

Crop and Soil Response to Acidic and Circum-Neutral Mine Influenced Waters

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Abstract

Acid mine drainage (AMD) requires treatment to circum-neutral pH using High-Density Sludge (HDS) or Biological Sulfate Reduction (BSR) processes to lower metal concentrations and reduce environmental impact. Further treatment to potable standards is very costly, making alternatives like irrigation with untreated or neutralised mine water worthy of consideration. A field trial tested the response of lucerne (*Medicago sativa*), sorghum (*Sorghum Bicolor*), soybean (*Glycine max*) and teff (*Eragrostis tef* [Zucc]) to irrigation with three mine waters [untreated AMD (pH \approx 3.1, EC \approx 407 mS m⁻¹), HDS-treated (pH \approx 8.5, EC \approx 350 mS m⁻¹), and BSR-treated (pH \approx 7.6, EC \approx 336 mS m⁻¹)], from a treatment plant in the Mpumalanga Coalfields, South Africa. Crops performed well with HDS water, with a 25% yield penalty for untreated AMD and 50% for BSR water. Elemental concentrations increased in soil and trace elemental accumulation in plants, raising concerns about long-term continuous irrigation.

Keywords: BSR neutralised AMD, fibre and biofuel crops, food safety, HDS neutralised AMD, mine water irrigation

Introduction

The mining industry produces large volumes of mine-influenced water that must be managed responsibly (Annandale *et al.* 2006; Hutton *et al.* 2009). These waters vary widely in quality, depending on geology and the mining method used. Most are unsuitable for release into the environment without some form of treatment. A common practice is to neutralise acid mine drainage (AMD) using hydrated lime or limestone in high-density sludge (HDS) plants or using sulphate reducing bacteria in BSR plants. Such treatment raises the pH and lowers metal concentrations, but water is still too saline for direct release to natural water bodies. Further treatment is required to remove salts, which can be achieved by reverse osmosis (RO) to produce potable water, but this is very costly and energy intensive. Furthermore, HDS and RO treatment generate by-products in the form of gypsiferous sludges and brines, which also need to be managed. Therefore, alternative responsible mine water

management options are sought. One being proposed is irrigation of crops on strategically limed soils with untreated acidic mine water, which, if successful, could eliminate the need for HDS or BSR treatment. If irrigation with acidic mine water proves to be problematic, then neutralisation will be essential before utilisation through irrigation, and significant savings would still be possible because there would be no need for RO and brine disposal.

Irrigation with such water has not been intensively studied. Therefore, a small-scale field trial was established at the centrally located mine water treatment plant at eMalahleni, Mpumalanga Province, South Africa. This location was strategically selected as it facilitated access to a range of mine influenced water. The specific aim of this study was to investigate crop and soil responses to irrigation with untreated highly acidic AMD with additional limestone applied to the soil, HDS neutralised AMD, and BSR treated AMD. Food and feed safety of the produce was also assessed.

Methods

Due to the limited area available, three water sources were tested alongside four cropping systems: soybean (*Glycine max*), lucerne (*Medicago sativa*), grain sorghum (*Sorghum bicolor*), and teff (*Eragrostis tef* [Zucc]), with four replicates. The main plots, representing different water treatments, had an area of 449 m², with 1.5 m spacing between them (Figure 1). Each block had nine permanent sprinklers. One full-circle sprinkler was placed centrally, with four quarter-circle sprinklers in the corners and four half-circle sprinklers in the middle of each side. To minimize the risk of wind drift, sprinkler height was set at 1 m, necessitating the selection of short crops. Subplots, representing different cropping systems, each had an area of 24 m², with a 0.5 m path between them. A structure supporting dense shade netting was erected between water treatments to reduce wind drift transporting irrigation waters to adjacent water treatment plots. Netting was rolled back after irrigation to avoid edge shading for this trial. Table 1 presents the average quality of the waters tested.

Soils were analysed for pH (measured in KCl), EC in a saturated soil paste extract, P using the Bray 1 method, and K, Na, Ca, S, and Mg in ammonium acetate extracts, with Cu, Fe, and Mn in Mehlich-3 extracts. Total concentrations of trace elements were determined through microwave-assisted aqua regia dissolution and analysed by Inductively Coupled Plasma Optical Emission

Spectrometry (ICP-OES) to establish baseline values (Table 2).

Crop height and canopy cover were measured weekly, and at maturity, vegetative plant biomass and yield where applicable were determined with plants cut at ground level and oven-dried at 65 °C for 48 h. Plant tissue analyses determined the concentrations of potentially toxic elements in biomass grain. Data were analysed using Microsoft Excel and GenStat, with mean separation performed using Duncan's multiple range test at a 95% probability level (P <0.05).

Results and discussion

Effects of mine water on soil pH and EC.

Weekly irrigation was applied during the summer of 2024/25 for 21 weeks, with ≈471 mm irrigation and ≈229 mm rainfall. Water EC and pH were monitored with each irrigation. Untreated AMD had the highest EC (≈407 mS m⁻¹) and lowest pH (≈3.1). BSR treatment improved water quality to an EC of ≈336 mS m⁻¹ and a pH of ≈7.6 and HDS water to an EC of ≈350 mS m⁻¹) and pH of ≈8.5. The limestone application rate was based on the total acidity (2015 mg L⁻¹) of the irrigation water, expressed as the amount of CaCO₃ necessary to neutralise the water to a target pH of 8.3. The estimated irrigation was 700 mm, with the soil amounting to 2 100 t ha⁻¹. The application of 14.1 t ha⁻¹ of limestone effectively neutralised the pH of the untreated AMD, as the pH of the soil increased only slightly from 7.7 to 7.8 by the

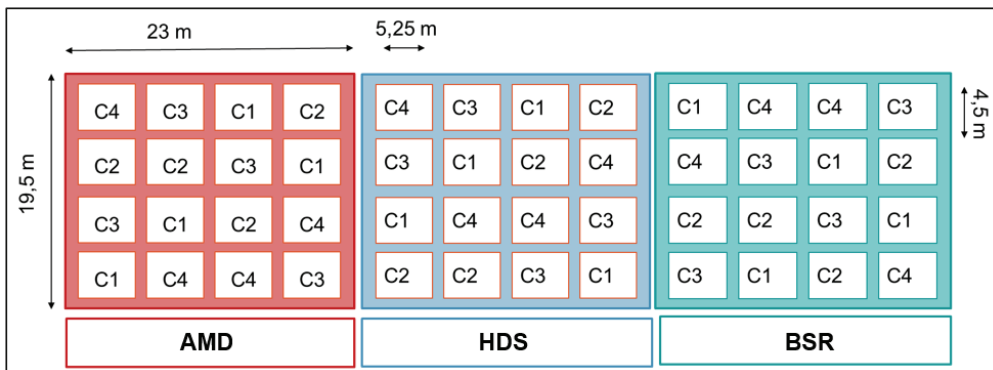


Figure 1 Trial layout design.



Table 1 Average chemical composition of the mine influenced water used for irrigation. Concentrations are in mg/L, EC in mS/m and pH is without unitless.

Constituent	AMD	HDS	BSR
pH	3.1	8.5	7.6
EC	407	350	336
Al	68	0.09	0.1
As	<0.01	<0.01	<0.01
Cd	0.004	<0.003	<0.003
Ca	412	683	264
Cl	11	31	-
Cu	0.03	<0.01	0.01
F	<0.2	0.64	0.4
Pb	<0.01	<0.01	<0.01
Mg	201	114	193
Mn	21	0.08	0.07
Hg	<0.001	<0.001	-
Ni	0.46	0.06	0.03
Se	0.02	BDL	0.00
Na	187	131	70
SO ₄	2871	2394	800
Fe	638	31	1.02
Zn	1.50	0.03	0.52
TDS	4910	3752	-
TSS	200	96	-

pH was averaged using the formula $-\log_{10}[(\sum C_i)/n]$. - indicates not analysed.

end of the season. Irrigation increased the pH of the BSR and HDS blocks to 7.9. All blocks showed higher conductivities than the pre-irrigation sample (189 mS m⁻¹), with topsoil EC increasing to 230 mS m⁻¹ (AMD), 224 mS m⁻¹ (BSR), and 215 mS m⁻¹ (HDS) after one irrigation season.

Crop response to irrigation with mine water

Sorghum and soybean irrigated with BSR water exhibited delayed seed germination, poor crop establishment, and signs of stunting compared to HDS and AMD treatments. Significant differences ($P < 0.05$) were observed in aboveground biomass production for all crops (Figure 2). Sorghum incurred yield penalties of 26% with untreated AMD and 52% for BSR-treated water relative to the HDS control. The effects on plant growth in the BSR treatment might have been caused by bicarbonate salinity which appears to be

more severe than calcium sulfate dominated salinity which tends to precipitate gypsum in the soil profile, thereby lowering root-zone salinity which reduces salinity stress of crops (Ossorio *et al.* 2017).

Food safety of crops irrigated with mine water

Sorghum grain was analysed for food safety, and irrigation with mine influenced water increased elemental concentrations. The presence of Ni at a threshold of 10 mg kg⁻¹ and Pb at 0.2 mg kg⁻¹ in all treatments and Hg at levels above 0.1 mg kg⁻¹ under irrigation AMD indicated that these levels were not safe for human consumption. However, the plant analysis data was deemed unreliable, as mass balance calculations indicated “measured” values were impossibly high. These analyses will be redone to ensure accuracy. Hg which was below the detection limit (<0.001) in

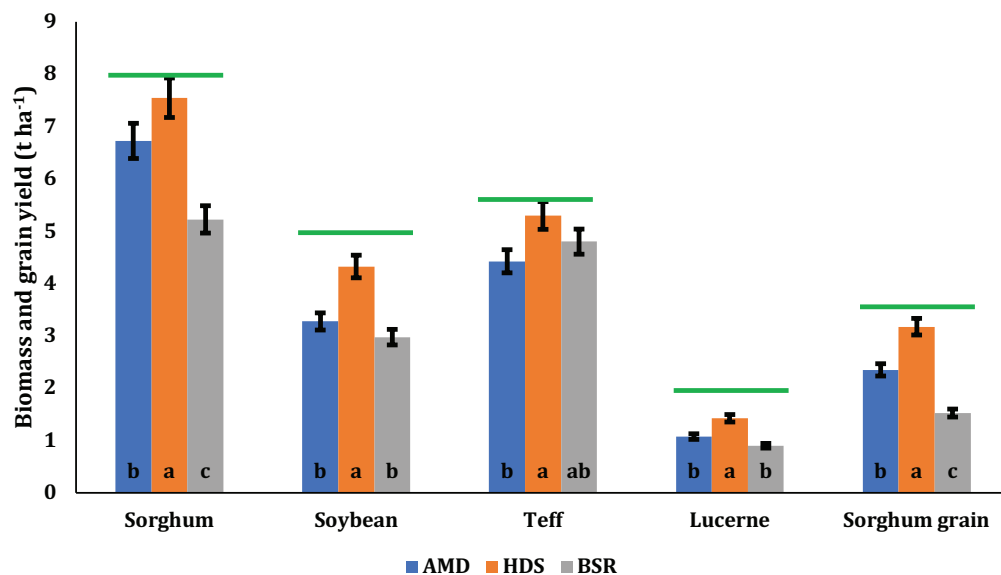


Figure 2 Aboveground biomass and grain yield of crops produced in the summer of 2024/2025. Horizontal green lines indicates published irrigated agronomic target yields for the different crops in the region. Different letters (a–c) indicate significant differences within a species ($p \leq 0.05$).

the waters, increased concentrations to 0.04 mg kg⁻¹ (HDS) and 0.06 mg kg⁻¹ (BSR) in circum-neutral waters. This proves that even though trace elements may be present in small amounts in the irrigation waters, when applied over prolonged periods, plus initial soil concentration, would result in increased accumulation, which is a major concern if irrigation is applied continuously. Therefore, careful monitoring is recommended to ensure that there are acceptable offsite environmental impacts and that the produce remains safe for consumption.

Conclusions

Irrigation with these mine influenced water increased soil pH and EC, with the increase in pH for the AMD treatment ascribed to limestone application. Irrigation with untreated AMD reduced aboveground biomass by 25%, and with BSR water, by more than 50%. This suggests that highly acidic AMD requires treatment prior to irrigation, and that high-bicarbonate BSR-treated water requires a polishing step to reduce bicarbonate salinity levels. Ca- and sulfate-rich HDS water, similar to that investigated

by Jovanovic *et al.* (1998), demonstrated considerable potential for irrigation, with plant growth and yields comparable to those expected under irrigation with good-quality water, with limited elemental accumulation. Plant tissue analysis from this experiment resulted in increased Ni, Pb, and Hg accumulation, which is a major concern if irrigation is applied continuously. It is understandable that concerns regarding food and feed safety may arise. Therefore, it is prudent to monitor these risks, and if concerns are perceived or real, non-edible industrial crops can be considered.

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