Article

Techno-Economic Analysis of the Reclamation of Drinking Water and Valuable Minerals from Acid Mine Drainage

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Abstract: The concept of circular economy in wastewater treatment has recently attracted immense interest and this is primarily fueled by the ever-growing interest to minimise ecological footprints of mining activities and metallurgical processes. In light of that, countries such as the Republic of South Africa, China, Australia, and the United States are at the forefront of water pollution due to the generation of notorious acid mine drainage (AMD). The disposal of AMD to different receiving environments constitutes a severe threat to the receiving ecosystem thus calling for prudent intervention to redress the prevailing challenges. Recent research emphasises the employment of wastewater treatment, beneficiation and valorisation. Herein, the techno-economic evaluation of the reclamation of clean water and valuable minerals from AMD using the Magnesite Softening and Reverse Osmosis (MASRO) process was reported. The total capital expenditure (CAPEX) for the plant is ZAR 452,000 (USD 31,103.22) which includes ZAR 110,000 (USD 7569.37) for civil works on a plant area of 100 m^2. The operational expenditure (OPEX) for the pilot is 16,550,000 ZAR (South African Rand) or USD 1,138,845.72 in present value terms (10 years plant life). The plant reclaimed drinking water as specified in different water quality standards, guidelines, and specifications, including Fe-based minerals (goethite, magnetite, and hematite), Mg-gypsum, and calcium carbonate. These minerals were verified using state-of-the-art analytical equipment. The recovered valuables will be sold at ZAR 368/kL (USD 25.32), ZAR 1100/t (USD 75.69), and ZAR 2000/t (USD 137.62) for water, gypsum, and limestone, respectively. The project has an NPV of ZAR 60,000 (USD 4128.75) at an IRR of 26%. The payback period for this investment will take 3 years. The total power consumption per day was recorded to be 146.6 kWh, and 103,288 kWh/annum. In conclusion, findings of this work will significantly contribute to improving the sustainability of the mining sector by proposing economically feasible solutions for wastewater streams treatment, beneficiation, and valorisation.

Keywords: acid mine drainage; treatment; reclamation; techno-economic analysis; valorisation; circular economy; recovery of valuable minerals

1. Introduction

The quest to minimise ecological footprints of wastewater treatment has been ameliorated by the emergence of circular economy in wastewater treatment [1,2]. This concept includes the treatment, beneficiation, and valorisation of wastewater prior to them being discharged to different receiving environments [2–5]. In light of that, research studies seek prudent ways to address the issue of mineral recovery from wastewater although the quest is still ongoing [2]. The emergence of acid mine drainage (AMD) post industrial revolution has led to the development of numerous technologies that aims at the recovery of valuable

minerals and reclamation of wastewater to drinking water, but the primary attempt is to off-set ecological impacts associated to AMD [6–9]. Depending on hydro–geochemical properties, the composition of AMD vary significantly but it is predominated by Al, Fe, Mn, and SO_4^{2-} as major elements and traces of As, Cr, Cu, Ni, Pb, and Zn including traces of radionuclides, rare-earth metals and metalloids [10–12]. The predominance of the elements is dependent on the weathered mineral. For instance, the oxidation of pyrite would lead to AMD that is rich in Fe and SO_4^{2-}, whereas the weathering of arsenopyrite will lead to the formation of AMD rich in As, Fe and SO_4^{2-} [6,10,13–17]. A similar trend applies for the weathering of other acid-forming sulphide bearing minerals [18].

Chemical species embodied in AMD pose numerous ecological problems on discharge to the environment [19–21], of which the majority could pose numerous eco-toxicological effects to living organisms since they are above the prescribed limits as stipulated in different water guidelines, standards, and specifications [22–25]. Countries such as South Africa, The United States, China, Australia, Russia, and Canada indispensably rely on coal and gold-based products and market, hence confirming the potential challenge that could be envisaged in these countries [6,11,21,26,27]. For example, the quantities of AMD produced by the Western Basin on the West Rand in Gauteng Province, South Africa amount to ~60 ML/d, with sulphate (SO_4^{2-}) concentrations of $\geq$5 g/L and ferrous iron (Fe^{2+}/Fe^{3+}) concentrations of $\geq$1.5 g/L but this depends on the seasons, underlying geology, and availability of catalysts, whilst the Mpumalanga coal basins comprise $\geq$1.8 g/L of sulphate and $\geq$6 g/L of Fe^{2+}/Fe^3 [28–31]. Specifically, the coal and gold could be mined using surface and underground mining approaches; however, the commonly used subsurface mining can potentially lead to flooding of the mine voids and storage facilities, thus causing numerous environmental problems such as the contamination of surface water resources, hence impairing their ability to support life [18,32–34].

Considering the magnitude and dynamics of the mining industry in South Africa, Australia, China, US, other countries, and afield, it must be accepted that the challenges of mine water management, and AMD in particular, cannot be administered by either government or the mining sector alone unless if the process of minerals recovery is practiced to make mining process sustainable [6,7,11]. Numerous technologies have been developed but the quest is still ongoing to fully crystallise the solution. This will ensure that the concepts of sustainability and circular economy in mine water management are practiced, crystally due to the valorisation, beneficiation and value recovery from real AMD. Consequently, there is a wide array of technologies that have been employed for the treatment of AMD specifically at lab scale, bench scale, pilot scale, and full plant implementation [6,18,34–36]; however, most of them have been reported to depollute the water with varying success, of which the main challenges are residual sulphates, generation of sludge that is toxic and expensive to dispose of, poor efficiencies in highly concentrated solutions, and high operating cost [5,18,37–40], whilst recent technological development has cascaded effort towards sequentially recovery valuable minerals from AMD, hence off-setting possible ecological footprints of conventional treatment technologies [6,8,11,18,41,42]. Researchers mainly rely on two- or multi-staged approaches to sequentially recover valuable minerals [43]. To this end, cross contamination and the inability of sulphate to precipitate at a solo-pH range has been a challenge of gypsum and oxyhydrosulphates cross contamination [13,44,45]. To fulfil this goal, active and passive technologies have been used for the treatment of acid mine drainage (AMD) [13]. These techniques rely on different mechanisms such as oxidation, neutralisation, adsorption, phyto-bio-absorption, and filtration amongst others [6,11,34,36,46]. Surface waters rely mainly on active and passive treatment whilst groundwaters rely on passive systems such as reactive permeable barriers [7,11,18,47,48].

In that regard, mining houses are looking for cheap and effective technologies that can treat acid mine drainage (AMD) and recover valuable minerals. Some of the technologies can reclaim drinking water but there is brine generation which becomes an environmental liability, whilst some produce sludge that requires proper handling and disposal [2,6–8,18,34,45]. In response to this call, the Council for Scientific and Industrial

Research (CSIR) has developed and patented a novel process for the treatment of acid mine drainage (AMD) using an integration of a number of steps (technologies) [2,39,45,49]. The developed technology can reclaim drinking water and synthesise a number of valuable minerals such as goethite, hematite, magnetite, gypsum and limestone [39,40,50]. Different steps allow for the recovery of a specific mineral and minimises cross-contamination hence making MASRO a unique technology and game changer. The recovered material can be used to off-set the running cost of the treatment process through their sales. However, the detailed techno-economic evaluation of this process was not thoroughly evaluated. According to the literature, techno-economic evaluation depicts the adoptability and feasibility of the developed technology on real applications [5,51–53]. As such, the primary aim of this study is to point out the operational expenditure (OPEX) and capital expenditure (CAPEX) of the magnesite softening and reverse osmosis (MASRO) process as developed by the CSIR, hence depicting its operational viabilities. This is an additional study to our previous study on the valorisation of AMD, since the economics were high-level. Specifically, this study will pursue the in-depth techno–economic analysis (TEA) of an integrated plant that can treat 3 kiloliters (kL) of acid mine drainage (AMD) per run and 20,000 L per day (LPD).

2. Materials and Methods

2.1. Characterisation of Solid Minerals and Water Quality

Metals were ascertained using Inductively coupled plasma mass spectrometry (ICP-MS), X-Series 2, ICP-MS, supplied by Thermo scientific, from Hanna-Kunath-Str. 11, 28199 Bremen, Germany. The ICP-MS was coupled to an ASX-520 Auto sampler (Thermo scientific, Bremen, Germany). Additionally, sulphate and other metals were ascertained using a Gallery plus photo spectrometer, an Automated chemistry analyser, Supplied by Thermo Fisher scientific, Made in Vantaa, Finland. pH was ascertained using a multi-meter (HANNA instrument, HI9828, Woonsocket, RI, USA). The morphological properties and elemental compositions were ascertained using a High Resolution (HR)-Focused-Ion Beam (FIB)-Scanning Electron Microscope (SEM) (Carl-Zeiss-Strasse, Oberkochen, Germany) equipped with Electron Dispersion Spectroscopy (EDS) (Carl-Zeiss-Strasse, Oberkochen, Germany), The Auriga Cobra FIB FESEM (Model: Sigma VP FESEM with an Oxford EDS Sputtering System, make: Carl Zeiss, Supplier: Carl Zeiss, Thornwood, New York, USA). Mineralogical composition was elucidated using the state-of the-art PANalytical X'Pert Pro powder diffractometer (Enigma Business Park, Grove wood Road, Malvern, WR14 1XZ, United Kingdom) in θ-θ configuration with an X'Celerator detector and variable divergence and fixed receiving slits equipped with Fe filtered Co-K-θ radiation (θ = 1.789Å). The phases were identified using X'Pert High-score plus software. Specifically, the relative phase amounts, i.e., in weight (Wt.) %, were estimated following the Rietveld method (Autoquan Program (High-score suit 4.8, Enigma Business Park, Grove wood Road, Malvern, UK).

2.2. Process Description

The Council for Scientific and Industrial Research (CSIR) has developed and patented the mine water treatment technology known as the Magnesite, Softening, and Reverse Osmosis (MASRO) process. The developed technology has the ability to produce either discharge water quality or drinking water and recover valuable minerals in the quest to ensure and achieve a zero liquid discharge (ZLD). The primary aim was to develop a cost-effective solution that could recover valuable products, which will in-turn off-set the OPEX of the plant hence reducing environmental footprint of mine water treatment. This technology could be a game changer when compared to other active treatment technologies. To determine the robustness of the technology and to fulfil the goals of this study, the developed technology was tested against AMD emanating from Gold and Coal mines. The assembled water treatment plant comprises the:

Clarifier;
Filtration;
pH balance;

RO Skid System;
Product water tank;
Brine storage tank.

This is a five-stage technology with a recycle stream for mine water neutralisation and mineral phase synthesis. It has a multi-function clarifier that also acts as a mixer and a clarifier.

Stage 1: Neutralisation of acid mine drainage using magnesite. This stage will remove all the metals in acid mine drainage and leave sulphate as a $MgSO_4$ complex due to high solubility.

Stage 2: Synthesis of gypsum using limestone. This stage will remove residual sulphate as gypsum and magnesium as brucite due to pH which is greater than 10.

Stage 3: Synthesis of limestone using soda ash. This stage will remove residual calcium as hydrated calcium carbonate. The sodium will be taken to an RO for filtration.

Stage 4: Acid dosing to neutralise the pH. The HCl dosing will neutralise the water for RO, thus prolonging the life and RO, and protecting it from pH attack.

Stage 5: Filtration of water using a reverse osmosis system. Brine and product water will be stored in the respective tanks. A schematic presentation of the MASRO process is shown in Figure 1.
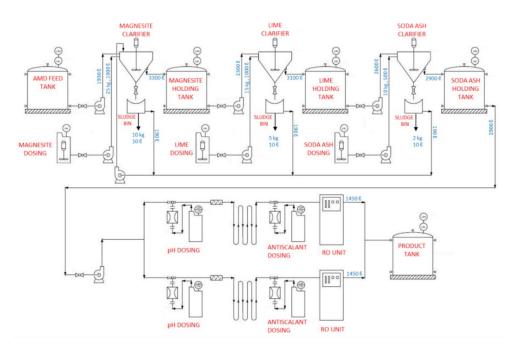

Figure 1. A schematic configuration of the MASRO process [2].

2.2.1. Clarification

Clarification involves the precipitation and sedimentation of pollutants from real AMD by the addition of different chemical reagents. This is a 3-stage process with each stage taking a total of 2.5 h. The following alkali reagents are used: magnesite, hydrated lime, and soda ash. The differentiator in this active process is the use of magnesite in the removal of inorganic contaminants in AMD as the first stage of the treatment process. Subsequently, stage 2, which mainly uses lime for the removal of residual sulphate and magnesium. This stage allows for recovery of high-quality gypsum (Stage 2) and, lastly, residual Ca and Mg from the lime reactor tend to be removed since this contributes to hardness. Therefore, stage 3 focuses on the synthesis of limestone using a softener (soda ash). The softener protects the membrane from scaling. Moreover, the clarifier is fitted with a variable speed drive (VSD) mixer, which is necessary for thorough mixing of dry reagent feed with an aqueous matrix. After each clarification stage, clear water is recovered into a Holding Tank and sludge is released into waste drums as denoted in Figures 1 and 2.

Figure 2. An illustration of the developed AMD treatment plant with the tanker loading AMD.

2.2.2. Valuable Minerals Recovery

This integrated technology can recover, reclaim, and synthesise a number of valuable minerals with huge economic value.

Drinking water reclamation.

This valuable mineral (resource) is reclaimed using RO system [2]. The brine is further purified using eutectic freeze (EF) and membrane distillation (MD). The use of EF and MD are going to be reported in our future publications. Most importantly, in between the processes, water can be reclaimed for use but it should be fit for applications.

Recovery of Fe^{3+} and Fe^{2+} in the first reactor.

Real AMD is rich in Fe (iii) and Fe (ii). Fe (iii) is used for the synthesis of Fe-hydroxide, goethite, and hematite whilst the mixture of Fe (iii): Fe (ii) at 2:1 ration leads to the synthesis of magnetite. All these minerals have a wide range of applications in the manufacturing industry [2,40,50].

Synthesis of Mg-rich gypsum.

The $MgSO_4$ from the activated magnesite reactor leads to the formation of Ca and S (gypsum) due to addition of lime [39].

Synthesis of calcium carbonate.

Residual Ca from the gypsum reactor is precipitated using soda ash to form calcium carbonate [39].

This picture illustrates the tanker loading AMD into the water treatment plant at CSIR vicinity (premises), Pretoria, South Africa. Essentially, real AMD is lifted from the clarifier using a centrifugal pump and transferred to an AMD storage tank which also acts as a surge tank. Due to the inherent batch nature of the process, a series of holding tanks are installed. At any given time of operation, alkali-treated water from one of the holding

tanks is supplied to the RO plant while the other one fills from the clarification process in the clarifier.

2.3. Economics Analysis

This section presents methods which were used to estimate the capital and operating costs of the developed system. Specifically, it reports the most important parameters used for economic analysis and defines the global outputs used as assessment criteria for the water treatment systems. The economic analysis is based on the calculation of the capital and operating expenditures (CAPEX and OPEX) of every unit.

2.3.1. Internal Rate of Return (IRR)

The return on the investment precisely refers to the percentage increase or decrease in the investment in the life cycle of the project.

$$\text{NPV} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \tag{1}$$

where NPV = Net Present Value, N = total number of periods, n = non-negative integer, C_n = cash flow, and r = internal rate of return.

2.3.2. Net Present Value (NPV)

The NPV principally focus on the difference between the present value (PV) of cash inflows and outflows over a specified period of time or project life cycle. Specifically, the NPV is the net of the PV of cash inflows and outflows by discounting the flows at a specified rate.

$$\text{NPV} = \frac{R_t}{(1+i)^t} \tag{2}$$

where NPV = net present value, R_t = net cash flow at time t, i = discount rate, and t = time of the cash flow.
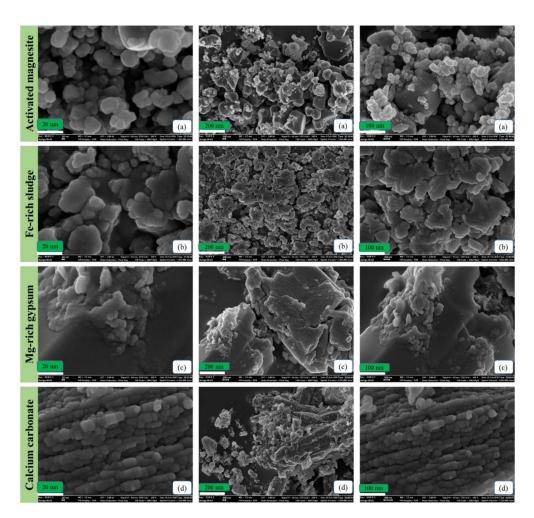
These mathematical formulae will be used to deduce the IRR and NPV of the system and potential return in investment of the developed system. This will then be used to define the viability and feasibility of the return in investment.

3. Results and Discussions

3.1. Characterisation of the Product Minerals

The morphological properties of activated magnesite, Fe-rich sludge, Mg-rich gypsum, and calcium carbonate at different magnifications, i.e., 20, 200, and 100 nm, are shown in Figure 3.

As shown in Figure 3, the morphological properties of activated magnesite (a), Fe-rich sludge (b), Mg-rich gypsum (c), and calcium carbonate (d) maintained the same characteristics at different magnifications (20–100 nm). Activated magnesite was predominated by spherical particles distributed across the surface (Figure 3a). The synthesised Fe-based sludge comprised the leafy-like structures distributed across the surface (Figure 3b), whilst the synthesised Mg-rich gypsum comprised the rod-like structures (Figure 3c). Lastly, the produced calcium carbonate was observed to comprise rod-like and spherical nods distributed across the surface (Figure 3d). The material was observed to be homogenous at different magnifications, i.e., 20, 200 and 100 nm. Similar results were reported in [2]. The elemental composition of activated magnesite, Fe-rich sludge, Mg-rich gypsum, and calcium carbonate are shown in Figure 4a–d.
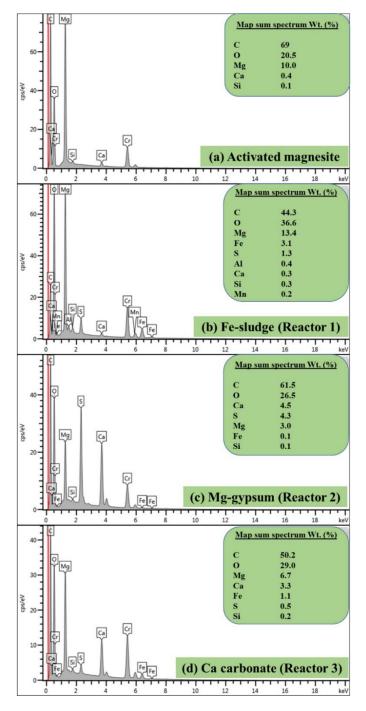
Figure 3. Morphological properties of activated magnesite (**a**), Fe-rich sludge (**b**), Mg-rich gypsum (**c**), and calcium carbonate (**d**) at different magnifications, i.e., 20, 200, and 100 nm.
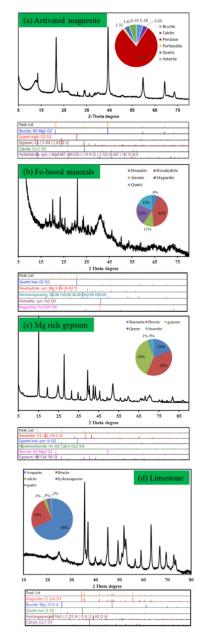
As shown in Figure 4a–d, the elemental composition of activated magnesite, Fe-rich sludge, Mg-rich gypsum, and calcium carbonate as determined by the EDS technique coupled to FIB-SEM system were reported. Activated magnesite was reported to be constituted of C, O, Mg, Ca and Si (Figure 4a). These elements will play a significant role in increasing the pH and attenuation of anions from the aquasphere [3]. The product sludge was observed to comprise C, O, Mg, Ca and Si from the mother magnesite and the addition of Fe, S, Al, and Mn (Figure 4b). These are the main elements in AMD thus confirming that the interaction of activated magnesite and AMD led to the attenuation of these elements. Figure 4c confirmed the S, Ca, Mg, O, C and traces of Fe and Si. This presence of Ca and S confirms the formation of gypsum rich in Mg. Lastly, the synthesised calcium carbonate was observed to comprise C, O, Mg, C, Fe, S, and Si (Figure 4d). This shows that soda is removing the carbonates of these chemical species. The mineralogical compositions of activated magnesite, hydroxides, gypsum and limestone are presented in Figure 5a–d.

As reported in our previous studies and the literature [2,13,37,39,44,54], activated magnesite was dominated by brucite, calcite, periclase, portlandite, quartz and veterite. These minerals contribute significantly towards an increase in pH. Furthermore, calcite will play a huge role in the removal of sulphate as gypsum (Figure 5a). Figure 5b shows the presence of hematite, magnetite, jarosite, hexahydrite and quartz. Magnesite and hematite confirm the presence of Fe-based minerals from real AMD whilst jarosite confirms the formation of oxyhydrosulphates. This corroborates results from our previous studies [40,50,55,56]. Quartz could be attributed to mother material. In stage 2 of the treatment, the Mg-rich gypsum is rich in basanite, brucite, gypsum, smectite, and quartz

(Figure 5c). Gypsum and basanite confirm the removal of sulphate from pre-treated water whilst brucite confirms the precipitation of magnesium. Smectite confirms the presence of alumino-silicate minerals and this could be attribute to residual Al, Fe and Si. Lastly, the limestone or calcium carbonate reactor (Figure 5d) confirms the presence of aragonite, brucite, calcite, hydromagnesite, and quartz. This confirms the precipitation of magnesite and residual calcite from the previous reactor due to carbonate. Magnesite also confirms the reaction of carbonate from soda ash to Mg in aqueous solution. Findings from this study corroborate findings from our previous studies and what has been reported in the literature [37,43,45,49,57–60].

Figure 4. Elemental composition of activated magnesite (**a**), Fe-rich sludge (**b**), Mg-rich gypsum (**c**), and calcium carbonate (**d**) as determined by the EDS technique.

Figure 5. Mineralogical composition of activated magnesite (**a**), Fe-rich sludge (**b**), Mg-rich gypsum (**c**), and calcium carbonate (**d**) as determined by the XRD technique.

3.2. Water Quality Characterisation

The water quality of real AMD, treatability index (TI), product water, and percentage removal against the SANS 241 specifications were reported in Table 1.

As shown in Table 1, real AMD was rich in Fe, S, Al, Mn, Ca, and Mg. The drainage was very acidic with pH < 2. A high level of metals was confirmed in the real mine water. The treatability index of AMD was observed to be drastically high hence denoting that the treatment of AMD will require high energy and chemical inputs. The product water was observed to be within the SANS 241:2015-2 specifications. The percentage removal confirmed that major contaminants in AMD were removed with an increase in pH to the required limit.

Table 1. Water quality of real AMD, treatability index (TI), product water, and percentage removal against the SANS 241 specifications [2].

Parameters	Units	SANS 241	Real AMD	TI	Product Water	% Removal
Aluminium	mg/L	0	70	233	0	100
Cadmium	mg/L	0	0	4	0	75
Calcium	mg/L	300	250	1	5	98
Chromium	mg/L	0	0	45	0	98
Colour	mg/lPt	15	600	40	6	99
Copper	mg/L	2	1	0	0	100
Iron	mg/L	2	1000	500	0	100
Magnesium	mg/L	100	800	8	1	100
Manganese	mg/L	0	50	125	0	100
Nickel	mg/L	0	1	10	0	100
pH	pH	10	2	0	8	N/A
Sulphate	mg/L	500	11681	23	8	100
Turbidity	NTU	1	43	43	1	99

3.3. Characteristics of the System

3.3.1. Characteristics of the Clarification Process

The description of the clarification system used in the reclamation of drinking water and valuable minerals from AMD are reported in Table 2.

Table 2. Description of the clarification process.

Unit	Characteristics		Functional Description
Clarifier	Type of Wastewater	AMD	Precipitation and sedimentation of inorganic contaminants Production of heavy metal-free soft water
	Feed Rate (klpd)	3.0	
	Reagents (kg/kL) — Magnesite	10.0	
	Lime	1.0	
	Soda Ash	4.0	
	Clean Water (klpd)	2.4	
	Recovery (%)	80	
	Motor Size (Kw)	3.0	

3.3.2. Characteristics of the Pre-Filtration Process

The soft alkali-treated water is delivered to the pre-filtration system from the Holding Tank using a 3.0 kW centrifugal pump. The pre-filtration stage consists of a sand filter, and 2 sets of cartridge filters of 20 μm and 5 μm, respectively. The pre-filtration stage is necessary to improve the performance and longevity of the membrane(s) due to the following reasons:

Removal of suspended solids, colloids and larger colour causing organics from the feed stream to protect against membrane fouling:

Achieving low SDI, colour, and turbidity to protect against membrane fouling;

Lower operating expense of the system;

Reduced capital expense.

The pressure drop across the filtration stage is no more than 0.8 bar. The feed pressure from the Holding Tank to the RO System is ≥3.0 bar.

3.3.3. Characteristics of the Acidification Process for pH Regulation

The Reverse Osmosis (RO) stage is preceded by an Acid Dosing station with diluted hydrochloric acid of pH of 1.0. The acid dosage is manipulated manually to control the pH of the RO feed water at a range between 6.5 and 7.5 to stabilise the RO feed water (Table 3). The acid dosing rate, at maximum 5L/Hr, is manipulated depending on the delivery rate from the centrifugal pump and the pH of the reagent-treated water.

Table 3. Specifications of the acid dosing station.

Unit	Characteristics			Functional Description
Dosing Station	PTFE Tank	Volume (L)	100	Control the acidity of the RO feed and stabilise calcium carbonate in aqueous phase
	Agitator	Speed (RPM)	150	
	FCE Pump	Min. Flow (LPH)	0.15	
		Max. Flow (LPH)	5.0	

3.3.4. Characteristics of the RO Process

The pressure of the acid-treated water is raised to greater than 15 bar using a 3.0 kW booster pump. This is sufficient to drive membrane filtration. The permeate production is controlled via a throttle valve of the brine while carefully monitoring the operating pressure (Table 4). The RO Skid is a standard single membrane with a design flow rate of 120 LPH. It is fitted with a control panel for flow and pressure monitoring, and in-line conductivity meter for quality control. The quality control is manual through manipulation of the position of the throttle valve. Previous campaigns with gold and coal AMD showed a drastic reduction in organic substances and salts, in excess of 90% and 99%, respectively. The specifications of the RO Skid are shown in Table 4.

Table 4. Specifications of the RO skid system.

Unit	Characteristics			Functional Description
RO Skid	×2 RO Membranes	Flow (LPH)	180	A filtration method that is used to remove ions and molecules by applying pressure to the solution on one side of a selective membrane.
	×1 Booster Pump	Power (kW)	3.0	
	×1 Conductivity Meter	(mS/cm)	≤4000	
	Feed Connection	NPT (mm)	50	
	Product Connection	mm	25	
	×2 Flowmeters	rotameters	-	

3.3.5. Characteristics of the Product and Brine Storage

The product/permeate and brine from the RO Skid is channelled to storage tanks of 10,000 L each. The recovery is optimised by passing the brine over a second stage RO membrane. The tanks are made of high quality, UV-resistant polyethylene and sourced from JoJo Tanks. These tanks are corrosion resistant. The tanks come standard with a 10-year warranty.

4. Mass and Energy Balance

The mass and energy balance of the MASRO treatment technology is provided in Tables 5 and 6. The plant is planned for an 8 h shift staffed by 2 technical personnel. The sludge from each stage of the process is dewatered before sale or disposal, whereas the filtrate is planned for feeding into the brine stream. Plans involve further treatment of the filtrate by installing an upgraded RO train. Therefore, the plant produces 1.92 klpd of clean water and 0.97 klpd of wastewater. Additionally, 30kg of Fe-species-rich sludge with 20% water content being taken to the beneficiation process for the production of goethite, hematite and magnetite.

The limestone and gypsum sludge is dewatered to 15% using a plate filter press. Each is stored on-site for sale.

The total power consumption per day is 146.6 kWh and totalling 103,288 kWh/annum.

Table 5. The mass balance of the MASRO treatment technology based on 3klpd.

	Inflows	1st Stage	2nd Stage	3rd Stage	Dewatering	RO	Outflows
Feed (klpd)	3.0	3.0	2.8	2.6	-	2.4	1.92
Sludge (klpd)	-	0.2	0.2	0.2	-	-	0.05
	-	-	-	-	0.55	-	0.55
Brine (klpd)	-	-	-	-	-	0.48	0.48
	-	10.0	-	-	-	-	-
Reagents (g/L)	-	-	1.0	-	-	-	-
	-	-	-	4.0	-	-	-

Table 6. The energy consumption of the MASRO treatment technology.

Unit	Mixer	Pumping	RO Booster
Quantity	1	4	1
Run Time (hrs)	3.0	16	8
Motor Size (kW)	3.0	7.1	3.0
Power Consumption (kWh)	9.0	113.6	24.0

5. The Determined Economics of the Developed System

A high-level financial model was constructed to evaluate the possibility of deploying the technology to potential clients in the identified market sectors. The estimated lifespan of the plant is 10 years. The evaluation showed positive results and yielded a 22% IRR and a NPV of ZAR 370 000 calculated with a hurdle rate of 15%. The capital cost was determined to be in the order of ZAR 452 000. A summary of the financial model results is shown in Tables 7 and 8. The discounted cash flow (DCF) method is used.

The distributions of the costs associated with the OPEX are shown in Figure 6. The cost of sludge disposal, at ZAR 27,500/t, is the largest contributor but this could be off-set if beneficiation of the Fe-minerals is explored. The case for this technology can be strengthened by demonstrating and commercialising technologies to further enhance magnesite-treated sludge. Then, the hydroxides as shown in the published research articles are sold to metallurgical houses.

Table 7. Inputs to the financial model.

Raw Materials	Volume	Price	Rand (ZAR)/yr
AMD Feed (klpd))	3.0	-	-
Products			ZAR 17,184,229
Water	-	ZAR 368/kL	ZAR 17,106,552
Limestone	-	ZAR 1100/t	ZAR 10,528
Gypsum	-	ZAR 2000/t	ZAR 67,149
Capex		ZAR 452,500	
Clarifier and Ancillaries	-	ZAR 60,000	-
Tanks	-	ZAR 64,000	-
RO Skid	-	ZAR 45,000	-
Acid Dosing Station	-	ZAR 7500	-
Pumps	-	ZAR 25,000	-
Piping and Fittings	-	ZAR 32,000	-
Civil Works	-	ZAR 112,000	-
RO CIP System	-	ZAR 15,000	-
PLC and DB Connection	-	ZAR 35,000	-
Opex			ZAR 16,552,612
Operating Labour	2	ZAR 90,000 pp	ZAR 180,000
Administration	-	4.0%	ZAR 94,448

Table 7. *Cont.*

Raw Materials	Volume	Price	
			Rand (ZAR)/yr
Magnesite (kg/kL)	10	ZAR 3500/t	ZAR 96,844
Hydrated Lime (kg/kL)	1.0	ZAR 2800/t	ZAR 5423
Soda Ash (kg/kL)	4.0	ZAR 5000/t	ZAR 54,233
Hydrochloric Acid (ml/L)	5.0	ZAR 240/L	ZAR 77,475
Electricity (kW)	14.6	ZAR 1.70/kWh	ZAR 206,099
Maintenance	-	10.0%	ZAR 674,035
Sludge Management	-	ZAR 27,500/t	ZAR 14,425,744

Footnote (Assumptions): Technical assumptions (the AMD quality data used are a good average, reagent dosages are optimised at 10 kg/kL, 1.0 kg/kL, and 4.0 kg/kL for magnesite, hydrated lime and soda ash, respectively, up-take of limestone and gypsum is consistent through-out project life, plant availability is 2920 hrs/y at 95% availability, clean water production from RO Skid is 1.44 klpd at 60% recovery, and maintenance costs are based on 15% of the sale of clean water produced) and financial assumptions (Capex—ZAR 489,331 or USD 33,672.06, Opex (Fixed and Variable)—ZAR 5,447,246 or USD 374,838.23, AMD cost—ZAR 0.0/kL or USD 0.0, plant life—10 years, discount rate—15%, contingency on Capex and Opex—5%, and ZAR 145/kL for water cost or USD 9.98/kL).

Table 8. Output from the financial model.

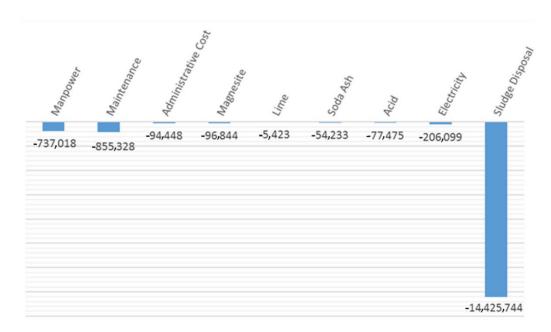| Plant Lifespan	10 Years
Hurdle Rate	15%
NPV	ZAR 60,000
IRR	26%
Payback	3 years

Figure 6. NPV for different factors that affect the project OPEX.

As shown in Figure 3, sludge disposal and handling will cost the project a huge OPEX layout but, if beneficiation is explored, The technology will reduce the OPEX and earn a massive return on the investment, hence enhancing the economic viability of the technology.

6. Project Risks

The risks associated with this project are summarised in Table 9.

<div align="center">**Table 9.** Project risks.</div>

Activity	Risk	Rating		Mitigation
		LOW	HIGH	
Environmental Authorisation	Project not approved by the relevant government departments	Higher environmental value will be gained		Include a contingency cost on the environmental budget
	Unattainable conditions attached to the authorisation		Project Cost will increase	
Financial	Financial Feasibility	A positive NPV		
	Fluctuation of reagent pricing		Increased OPEX and decreased NPV	Negotiate medium-term pricing contract with vendors
Technology	Technological Feasibility	The proposed technology package has been proven during campaigns at the CSIR Campus		
Human Resources	Available skilled human resources	Semi-skilled labour required for plant operation and maintenance		
Equipment	Equipment Availability (lead time)	Most equipment is off-the-shelf/standard, except for the custom designed Clarifier		Designs are available and relationships exist with engineering works consultants
Waste Streams	Additional production of sludge	The clarification process has been optimised in-house		Source additional up-takers for the limestone and gypsum
	Additional production of brine			

7. Conclusions

This study successfully evaluated the techno-economic feasibility of the treatment process. Findings from this techno-economic evaluation were explicitly confined to 3.0 KL/d of the AMD treatment plant. Furthermore, the treatment system, also known as the MASRO process, successfully proved that clean water, gypsum and limestone can be reclaimed and synthesised from AMD, hence confirming the viability of beneficiation and valorisation of AMD. This will go a long way to curtail potential ecological footprints associated with AMD. The total capital expenditure (CAPEX) for the plant is ZAR 452,000 (USD 31,103.22) which includes ZAR 110,000 (USD 7569.37) for civil works on a plant area of 100 m^2. The operational expenditure (OPEX) for the pilot is ZAR 16,550,000 (South African Rand) or USD 1,138,845.72 in present value terms (a 10-year plant life). The plant reclaimed drinking water as specified in different water quality standards, guidelines, and specifications, including Fe-based minerals (goethite, magnetite, and hematite), Mg-gypsum, and calcium carbonate. These minerals were verified using state-of-the-art analytical equipment. The recovered valuables will be sold at ZAR 368/kL (USD 25.32), ZAR 1100/t (USD 75.69), and ZAR 2000/t (USD 137.62) for water, gypsum, and limestone, respectively. The project has an NPV of ZAR 60,000 (USD 4128.75) at an IRR of 26%. The payback period for this investment will take 3 years. The total power consumption per day was recorded to be 146.6 kWh, and 103,288 kWh/annum. The developed technology is a prototype that advocates for a Zero-Liquid-Discharge (ZLD)

motion. It is a gate to gate solution that aims at evaluating the valorisation of acid mine drainage. The techno-economic evaluation depicted promising results but there are areas that need some improvements:

- Plant stability needs to be evaluated prior deploying the plant to the mine.
- Maintenance costs need to be factored into the techno-economic evaluation
- Market analysis and quality grading of recovered materials need to be established.
- For sustainability purposes, the plant needs to be run for more than 6 months within the CSIR premises or on site. This will enable the process developers to determine the robustness of the developed system under harsh ecological conditions.

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