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Assessing the sustainability of acid mine drainage (AMD) treatment in South Africa

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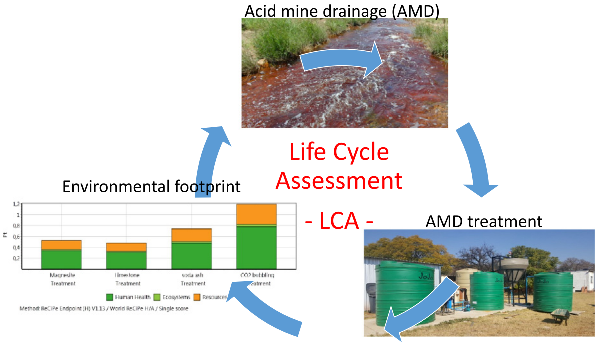
HIGHLIGHTS

- Environmental impacts of AMD treatment were assessed by life cycle assessment (LCA).
- An integrated active process, i.e. magnesite, lime, soda ash and CO2 treatment, was used.
- The process is cost effective, treatment cost as low as R112.78/m^3 (€7.60–$9.35/m^3).
- The high environmental footprint was attributed to electricity and liquid CO_2 use
- Introduction of solar energy and gaseous CO_2 can axe environmental footprint by 81%.
- AMD sludge valorisation, i.e. mineral recovery, seems promising but more research is needed.

GRAPHICAL ABSTRACT



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ABSTRACT

The environmental sustainability of acid mine drainage (AMD) treatment at semi-industrial scale is examined by means of the life cycle assessment (LCA) methodology. An integrated process which includes magnesite, lime, soda ash and CO_2 bubbling treatment was employed to effectively treat, at semi-industrial scale, AMD originating from a coal mine in South Africa. Economic aspects are also discussed. AMD is a growing problem of emerging concern that cause detrimental effects to the environment and living organisms, including humans, and impose on development, health, access to clean water, thus also affect economic growth and cause social instability. Therefore, sustainable and cost effective treatment methods are required. A life cycle cost analysis (LCCA) revealed the viability of the system, since the levelized cost of AMD treatment can be as low as R112.78/m^3 (€7.60/m^3 or $9.35/m^3). Moreover, due to its versatility, the system can be used both at remote locales, at stand-alone mode (e.g. using solar energy), or can treat AMD at industrial scale, thus substantially improving community resilience at local and national level. In terms of environmental sustainability, 29.6 kg CO_{2eq} are emitted per treated m^3 AMD or its environmental footprint amount to 2.96 Pt/m^3. South Africa's fossil-fuel depended energy mix and liquid CO_2 consumption were the main environmental hotspots. The total environmental

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footprint is reduced by 45% and 36% by using solar energy and gaseous CO_2, respectively. Finally, AMD sludge valorisation, i.e. mineral recovery, can reduce the total environmental footprint by up to 12%.

1. Introduction

Access to clean water is a basic human right, and one of the cornerstones of environmental protection in Europe (Eurostat, 2017). Water is critical for sustaining ecosystems, plays a fundamental role in the climate regulation cycle and is also the primary requirement for human survival and socioeconomic development (Eurostat, 2017; Naidoo, 2016). Even though clean water access is taken for granted in the developed world this is not the case for developing countries, which are struggling to keep economic growth but often at the expense of environmental protection and water quality. South Africa is a developing country that faces water scarcity issues. On top of this, its water systems are severely harmed by different forms of pollution, including acid mine drainage (AMD) (Naidoo, 2016). AMD, also known as acid rock drainage (ARD), is a common problem at mine sites, primarily at abandoned ones, and one of the main environmental challenges facing the mining industry worldwide (Council for Geoscience, 2010; Johnson and Hallberg, 2005). It is mainly produced from the bio-hydro-geochemical weathering of pyrite and other reactive sulphide bearing minerals, when exposed to oxidising conditions (Masindi et al., 2017). AMD emanating from active or abandoned mines and from mine wastes are often net acidic. These effluents pose an additional risk to the environment, since they often contain elevated concentrations of metals (iron, aluminium and manganese, and possibly other heavy metals) and metalloids (Johnson and Hallberg, 2005). South Africa has a long history in mining and its economy is still largely driven by a strong mining industry; nonetheless growing evidence suggests that its water resources have been grossly impacted by AMD (Council for Geoscience, 2010; Naidoo, 2016).

A wide array of treatment methods, such as ion-exchange, adsorption, bio-sorption, chemical-neutralising agents, coagulation and precipitation, have been proposed for AMD treatment (Johnson and Hallberg, 2005; Masindi et al., 2017). In general, treatment methods can be divided into those that use either chemical or biological mechanisms and they can be further classified as i) active (they require continuous inputs of neutralisation materials, such as magnesite, periclase, brucite, lime, hydrated lime, and limestone, to sustain the process), ii) passive (they require relatively little resource input once in operation and could involve the use of wetland, reactive barriers and lime drains), or iii) integrated (i.e. they entail the combination of both) (Johnson and Hallberg, 2005; Masindi, 2017). The most widespread method for AMD neutralisation is active treatment, involving addition of an alkaline material (chemical-neutralising agent such as magnesite, lime, calcium carbonate, sodium carbonate, sodium hydroxide, and magnesium oxide and hydroxide) that will raise the pH, accelerate ferrous iron rate of chemical oxidation (to this end active aeration or additional chemical oxidising agent are also required) and cause many of the metals present in solution to precipitate as hydroxides and carbonates (Johnson and Hallberg, 2005). Lime treatment is the most commonly used active treatment method, due to its high efficiency and low cost (Potgieter-Vermaak et al., 2006).

Even though treatment efficiencies of the available AMD methods are well-established and explored (e.g. (Johnson and Hallberg, 2005; Potgieter-Vermaak et al., 2006)), this is not the case for their environmental sustainability, where only a few cases dealing with the environmental sustainability of AMD treatment systems are available (Hengen et al., 2014; Tuazon and Corder, 2008). Therefore, herein a full life cycle assessment (LCA) of a typical AMD treatment method is carried out, using primary life cycle inventory (LCI) data collected from a semi-industrial AMD treatment plant. The goal is to assess the environmental sustainability of a typical AMD treatment process, identify environmental hotspots and identify avenues to improve its environmental sustainability, such as resource extraction from AMD sludge. Also, economic and social aspects regarding the sustainability of the treatment system are discussed.

2. The case study

Acid mine drainage (AMD) was collected from a coal mine in Mpumalanga Province, South Africa, and was transferred to the premises of the Council for Scientific and Industrial Research (CSIR), Pretoria campus, South Africa, for treatment. The raw mine water was initially colourless, but after reacting with atmospheric air it turned red (Fig. 1), due to the oxidation of ferrous to ferric ions. The AMD tetrahedron in Fig. 1b shows all relevant components that contribute to this process. Co-existence of raw mine water, atmospheric oxygen, sulphide minerals (as a source of iron) and waterborne bacteria (to accelerate the reactions) can lead to the production of AMD (Pondja, 2017).

As far as its physical and chemical characteristics are concerned, the AMD under study is very acidic with pH 2, and contains high amounts of sulphate, Fe, Al and Mn, Mg and Ca (Table 1).

As shown in Fig. 2 the AMD treatment system comprises the following four discrete process steps: (1) neutralisation of AMD and partial removal of sulphates achieved by using calcined cryptocrystalline magnesite (magnesite treatment); (2) addition of limestone to reduce water hardness and residual sulphate as gypsum (limestone treatment); (3) soda ash addition to reduce residual Ca and hardness (soda ash treatment); (4) CO_2 bubbling to correct the pH to 7.5 and recover limestone (CO_2 bubbling). The main products of this treatment process comprise the treated AMD effluent and the produced sludge. The latter is typically discarded for landfilling, but it can be also valorised as will be discussed in the sensitivity analyses section. As shown in Table 1, the system is capable of providing a high quality treated water output, which meets South Africa's water quality standards to be safely returned to nature, or used for industrial and agricultural purposes (DWAF, 1996).

The aforementioned system was designed, constructed, and commissioned at the premises of CSIR Pretoria campus, South Africa, where it operates at semi-industrial scale and is able to effectively treat 3.5 m^3 of AMD daily (Fig. 3).

At the time of writing, a reverse osmosis (RO) followed by chlorination tertiary treatment system is under testing (SUT) in order to explore the possibility to produce drinking water; a viable product for South African rural communities. All process steps take place in the same reactor (i.e. clarifier), since each process step has to be completed before moving on to the next step. This reduces the system's initial capital expenditure and less space is occupied, i.e. land use is minimized.

A detailed discussion regarding the four process steps under study can be found in Masindi (2017). For the magnesite treatment stage 10 kg of magnesite per m^3 of AMD are added to the clarifier, shown in Figs. 2 and 3. The mixture is agitated for 60 min and then it is left for another 60 min to settle, where solid precipitates are gravity settled. Then, the magnesite treated AMD is transferred to a holding tank and the sludge is transferred to a separate tank (sludge tank). In this stage Fe-species can be recovered from the sludge. For the limestone treatment stage, the magnesite-treated effluent is recycled back to the clarifier and 10 kg/m^3-AMD of limestone are added into it. The mixture is then agitated for 60 min and is left for another 60 min unstirred, to allow solid precipitates to settle. The magnesite/limestone treated AMD and the sludge are transferred back to the holding and the sludge tank,