THE USE OF SULFATE REDUCTION TO REMOVE METALS FROM ACID MINE DRAINAGE[1]

by

P. Eger[2]

Abstract. Four combinations of organic substrates have been studied for their ability to support sulfate reduction and remove metals from acid mine drainage. The substrates include 45-day-old municipal compost, composted yard waste, horse manure, and wood shavings. Four rows of three 55-gallon barrels connected in series received drainage from a lean ore stockpile. The input had an average pH of 5.1, with an average sulfate concentration of 860 mg/L and average trace metals concentrations of 7.7 mg/L copper, 1.2 mg/L cobalt, 26.0 mg/L nickel, and 1.4 mg/L zinc. All the substrates were successful in neutralizing the drainage and reducing trace metal concentrations by greater than 90%. Nickel, which is the major trace metal of concern, was reduced by over 99%.

Additional Key Words: trace metals, copper, cobalt, nickel, zinc, acid neutralization.

Introduction

Acid mine drainage is a serious environmental problem. Thousands of miles of streams have been affected by acid drainage from both coal and metal mines (U.S. Bureau of Mines 1985). Acid drainage associated with metal mines contains elevated concentrations of the metals associated with the ore body. These metals, in addition to the acid, can pose dangers to both downstream human and aquatic communities. Although this type of drainage can be chemically treated in an active treatment plant, this is an expensive and long-term commitment, particularly since drainage problems can persist for over a hundred years.

An alternative approach to chemical treatment is the development of "passive" technologies. These types of treatment systems tend to be lower in cost and maintenance and often employ natural processes to remove contaminants. Wetland treatment of mine drainage is a common example of passive treatment. Although commonly used in the removal of iron from coal mine drainage, the application to metal drainage has just begun. In coal mining applications, wetlands are typically constructed so that flow occurs across the surface of an organic substrate which has been planted with cattails (Weider 1989, Hedin 1989). Iron removal primarily occurs through the oxidation of ferrous iron to ferric iron and the subsequent removal as a ferric oxyhydroxide. Although this reaction removes iron, it also reduces pH.

For neutral metal mine drainage, wetland systems similar to those used for coal drainage can effectively remove low levels of metals from the drainage (Eger 1991). Removal occurs primarily in the aerobic zone through a variety of reactions including adsorption, chelation, and ion exchange. Ion exchange reactions often involve the exchange of a hydrogen ion for the metal ion, therefore causing pH to decrease.

However, when metal concentrations are high and the pH is low, aerobic processes have a very limited ability to effectively remove metals. Metal removal by adsorption and ion exchange decrease as pH decreases. In laboratory studies (Lapakko et al. 1988), metal removal decreased as pH decreased from 7.4 to 4.0. The aerobic processes of adsorption, ion exchange, and complexation do not

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increase pH, so even if metals could be removed, some form of neutralization would be required.

However, anaerobic reactions, specifically sulfate reduction, cannot only remove metals but also increase pH. The reactions involved can be represented as follows:

$$SO_4 + 2\ \text{lactate} \rightarrow 2\ \text{acetate} + H_2S + 2HCO_3 \tag{1}$$

$$H_2S + M^{+2} \rightarrow MS + 2H^+ \tag{2}$$

Complex organics are reduced to simpler organics by bacteria. These simpler organic compounds can then be utilized by the sulfate reducing bacteria. Sulfate reducing bacteria are ubiquitous and tolerate a wide range of environmental conditions. Their optimal pH range has been reported to be from 5 to 9, but they can control their microenvironment even when the bulk solution pH is below 5. Successful sulfate reduction has been reported for a drainage with a pH as low as 2.6 (Bolis et al. 1991).

Another advantage of sulfate reduction treatment is that waste material can be used for the organic substrate. Spent mushroom compost has been commonly used in constructed wetlands in the eastern United States (Weider 1989). Recent experiments in Colorado and Arkansas have used other local waste products such as steer manure, rice hulls, and chicken litter as the substrate (Howard et al. 1989, Gross et al. 1991). The U.S. Bureau of Mines is also investigating the use of waste materials for supplementing the substrate and thereby increasing the rate of sulfate reduction (Hammack 1991).

Objectives of the study were as follows:

1. Assess the effectiveness of sulfate reduction to remove copper, cobalt, nickel, and zinc from acid mine drainage.
2. Assess the effectiveness of various organic media to sustain sulfate reduction.

Methods

Materials

Four different organic materials were selected for this test, all produced within Minnesota: 45-day-old municipal compost, screened composted yard waste, mixed hardwood sawdust from a local sawmill, and horse manure. These materials were chosen for their suspected ability to support sulfate reduction, their availability, and the lack of contaminants. Samples of each organic material were collected and analyzed for total solids (percent moisture), percent organic material, major cations (calcium, magnesium, sodium, potassium), sulfur (total, sulfate and acid volatile), copper, nickel, and zinc. Additional samples of the 45-day-old compost and the yard waste were also analyzed for available nutrients, pH, cation exchange capacity, lead, chromium, and cadmium (Table 1).

When the municipal compost is produced, most of the metal, glass, and plastics have been screened

Table 1. Properties of Organic Substrate.

Organic Substrate	Municipal compost	Composted yard waste	Sawdust
Row	1, 4	2	3, 4
Solids %			
Total	78.4	59.3	92.8
Volatile	42.4	25.3	>99.5
Ash, %	57.7	74.7	< 0.5
pH[1]	6.8	7.3	NA
CEC[1]	108.3	86.2	NA
Nutrients[1]			
Organic N[2]	0.78	1.18	NA
NH_4-N[2]	1.22	10.4	NA
NO_3-N[2]	0.001	136	NA
Total P[3]	2.1	0.2	NA
Major cations %			
Ca	2.6	2.0	0.08
Mg	0.33	0.36	0.004
Ni	0.42	0.04	0.003
K	0.38	0.56	0.05
Metals mg/kg			
Cu	383	16	< 3
Ni	36	9	< 3
Zn	472	142	105
Pb[1]	268	7	NA
Cr[1]	27	0.5	NA
Cd[1]	2.2	33	NA
Sulfur (mg S/kg)			
Total S	5060	1640	NA
Sulfate S	4730	1860	5780
AVS[4]	3	< 1	< 2

[1] representative samples of bulk material, not collected directly from barrels

[2] % as N

NA not analyzed

[3] % as P

[4] Acid Volatile Sulfur

from the compost. By screening and not shredding, the introduction of contaminants into the compost is minimized. The composting process is complete after about 180 days. However, 45-day-old compost was chosen since it would tend to be more biologically active than finished compost.

Drainage from a stockpile of Duluth Complex material was selected as the input to the treatment system. The drainage was acid with a pH of around 5 and contained 26.0 mg/L of nickel, 7.7 mg/L of copper, 1.2 mg/L of cobalt, and 1.4 mg/L of zinc. Sulfate concentrations were on the order of 800 mg/L.

Experimental Design

Water was pumped from the outflow of the stockpile to two 500-gallon holding tanks. These tanks were connected together to provide about a 1,000-gallon storage reservoir. Water flowed from the storage reservoirs to four rows of three 55-gallon barrels (connected in series), each containing organic material (Figure 1).

Flow entered the barrel from the bottom and flowed upward through the organic material in the barrel. Pea rock was used in the bottom and top of each barrel to help distribute flow, and a geotextile (Mirafi 140 S) was used to minimize the movement of substrate particles. Each barrel contained about 50 gallons of organic substrate (Figure 2).

The composition for each row of barrels was as follows:

Row 1: All barrels contained 45-day-old municipal compost.

Row 2: All barrels contained composted yard waste.

Row 3: All barrels contained a mixture of horse manure and sawdust (91% horse manure by dry weight).

Row 4: The first two barrels contained 45-day-old municipal compost, and the last barrel contained sawdust.

The weight of the organic material added to each barrel was recorded, and the porosity of each material was estimated in the field by measuring the amount of water needed to saturate the substrate fully. Total dry weight of material in each row ranged from 77 kg for the horse manure-sawdust mixture to 288 kg for the composted yard waste, while porosity ranged from 40.2% for the yard waste to 84.5% for the sawdust. Inflow was adjusted manually with a PVC valve and measured volumetrically. Outflow was also measured; but presumably due to gas buildup in the system, the outflow surged and flow rates varied substantially. Since the system is closed, input volume must equal output volume, and the inflow rate was used to represent the flow through the system. Initially all input flow rates were on the order of 30 ml/min. Flow rate into line 4 was increased to around 60 ml/min in September 1991.

The system began operating on July 2, 1990. Air locks in the system prevented flow initially, and vents had to be designed and installed (Figure 2). After the barrels were filled, the input was shut off, and the barrels were allowed to stand for two weeks so that the sulfate reducing bacteria could become established. Weekly sample collection began in Augnst 1990. The barrels were shut down in October, and the water was drained to prevent freezing and splitting of the barrels.

Flow to the system began again in May of 1991, with another two-week conditioning period. Input flow to all lines was on the order of 30 ml/min until late August when, as a result of low rainfall, there was insufficient drainage to feed the system. Input to the barrels was stopped for about ten days, from August 30-September 10. Water was kept in the barrels for the entire time. Flow to row 4 (municipal compost followed by wood chips) was doubled to 60 ml/min on September 17 and remained at that rate until mid October when the system was shut down for the winter.

Results

Flow

Flow into the barrels was adjusted by a one-inch PVC valve. Given the low target flows (around 30 ml/min), precise flow adjustment with this type of control was difficult. Although average flow rates were close to the target rate of 30 ml/min, daily flow rates varied from 6-70 ml/min. Over 70 percent of all the measurements were between 20 and 35 ml/min.

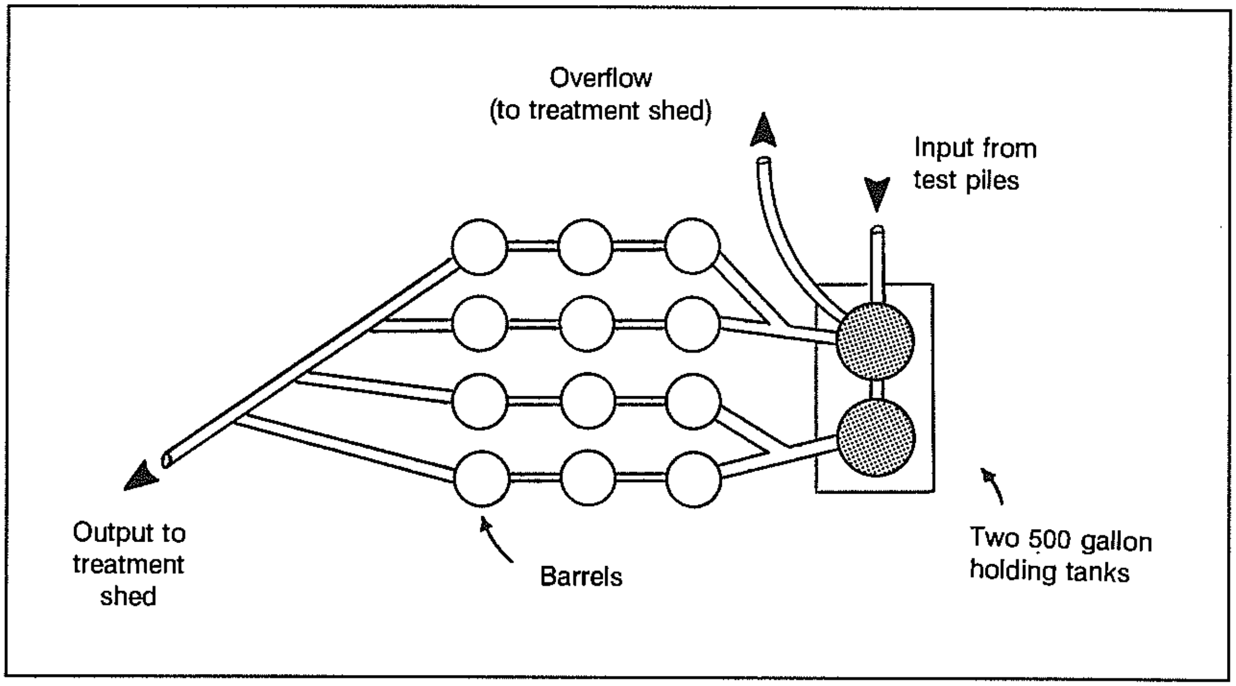

Figure 1. Sulfate reduction test system.

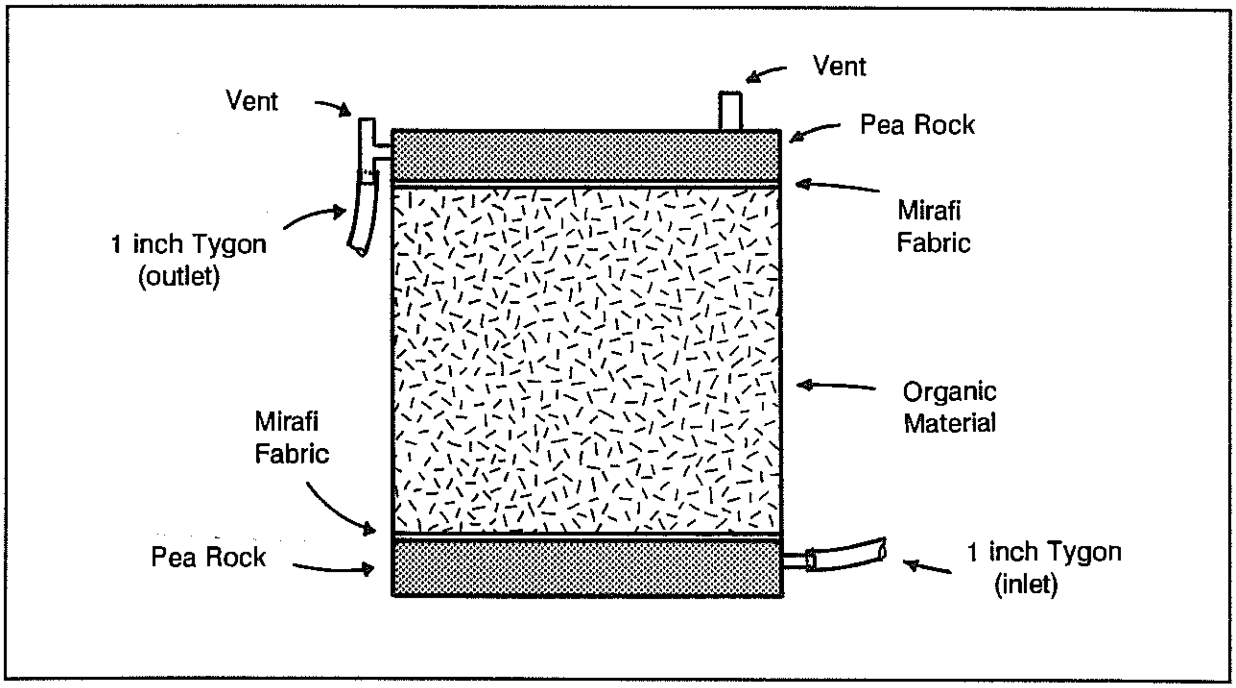

Figure 2. Barrel design for sulfate reduction experiment.

Residence times in each row were determined by:

$$\text{Residence Time} = \frac{\text{Pore Volume}}{\text{Average Flow Rate}} \qquad (3)$$

In 1990 residence time estimates ranged from 5.5 days for composted yard waste to 9.5 days for the horse manure, sawdust mixture (Table 2). In 1991 the residence times were similar to the 1990 values, except when the flow rate into the municipal compost and sawdust was doubled (row 4). This increase in flow decreased the residence time from eight to four days.

The number of bed volumes treated provides a measure of the length of time a material remains viable as a treatment media. One bed volume is a measure of the amount of drainage needed to completely fill the void space in the system.

$$\text{Bed Volumes Treated} = \frac{\text{Total Vol. of Drainage Treated}}{\text{Total Pore Volume}} \qquad (4)$$

The number of bed volumes treated by the various organic substrates varied from 19.1 (row 3) to 33.4 (row 2) (Table 2).

Water Quality

pH and alkalinity. The pH of the drainage generally increased from about 5 to over 7 for all substrates, while the alkalinity increased by 1 to 2 orders of magnitude (Table 3). Alkalinities in the initial samples from the barrels were on the order of 1400 to 3800 mg/L as $CaCO_3$. The initial samples contained significant amounts of fine organic material and ranged in color from dark brown to almost black. Some of the initial alkalinity could be associated with this particulate matter. By the end of 1990, output alkalinities had decreased by about a factor of 10 from the initial values and ranged from 43 for the horse manure-sawdust mixture (row 3) to 422 for the municipal compost and sawdust (row 4). Similar trends were also observed in 1991, although the initial alkalinities were less than in 1990 (Figure 3).

Sulfate. Sulfate was removed from the drainage by all substrates, but the municipal compost removed the largest amount, around 75% for both 1990 and 1991. The average rates of sulfate removal ranged from 7 to 27 gm/day in 1990, and from 9 to 22 gm/day in 1991 (Table 4).

Table 2. Average Flow Rates and Total Volume of Drainage Treated, 1991.

Row	Organic Substrate	Average Daily Flow Rate (ml/min)	Total Annual Volume (L)	Average Residence Time (Estimated days)[1]	Bed Volumes Treated 1991	Bed Volumes Treated Cumulative
1	municipal compost	28	5260	7	18.8	26.6
2	composted yard waste	29	5390	5.5	23.4	33.4
3	horse manure sawdust mixture[2]	27	5060	10	13.1	19.1
4	2 barrels municipal compost, 1 barrel sawdust	29-56[3]	6480	8-4[3]	18.8	25.8

[1] rounded to nearest half day

[2] 10 lb. manure to 1 lb. sawdust

[3] flowrate was increased on 9-17

Note: Average Residence Time and Bed Volume are based on estimated pore volume in the barrels
Total Pore Volume (L) = (Σ Volume of the organic material in the barrel) x (porosity of the material.)

Table 3. Water Quality Results, 1990-1991.

Average Concentrations, mg/L						
Row	Input	1	2	3	4	Water Quality Standards
Organic Substrate	NA$_p$	municipal compost	composted yard waste	horse manure-sawdust mixture[1]	2 barrels municipal compost, 1 barrel sawdust	NA$_p$
pH	5.2	7.4	7.6	7.2	7.2	6.5-8.5
alkalinity	4	1360	440	620	1110	NA$_p$
acidity [2]	50	160	40	130	150	NA$_p$
copper	7.3	0.10	0.05	0.06	0.06	0.023
nickel	24.5	0.12	0.12	0.12	0.11	0.21
cobalt	1.2	0.04	0.04	0.04	0.04	0.05
zinc	1.4	0.13	0.04	0.05	0.06	0.34
sulfate	820	250	630	580	370	NA$_p$

[1] 10 lb. manure to 1 lb. sawdust

[2] By titration; recent data indicates that these values are low since metal precipitation is not instantaneous, and neutralization reactions were not complete when acidity was measured.

NA$_p$ Not applicable

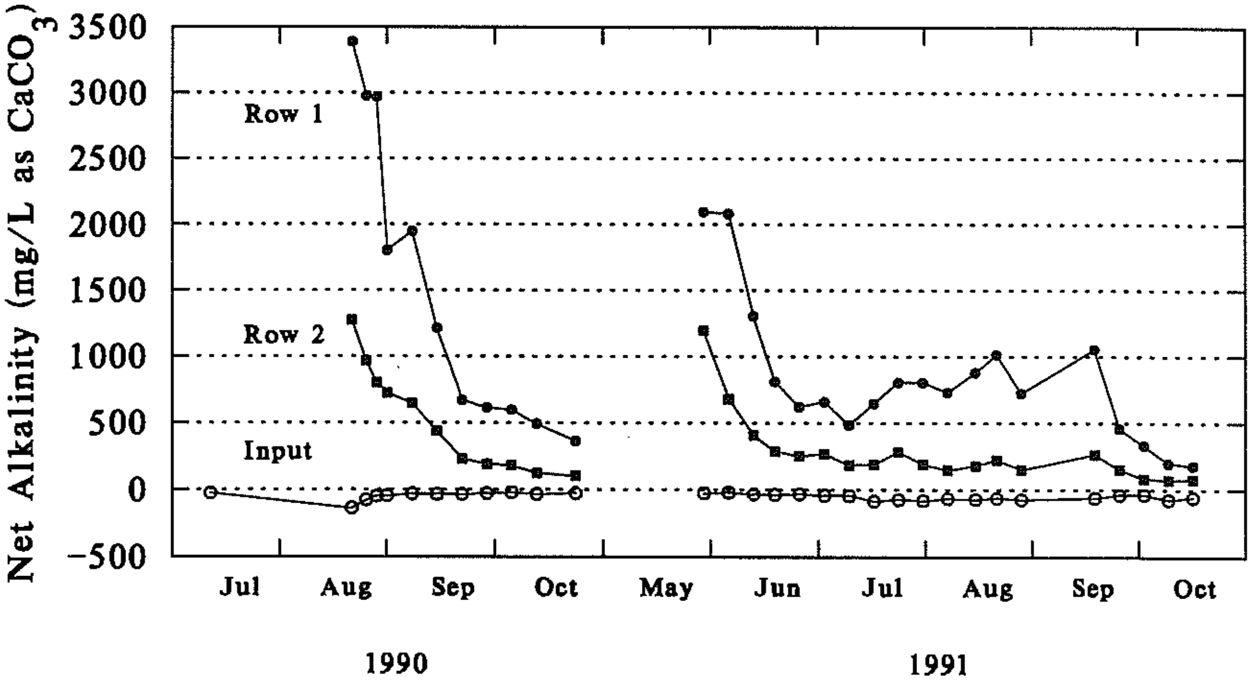

Figure 3. Alkalinity generated from the municipal compost (Row 1) and composted yard waste (Row 2), 1990-91.

Table 4. Sulfate Removal Rates 1990-1991.

		1990			1991		
		Average Removal Rates			Average Removal Rates		
Row	Organic Substrate	gm/day	$\frac{\text{mmole}}{\text{day kg}}$	$\frac{\text{mmole}}{\text{day m}^3}$	gm/day	$\frac{\text{mmole}}{\text{day kg}}$	$\frac{\text{mmole}}{\text{day m}^3}$
1	municipal compost	27	1.2	490	22	1.0	400
2	composted yard waste	8	0.3	165	9	0.3	165
3	horse manure-sawdust mixture[1]	7	0.9	125	15	2.0	275
4	2 barrels municipal compost, 1 barrel sawdust	22	1.3	395	20	1.2	365

[1] 10 lb. manure to 1 lb. sawdust

Although sulfate was removed in all rows, there was considerable variation between rows and over time. In 1990 the maximum reduction rates occurred during the initiation of the test. Removal in all rows decreased in September and October and reached their minimum value in October.

In 1991 removal rates also varied but by a smaller amount than observed during 1990. Initial rates in 1991 exceeded those of the preceding fall, and average rates for 1991 were generally similar to those observed for 1990, with the exception of the row containing horse manure and sawdust (row 3). Here the average rate more than doubled from about 7 gm/day to 15 gm/day (Table 4). Rates again decreased in the fall but not to the extent observed in 1990, and all rows had positive removal rates until the system was shut down in the middle of October (Figure 4).

Trace Metals. In general, the results presented are for unfiltered samples, and the metal values represent total digested values. During 1990 some of the metal samples were filtered, but filtered values were comparable to unfiltered values.

At the discharge from the last barrel, all organic substrates had reduced the input metal concentrations by over 90%. There was little difference in removal between rows and little scatter in the output concentrations (Table 3, Figure 5).

To determine the impact of shorter residence times on removal, samples were collected from the individual barrels in each row. For copper, essentially all removal occurred in the first barrel for all rows (Table 5).

For nickel, all the removal occurred in the first barrel for the municipal compost (row 1) only. For the rows containing composted yard waste and municipal compost and sawdusts (rows 2, 4) removal was complete by barrel 2, while for the row containing the horse manure-sawdust mixture (row 3), removal was not complete until the final discharge from the system (Table 5).

The increase in nickel concentration in row 4 (municipal compost and sawdust) occurred at the time when the flow rate through the system was doubled.

Discussion

Although sulfate reduction occurred in all organic substrates, the highest reduction rates were

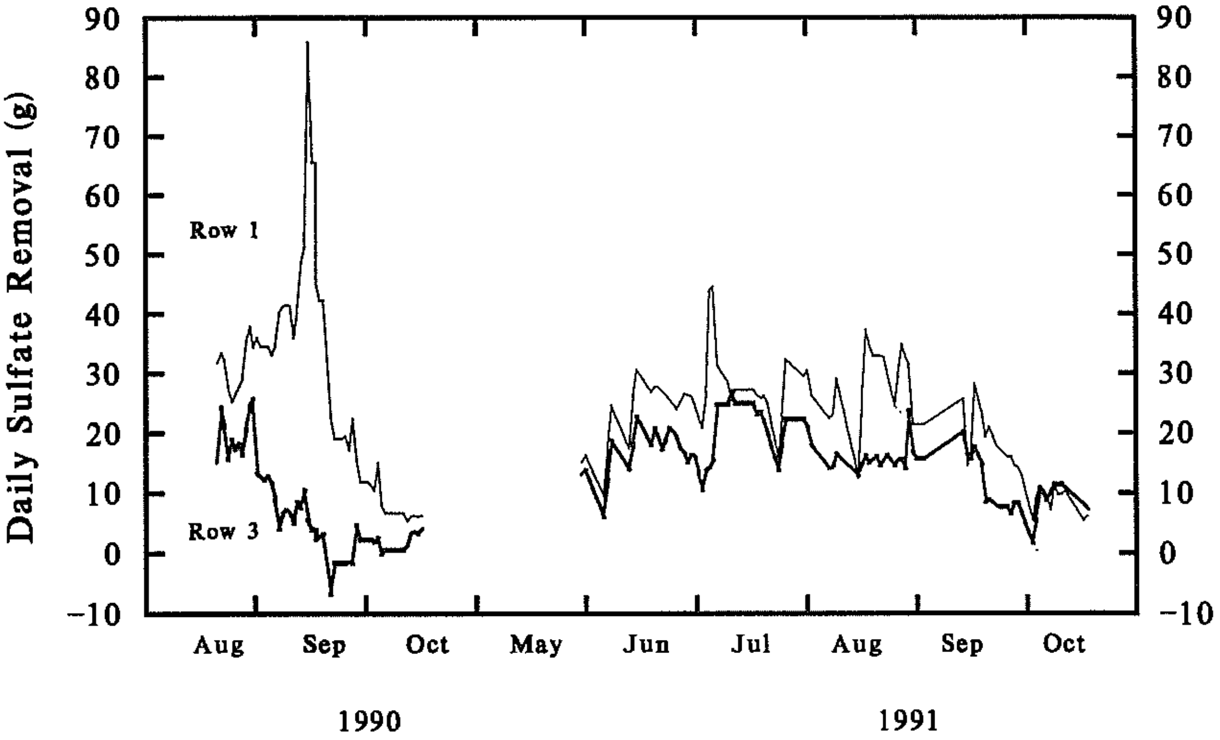

Figure 4. Daily Sulfate removal in municipal compost (Row 1) and the horse manure, sawdust mixture (Row 3), 1990-91.

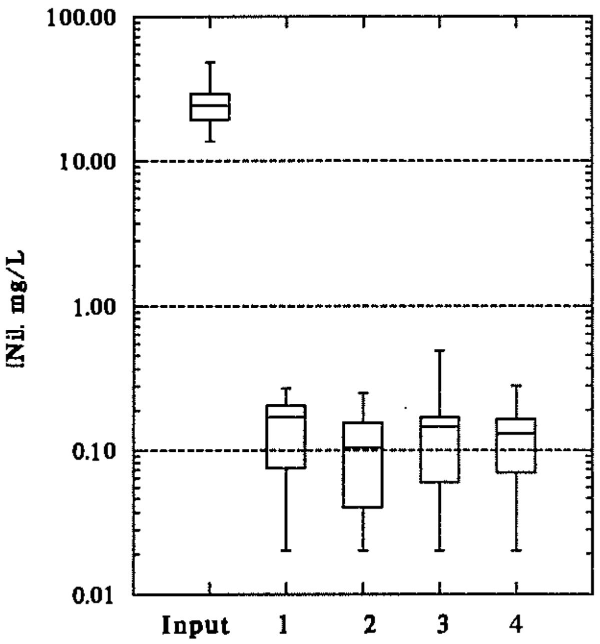

Figure 5. Box plot of nickel concentrations in the inflow and in the outflow from each organic substrate, 1990-91. Box plots represents the entire data set, and the box is made from the upper and lower quartiles, with the line inside the box representing the median. Minimum and maximum values are also shown.

measured in the 45-day-old municipal compost. The average rate of sulfate removal measured for the municipal compost exceeded the rates for the horse manure, sawdust mixture, and the composted yard waste by factors of about 2 to 3.

The rate of sulfate reduction is a function of the concentration of labile organic compounds, sulfate concentration, temperature, pH, and the population of both fermentative and sulfate reducing bacteria. Since all the organic substrates in our system receive the same feed water and are at the same external temperature, the difference in sulfate reduction rates is due to the difference in the organic substrate. The 45-day-old municipal compost can apparently supply more labile organic compounds than the other substrates.

Sulfate reduction rates measured for the municipal compost in this study were generally in the range of rates measured by other investigators for mushroom compost (Table 6). Most of the wetlands constructed to treat mine drainage have used spent mushroom compost as the organic substrate. Although these wetlands can remove contaminants as a result of sulfate reduction, mushroom compost is not a widely available material.

Table 5. Metal Data Between Barrels.

		Average Copper Concentrations,[2] mg/L			
Row	Organic Substrate	Input	After Barrel 1	After Barrel 2	After Barrel 3
1	municipal compost	9.6	0.06	0.05	0.10
2	composted yard waste	9.6	0.06	0.05	0.08
3	horse manure-sawdust mixture[1]	10.5	0.06	0.05	0.08
4	2 barrels municipal compost, 1 barrel sawdust	10.5	0.05	0.05	0.07
		Average Nickel Concentrations,[2] mg/L			
1	municipal compost	32.5	0.10	0.12	0.14
2	composted yard waste	32.5	0.80	0.10	0.12
3	horse manure- sawdust mixture[1]	36.7	17.0	0.373	0.12
4	2 barrels municipal compost, 1 barrel sawdust	36.7	1.0[3]	0.09	0.12

[1] 10 lb. manure to 1 lb. sawdust.

[2] Average of six samples collected between 7-22 and 10-14.

[3] Input flow rate was doubled on 9-17.

Table 6. Summary of Sulfate Reduction Data From Other Studies.

Study	Organic Substrate	Drainage pH	Metals in Drainage	Rate of Sulfate Reduction	Units	Type of Study
Hammack & Edenborn	mushroom compost	4.5	Ni	8-13 92[(a)] 40[(a)]	nmol/gm/day nmol/cm^3/day	Lab
McIntire, et al.	mushroom compost	2.5	Fe	2-600 150-200[(b)]	nmol/cm^3/day	Field
Dvorak, et al.	mushroom compost	3.7	Fe	377	nmol/cm^3/day	Field
Dvorak, et al.	mushroom compost	6.3	Zn, Mn	250	nmol/cm^3/day	Field
Reynolds, et al.	mushroom compost	3.0	Fe, Mn, Zn	1200	[(c)] nmol/cm^3/day	Lab
Present Study	municipal compost	5.0	Cu, Ni, Co, Zn	400[(d)] 90-820[(e)]	nmol/cm^3/day	Field

(a) with lactate addition
(b) average values
(c) assuming bulk density of 1.28 gms/cm^3, from Wildeman.
(d) average rate, 1991
(e) range, 1991

As more communities close their landfills, alternatives such as composting are likely to become more attractive. Municipal compost, although present now in certain regions, should become more widely available. Based on the rate of sulfate reduction observed in this study, municipal compost should provide a substrate which will be as reactive and more available than mushroom compost.

If the sulfate reduction system was 100 percent effective at removing metals, then one mole of sulfate would be reduced for each mole of divalent metal precipitated (Equation 1, 2). The removal of each mole of aluminum and ferric iron requires 1.5 moles of sulfate reduction. Aluminum does not form a stable sulfide in the presence of water, and therefore aluminum removal probably occurs due to the formation of a hydroxide:

$$Al^{+3} + 3\,H_2O \rightarrow Al\,(OH)_3 + 3H^{+} \qquad (5)$$

To neutralize the acid generated by this reaction requires that 1.5 moles of sulfate be reduced (Equations 1, 2). Ferric iron (Fe^{+3}) could be removed as a hydroxide, but removal probably occurs through the reduction of ferric iron to ferrous iron and subsequent precipitation as a divalent metal sulfide (Dvorak et al. 1991):

$$4\,Fe^{+3} + CH_2O + H_2O \rightarrow 4\,Fe^{+2} + CO_2 + 4H^{+} \qquad (6)$$

To remove one mole of ferrous iron, one mole of sulfate must be reduced; and to neutralize one mole of acid, one-half mole of sulfate must be reduced (Equation 1). Therefore, to remove all the metals and acid in the input, the required rate of sulfate reduction can be calculated from

$$\begin{array}{ll} \text{Required rate of} & = \Sigma \text{ mmole divalent metals } (M^{+2}) \\ \text{sulfate reduction} & \quad \text{in input} \\ & \quad + \\ & \quad 1.5\,\Sigma \text{ mmole } Al^{+3}, Fe^{+3} \qquad (7) \\ & \quad + \\ & \quad 0.5\,(1000 \times 10^{-pH}) \end{array}$$

For the drainage in this study, copper, nickel, cobalt, and zinc are the major contaminants. They account for about 90% of the total sulfate reduction required to treat the input water.

For treatment by sulfate reduction to be effective, the rate of sulfate reduction must equal or exceed the input of acid and metals. For the rows containing municipal compost, horse manure, and sawdust (rows 1, 3, 4), the overall sulfate reduction rate always exceeded the input rate, and complete treatment of the input could be provided by sulfate reduction (Figure 6). For the composted yard waste (row 2), the input rate equalled or exceeded the sulfate removal rate at the end of 1991 (Figure 7). Sulfate reduction processes were not sufficient to completely treat the input during this time period. However, since metal removal still occurred, removal processes other than sulfate reduction, such as precipitation, adsorption, or ion-exchange probably accounted for some of the metal removal.

Although the overall sulfate reduction rate for the entire row of barrels generally exceeded the input load, the rate in the first barrel was sometimes not sufficient to treat all the drainage.

As the rate of sulfate reduction approached the rate of metal and acid input in the first barrel of the horse manure-sawdust mixture (row 3), the pH of the effluent began to decrease, and nickel concentration began to increase. Insufficient sulfate reduction was occurring in the first barrel to treat the drainage (Figure 8).

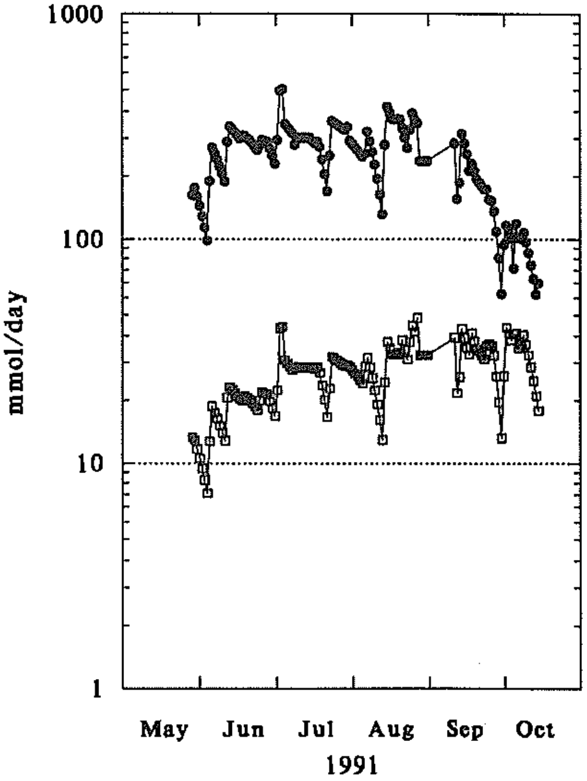

Figure 6. Rate of sulfate reduction (darkened circles) and the rate of metals and acid input (open squares) to the municipal compost (Row 1), 1991.

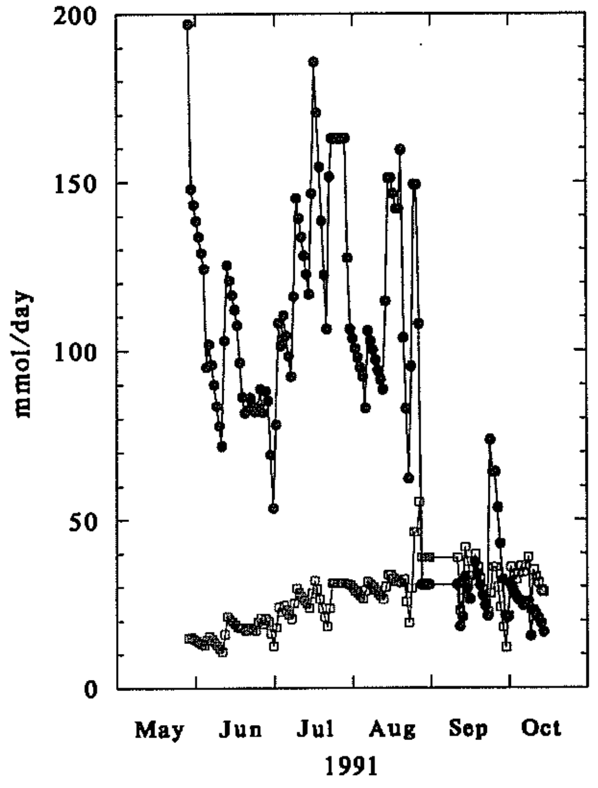

Figure 7. Rate of sulfate reduction (darkened circles) and the rate of metals and acid input (open squares) to the composted yard waste (Row 2), 1991.

Designing a system to treat acid mine drainage successfully will require that the input load of metals and acid always be less than the sulfate removal rate. The minimum size of the system would be determined by

$$\text{volume of organic substrate } (m^3) = \frac{\text{input divalent metal load, mmole/day} + 1.5 \text{ aluminum and ferric iron load} + 0.5 \text{ input acid load mmole/day}}{\text{sulfate removal rate mmole/day } m^3} \qquad (8)$$

Given a fixed volume of organic substrate, the same equation can be used to calculate the maximum metal loading for the system. Based on this approach, the organic substrate in our study should be able to treat from about 2 to 5 times as much flow as they are currently treating. The residence times at these higher flows would be on the order of 1 to 2 days (Table 7).

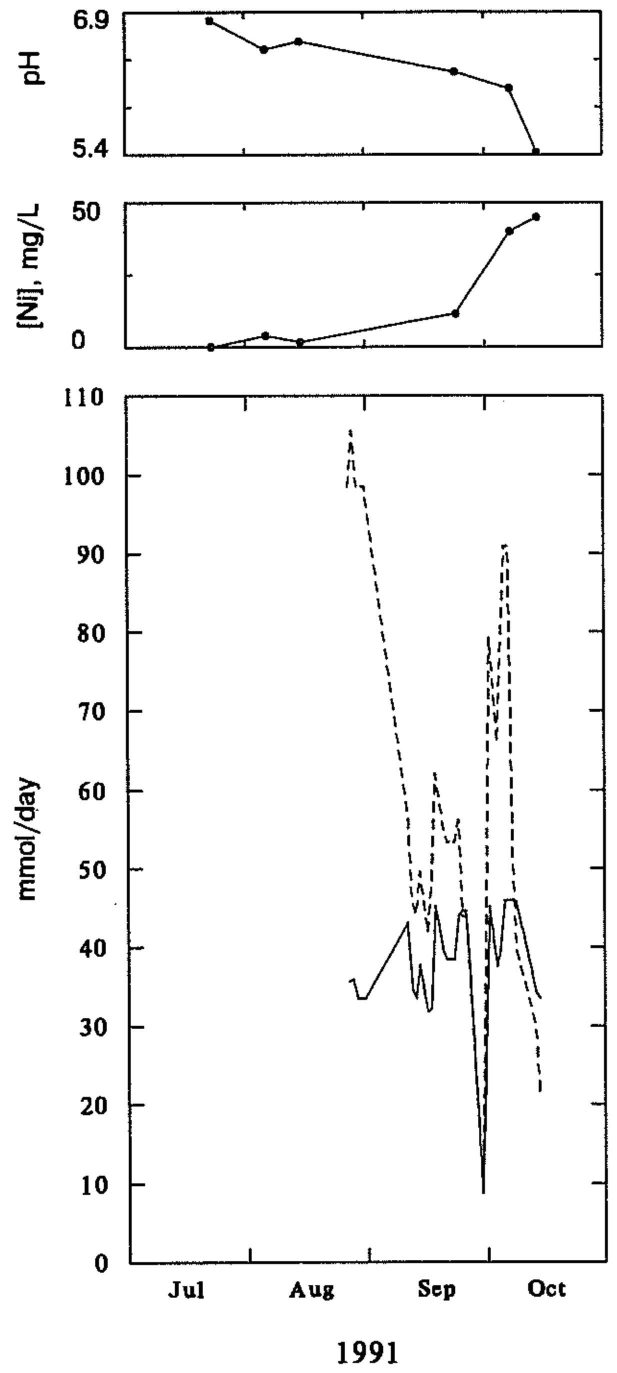

Figure 8. Rate of sulfate reduction (dashed lined), input metals and acid load (solid line), and outflow pH and nickel concentration for the first barrel of the horse manure, sawdust mixture (Row 3), 1991.

In an actual design, a safety factor should be employed since sulfate removal, metal input, and acid input will vary with time. Additional consideration must also be given to the hydraulic conductivity of the organic substrate. Typical

Table 7. Average Sulfate Removal Rates and Maximum Input Flows, based on 1991 Results.

Row	Organic Substrate	Average Annual Sulfate Reduction	Required rate of sulfate reduction[1]	Maximum Input Flow	Hydraulic[3] conductivity	Estimated residence time at maximum flow
		mmole/day	mmole/L	ml/min	cm/sec	(days)
1	municipal compost	230	0.7	230	5.5×10^{-3}	0.9
2	composted yard waste	80	0.7	80	1.8×10^{-3}	1.9
3	horse manure-sawdust mixture[2]	160	0.7	150	3.6×10^{-3}	1.8
4	2 barrels municipal compost, 1 barrel sawdust	210	0.7	210	4.9×10^{-3}	1.1

[1] Based on the rate needed to remove all the metals and acid load from the input, the input load was calculated from copper + nickel + zinc + cobalt + manganese 0.5 x (1000 x 10^{-pH}) + 1.5 (iron + aluminum). This assumes that aluminum is removed as a hydroxide.

[2] 10 lb. manure to 1 lb. sawdust

[3] Hydraulic conductivity required to transmit maximum flow assuming a hydraulic gradient of 1/3.

permeability values for mushroom compost have been reported to be in the 10^{-3} to 10^{-4} cm/sec range, with permeability decreasing over time (Wildeman et al. 1991). Based on preliminary estimates, the hydraulic conductivities of the organic substrates in this test are on the order of 10^{-3} cm/sec. If permeability of the substrate decreases, the hydraulic head would have to be increased to maintain the current flow through the system. For a well-designed treatment system, both metal loading and hydraulic loading must be compatible with the size of the system.

Conclusions

Sulfate reduction was successful in neutralizing acid mine drainage and in removing copper, nickel, cobalt, and zinc from the drainage. Metal concentrations were reduced by one to two orders of magnitude and generally met water quality standards. Municipal compost appears to be a more generally available organic substrate for constructed wetlands than spent mushroom been commonly used in wetland constructions, the rates of sulfate reduction in 45-day-old municipal compost were comparable to the rates measured in mushroom compost.

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