Stem height

Generally, the average stem height did not vary substantially among treatments (Fig. 8). Because the stem height data were not normally distributed ($p < 0.05$), a non-parametric analysis (Wilcoxon / Kruskal-Wallis) was used for statistical analysis. Few statistical differences were observed (Fig. 8).

Soil media

The pH ranged from 6.7 to 7.3 for the duration of the study; the highest pH (7.3) was recorded in the 50% sludge treatment. Organic matter (OM) was greater than 38% due to use of commercially available topsoil. Electrical conductivity (EC) ranged from 1.1 to 1.3 dS/m at the beginning of study and 0.3 to 0.9 dS/m at end of study (Tables 3 and 4).

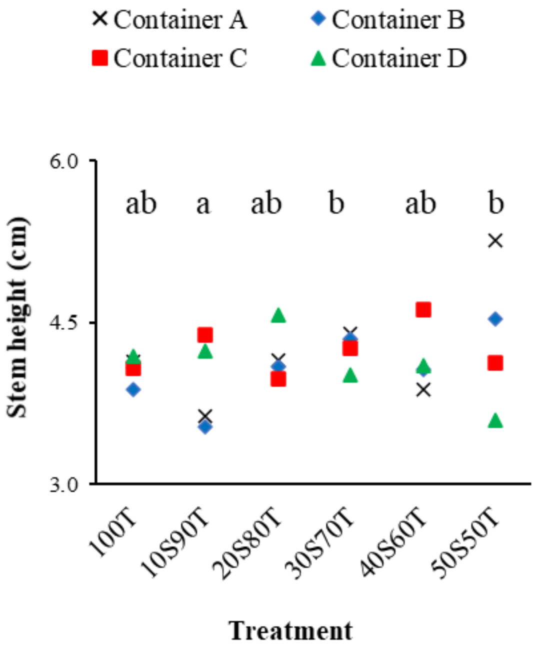

Figure 8. Stem height. Letters above plots denote statistical significance; outlier removed from statistical analysis shown.

Table 3. Soil summary results based on a composite sample during set up, 24 September 2021

	Treatment					
	100T	**10S90T**	**20S80T**	**30S70T**	**40S60T**	**50S50T**
pH	6.7	6.8	7	6.9	7	7.3
OM (%)	42.6	42.7	40.3	41.4	39.7	38
EC (dS/m)	1.1	1.2	1.2	1.3	1.3	1.3
P (ppm)	61	30	5.3	5.5	5.7	0.8
K (ppm)	540	570	540	560	330	350
Ca (ppm)	2,690	3,160	3,680	3,680	3,650	3,120
Mg (ppm)	490	530	600	580	570	570

Table 4. Mean soil summary results (*n*=4 per treatment); 10 December 2021

	Treatment					
	100T	**10S90T**	**20S80T**	**30S70T**	**40S60T**	**50S50T**
pH	7.0	7.2	7.2	7.1	7.1	7.3
OM (%)	41.2	39.1	39.0	39.3	37.7	35.2
EC (dS/m)	0.3	0.3	0.4	0.4	0.7	0.9
P (ppm)	51.5	23.5	11.3	10.2	5.1	2.8
K (ppm)	365	358	353	433	435	383
Ca (ppm)	3,745	4,210	4,330	5,113	4,643	5,285
Mg (ppm)	560	648	658	730	685	823

Discussion

While AMD sludge is produced in high amounts during the AMD chemical treatment (Wei *et al.* 2008), the safe handling and disposal is a costly environmental concern. Finding a sustainable application for this material represents a gain not only by reducing environmental impacts or costs, but by transforming a waste in a valuable material (Anwar *et al.* 2021). Land application is one of the many alternative ways of disposal that have been studied for this material.

For land application, the AMD sludge must be demonstrated to be non-hazardous as defined by the Resource Conservation and Recovery Act (RCRA) Subtitle C. All metal concentrations were below the method detection limits except for barium (=4.62 ppm) (Table 5). Considering the Rule of 20 (Davis 2001), arsenic, barium, chromium, lad, mercury, and silver meet basic requirements for land application. Selenium concentrations need to be further evaluated; however, concentrations for the sampled sludge were below detection limits. Cadmium was not tested in this study and needs to be considered in the future. It should be noted that AMD sludge characteristics vary by source and the sludge should be tested prior to land application.

Table 5. Metal concentration of sludge with regulatory limits

Metal	Regulatory limit (ppm)	Sludge (ppm)
Arsenic	5.0	*16.85*
Barium	100	4.62
Chromium	5.0	*17.8*
Lead	5.0	*14.75*
Mercury	0.2	*0.29*
Selenium	1.0	*32.30*
Silver	5.0	*12.95*

Note: Italicized values reported as half of the method detection limit

Zink (2006) suggested that sludges with low metal concentrations and excess alkalinity may be used to increase soil pH. Presence of acidic soils is a common concern of disturbed sites, but soil pH was not a concern in this small study because commercially available soil was used as the substrate combined with the sludge; however, soil pH increased from 6.7 to 7.3 with the addition of 50% sludge (Tables 3 and 4), providing support that AMD sludge can impact pH.

This study did not include fertilizer or lime that will likely be considered in field applications. With addition of AMD, levels of P and K decreased below optimum levels (<15) (AgSource 2022), suggesting that soil testing for fertilizer amounts will be a necessary part of the implementation of AMD in land application.

Construction stormwater general permits for the National Pollutant Discharge Elimination System require 70% ground cover (WVDEP 2022). This metric was reached for only one sample in this small-scale study. This result may have been due to the small scale and short timeline of the study.

To be considered a soil amendment, the AMD should improve growth (Brady and Weil, 2002). With large amounts of AMD sludge (50%), the amended soil performed as well as (i.e., ground cover and stem height) or better than (i.e., biomass) the topsoil control. There is also the potential for AMD to improve soils with low pH (Tables 3 and 4). These results suggest that AMD should be further explored for the use as a soil amendment.

Conclusions

This study evaluated land application as an alternative means of disposal for AMD sludge. Results suggest land application meets regulatory standards for one location and supports growth of one grass species, *Festuca arundinacea.* Even though ground cover only met permit limits for one sample, the addition of AMD up to 50% did not reduce ground cover significantly as compared to a commercially available topsoil. In addition, 50% sludge treatments performed well as (i.e., ground cover and stem height) or better than (i.e., biomass) the topsoil control. Therefore, this preliminary study provides support for the further study as AMD sludge as a soil amendment.

Acknowledgements

The work described in this publication was supported by Grant/Cooperative Agreement Number S21AC10054 from the Office of Surface Mining, Reclamation, and Enforcement. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the OSM. This work is also in collaboration with the West Virginia Department of Environmental Protection, Office of Special Reclamation.

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