Conceptualising a regionally integrated approach for the valorisation of coal mining-related waste: A case study in the Mpumalanga Province, South Africa

Helene-Marie Stander[1,*], *Jennifer L* Broadhurst[1]
[1]Minerals to Metals Initiative, Department of Chemical Engineering, New Chemical Engineering Building, Upper Campus, University of Cape Town, Rondebosch, Cape Town, South Africa.

Abstract. Coal is currently an important energy source for the South African economy and is likely to remain so in the medium term. Coal extraction, processing and combustion, however, produce industrial wastes, which can pollute soils, water resources and air and also occupy large tracts of land, sterilising these for a variety of uses. Current waste management approaches, including co-disposal, lining tailings dams and covering waste facilities with soil and vegetation, require monitoring and maintenance over hundreds of years, increasing the risk of environmental failure in the future. An integrated approach aimed at valorising whole waste bodies and simultaneously remediating the surrounding environment is proposed here. This approach considers solid and slurry coal mine wastes, fly ash, acid mine drainage, and gypsum. Different repurposing options are identified for each waste stream, these are screened, and an integrated solution to mine waste repurposing for the Mpumalanga coal mining region is recommended. Among the recommendations that form part of the integrated approach are that benign coal mine waste be used for a combination of fabricated soil production and backfill and that iron be recovered from acid mine drainage prior to neutralisation.

1 Introduction

Coal mining and processing has historically been central to development in South Africa and remains the country's primary source of energy production and a major generator of export revenue [1], [2]. Mpumalanga Province accounts for around 87% of South Africa's coal production from at least 53 coal mines to produce 39 GW of coal-fired electricity in addition to liquid fuels, exports and other products [3]. Coal mining is, however, not without impacts on the environment within which it is located.

The geographically dispersed and often irreversible impacts associated with the land disposal of large volumes of solid and slurry waste including coal overburden from surface coal mines [4], discard and slurry waste from coal processing [4], and fly-ash from combustion [5] are causes of concern. Of particular concern is the ongoing emission of large volumes of acid mine drainage (AMD) from deposits of coal mining and processing wastes, and from coal mine workings [6], [7], [8]. The impacts of AMD can extend beyond

* Corresponding author: Helene-Marie.Stander@uct.ac.za

the mine site, adversely affecting the quality of water sources and soils and ultimately impacting natural ecosystems, human health and livelihoods of local communities [8], [9]. This is particularly worrying given that Mpumalanga accounts for a large proportion of South Africa's major arable soils and is the second biggest producer of maize, a food staple, in South Africa [10].

It is widely recognised that effective remediation and rehabilitation of coal production and power generation sites and facilities is key to mitigating these environmental impacts and ensuring that the land and existing infrastructure are returned to productive use at the end of the project life cycle [11]. This includes ensuring that the topsoil, which is a resource in short supply [12], on rehabilitated areas is fertile and able to sustain plant and microbial life [13]. Closure and rehabilitation of coal mines in line with International Council for Mining and Metals guidelines, however, remains elusive in South Africa [12]. Apart from the repurposing of land and buildings, opportunities also exist to reuse or repurpose the large volumes of solid, slurry and liquid wastes generated during coal production and combustion. This could simplify and expedite the task of rehabilitation and reduce associated costs and liabilities. There has nevertheless been little systematic development and commercial implementation of opportunities for the repurposing of coal beneficiation and combustion waste [14]. Furthermore, whilst both mine rehabilitation and downstream application of coal combustion wastes have been identified as opportunities to diversify economies and the coal value chain in coal-intensive regions [15], such opportunities have yet to be considered in a holistic and integrated manner.

It is in this context that this paper sets out to provide an overview of- and assess the public literature and data pertaining to repurposing opportunities and market applications for large volume wastes arising from coal production and coal-fired power generation. The focus is on coal processing wastes, fly-ash, AMD and gypsum. Based on these opportunities and potential applications, a conceptual matrix of options is developed for integrating the repurposing of mine waste with mine rehabilitation, considering the entire mine-to-power coal value chain in the province of Mpumalanga, South Africa. The aim is that it will ultimately result in a zero or minimal waste scenario, whilst simultaneously rehabilitating mine land for productive post-mining use.

2 The generation and management of waste across the coal value chain

In order to identify opportunities for the repurposing of wastes, it is first necessary to understand their sources and current management practices. Fig. **1** shows the key high volume waste streams generated during the various stages in the coal deposit to coal-fired electricity value chain [16]. These waste streams include overburden and interburden from open-pit mining or extraction of coal deposits; discards and slurry wastes from the processing or beneficiation of the run-of-mine (ROM) coal; coal combustion wastes, comprising mainly of fly-ash, from subsequent combustion of the coal to generate electricity; and AMD from both coal mining and processing. Carbon dioxide, while a critical waste stream, will not be considered further since this paper focuses on land-disposed wastes. The generation, key characteristics, impacts and management of these coal mining-related wastes are discussed below.

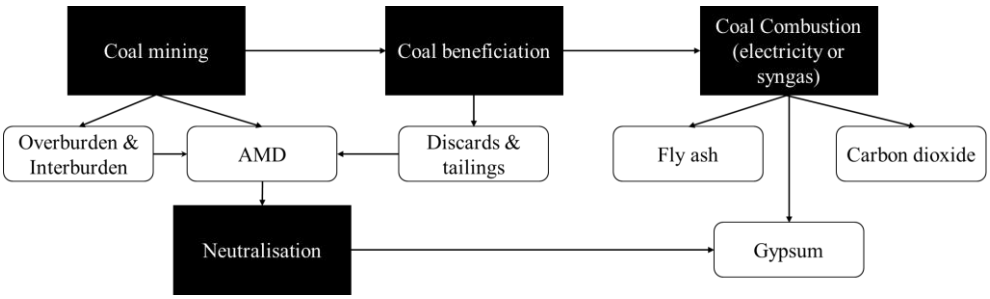

Fig. 1 Summary of major wastes produced at key stages of the coal value chain.

2.1. Coal mining wastes

In surface mining (sometimes called open pit or 'opencast' mining), the coal seam is accessed by removing overlaying rock and soil. The material covering the topmost coal seam is called overburden, whilst material dividing coal seams within strata is called interburden. This material, which typically makes up a large volume, is normally stockpiled in waste rock dumps which are then rehabilitated in-situ or after replacement in mine voids (backfill) [13]. The compositions and properties of coal mine spoils are very site-specific and highly heterogeneous and can contain significant quantities of the iron sulphide mineral pyrite, coal, and soluble salts and metals which can become released on weathering [17]. In accordance with Welch [17], weathering abandoned, or poorly rehabilitated coal waste rock dumps can give rise to contaminated leachate for decades or even centuries. Repurposing of this material is crucial, but characterisation and partitioning of it have not yet received the attention due. Consequently, it will not be considered further.

2.2. Coal processing wastes

Coal in South Africa has a relatively low calorific value and high ash content (20-40%) [18]. Whilst, in many cases ROM coal is sent directly to power generation, around 60% is beneficiated to reduce the ash content and improve the calorific value before being sold for domestic purposes or exported [18]. Coal processing typically entails crushing and screening followed by dense medium separation of the fine to coarse fractions, commonly termed “washing” [18]. Although still not widely practised in South Africa, some plants also use froth flotation to upgrade the ultra-fine (100-150 micron) coal generated during screening and subsequent classification [18]. Two main types of coal wastes are generated during processing, namely discards from the washing of coarse, small and fine coal, and ultra-fine slurry waste or slurry tailings [18]. In accordance with available statistics, approximately 20-22 % of the ROM coal deports as discards, of which 4-6% is in the form of ultra-fine slurry [18].

- high ash (30-60%) and sulphur (1-5%) values and would require further upgrading (either through washing or blending) to render them suitable for down-stream use [19].

Historically these wastes have been largely land-disposed, with the slurry from the thickener underflow being largely deposited in surface slurry dams on discard dumps, which have been estimated to occupy more than 4000 hectares of land in the Mpumalanga coalfields [19]. These dumps have had a significant impact on the local environment. In accordance with the Department of Minerals and Energy [19] *“old discard dumps in South*

Africa are one of the greatest polluters of the environment, polluting the atmosphere, rivers, ground water and the esthetics of the countryside". As environmental regulation has become more stringent, so the methods of disposal for coal processing wastes have improved, with most discard dumps now being designed to minimise spontaneous combustion and environmental pollution, through compaction, collection of seepage and rehabilitation using topsoil and revegetation [13]. Ultra-fine slurry wastes are now commonly dewatered in filter presses and co-disposed with discards in an integrated manner, whilst many collieries are reprocessing their older discards to extract a low-grade steam coal, mainly for use in local power stations [18]. The effectiveness of many of these methods to prevent long-term environmental degradation has, however, yet to be proven.

2.3. Coal combustion wastes

Conventional coal-fired power stations produce several solid and slurry wastes, commonly termed coal combustion wastes (CCWs), including fly ash, bottom ash (or boiler slag) and flue gas desulphurisation gypsum (FGD). As these wastes all have identified commercial uses, they can all be considered as by-products of coal-fired electricity generation and are thus also frequently referred to as coal combustion products (CCPs).

Fly ash, also known as pulverised fuel ash, accounts for almost 85% of the total coal combustion ash generated by ESKOM [21]. Recent figures quoted by ESKOM put the total annual ash generation at 35 Mt [5], [21]. Depending upon the source and composition of the coal being burned, the components of fly ash vary considerably, but fly ash in South Africa is typically classified as Class F since the combination of SiO_2, Al_2O_3 and Fe_2O_3 in the fly ash is higher than 70% [5], [22].

In South Africa, around 74% of fly-ash is disposed of together with coarse ash or as a slurry in ash dams close to the power stations, the latter method being largely practised at older power stations [5]. This is largely because the ash dams and dumps play an important role in compliance with Eskom's water management strategy, serving as a sink for saline effluents and poor-quality water [22]. Whilst mostly considered a relatively low risk, Zielke-Olivier and Vermeulen [23] and Eze et al. [24] have provided evidence that these fly-ash-brine dumps become a source of groundwater contamination over time. Also, when the dried fly-ash becomes wind-dispersed, it comes into contact with people and the natural environment, to which it has also been shown to be hazardous [25], [26].

Rehabilitation of Eskom ash dumps involves covering the ash dumps with fertile soil and planting grass and trees, but as mentioned before, ash dumps are potential sources of groundwater pollution. Use of the fly ash is therefore a better proposition. In South Africa, exemption from waste disposal legislation for specific beneficial uses has been granted [27]. Apart from the potential direct economic benefits associated with fly ash reuse, Reynolds-Clausen and Singh [22] note that many of the older power stations are nearing end-of-storage life at the ash-handling facilities, and urgent interventions are required to alleviate this problem.

ESKOM's Kusile power station is fitted with a wet flue gas desulfurisation (FGD) system (capacity 900 ktpa of FGD gypsum [5]) to reduce its sulfur dioxide emissions [28]. This process uses limestone and produces gypsum as a by-product [28]. While the exact characterisation of the gypsum is currently not in the public domain, the impurity levels of the final FGD gypsum will be strongly affected by the purity of the limestone used in the

FGD gypsum units [5]. The neutralisation of AMD with fly ash also produces gypsum as a by-product, though mixed with the amorphous silicates and aluminosilicates inherent in fly ash and consequently of lower purity [29].

2.4. Acid mine drainage

AMD, while not technically a waste product from mining, is a result of the land- and water-course disturbance that accompanies mining [30]. The coal mining industry in South Africa is associated with significant AMD pollution, which can be attributed to the presence of pyrite in the coal deposits [8]. As an unwanted or gangue mineral, this exposed pyrite is separated from the targeted minerals as much as possible during the extraction and early processing stages and largely reports to the large volume wastes (waste rock, discards and slurry waste) generated during the subsequent beneficiation of the ROM coal. Given that it is found in the host ores, some pyrite is also naturally present in the mine cavity walls, also leading to acid generation. AMD subsequently forms as a result of the weathering of this pyrite, when exposed to air and water [31], [32]. The characteristics of mine water in the Mpumalanga coalfields varies considerably between mines and with different seasons with the acidity, total dissolved solids and iron concentrations differing by orders of magnitude [7]. Neutral mine drainage (pH>6) is characterised by moderately elevated total dissolved salt (TDS) levels and relatively low levels of metals, whilst acidic mine decant waters are typically characterised by pH values <3, high TDS (> 4000 ppm) and elevated levels of Ca, Mg, Fe, Mn and Al [33]. AMD is considered to be the most significant surface water and groundwater water quality concern relating to the mining industry in the Mpumalanga coalfields in South Africa [8]. It also results in degradation in soil quality and fertility, through acidification, salinization and the deposition of metal-rich secondary precipitates [9], [34]. This pollution, in turn, impacts on natural ecosystems, human health, and livelihoods of local communities involved in activities such as farming and fishing.

Due to its significant environmental impacts, AMD decant is typically collected at the source and treated to improve the quality of the water and prevent off-site environmental pollution [30]. Currently, around 100ML[1] per day of AMD is treated at mines in Mpumalanga. AMD treatment, however, also produces waste, including metal-rich gypsum sludges and brine [35]. In accordance with the data reported by Gunther and Naidu [35], the EWRP generates between 4-5 tons of gypsum waste (dry basis) and 6-8 m^3/day of liquid (brine) waste per 1000 cubic meter (i.e. 1 Megalitre) of potable water produced. Disposal of these wastes also accounts for 25% to 30% of the costs of water treatment and down-stream uses for these are necessary to control costs [35]. The metal rich gypsum sludge, for instance, is sold for agricultural purposes [35]. The brine, however, still needs to be valorised.

[1] 17.6ML (Glencore Tweefontein) + 50ML (eMalahleni water reclamation plant) + 20ML (Middelburg water reclamation plant) + 10ML (Matla water treatment plant) + 2ML (Klipspruit water treatment plant) ≈ 99.6ML

3 Overview of coal waste valorisation opportunities along the value chain

The overview in the previous section bears testimony to the large volumes of waste generated during the extraction, beneficiation and combustion of coal in the Mpumalanga coalfields. This section identifies options for repurposing these wastes based on literature.

3.1 Coal processing wastes

While coal mine waste can be valorised without pre-treatment or separation, the options for this may be limited due to the relatively high carbon and sulfur content of the fines and even the discards. Several authors have, however, recommended waste partitioning as a way of improving the characteristics of waste fractions for specific applications [36], [37], [38]. As early-adopters of this approach, researchers at the University of Cape Town developed the two-stage separation process to separate fine and ultra-fine (D75 <150μm) coal slurry waste into recovered coal, sulfide-enriched and sulfide-lean streams [39], [40], [41], [42]. The recovered coal is generally of a saleable quality and can provide an additional income stream to offset costs. The larger size fractions tend to have a lower residual coal component due to washing, but separation of mineral sulfides may be possible with dense medium separation and reflux classification [43], [44].

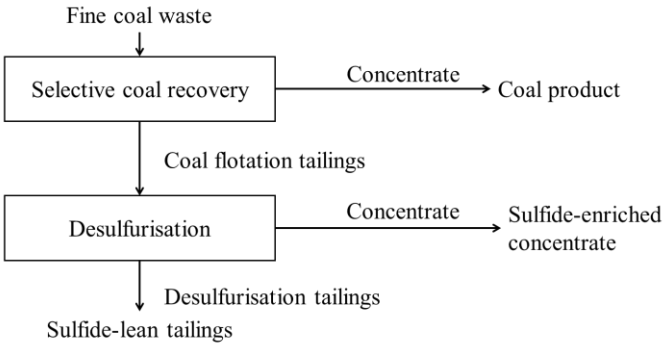

Fig. 2 The UCT two-stage flotation process [41], [45].

A key finding of the UCT process for fine/ultrafine coal from is that, whilst the performance of the flotation pre-separation process varied quite significantly for different coal wastes and collectors, in all case studies the two-stage flotation process resulted in a coal product with reduced ash and sulfur contents, and a final sulfide-lean tailings fraction with reduced sulfide content and negligible ARD risk potentials [45]. This is important to keep in mind when considering the potential uses for the coal processing wastes. In the following sections, several potential uses for coal processing wastes will be shown. The characterisation of these wastes as well as the potential uses have been considered in more detail in a supplementary document, obtainable at Stander and Broadhurst [46].

3.1.1 Sulfide-lean coal waste

The sulfide-lean coal waste produced by flotation processes have consistently been non-acid generating [45] and initial minor and trace element analysis shows that the material is unlikely to be hazardous [47]. Other mine wastes are inherently not acid generating with a

greater or lesser extent of leaching of toxic elements. These materials therefore have several potential opportunities for repurposing, as shown in Fig. **3**.

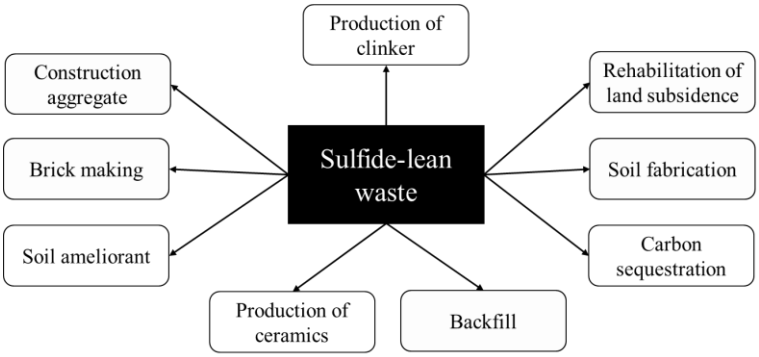

Fig. 3 Alternative options for repurposing sulfide-lean coal waste.

Several of the potential options centre on the construction industry. If coal waste is roasted to produce clinker, the precursor to cement, the residual coal component may be useful for reducing the need for additional energy input and thereby drive down the costs [36]. The waste material must, however, have a specific composition for this repurposing option to be technically feasible. The sulfide-lean waste can also be used as aggregate for concrete production or road paving [36], [38], [48]. This lowers the cost of infrastructure development, which is needed in Mpumalanga, and the technology is relatively mature. Another potential repurposing option is brick making [49], which is a mature technology and can produce good quality bricks. The last construction-related repurposing option is the manufacture of ceramics [50], such as silicon carbide, from the sulfide-lean waste when it has a suitable composition.

The sulfide-lean coal waste can also be used for land rehabilitation purposes, such as producing fabricated soil to supplement degraded mine soils in the rehabilitation of post-closure mining areas [47], [51]. In cases where the sulfide-lean waste is enriched in plant-critical minerals, it can also be used to supplement deficient soils [36]. Other options are backfill [52], [53], using the material to fill and thereby stabilise mine cavities to prevent ground subsidence, and rehabilitation of ground subsidence by filling in the holes [54]. Cemented paste backfill (CPB) is a relatively mature technology and has been shown to be necessary in Mpumalanga due to problems associated with land subsidence [8, 55].

The last option is that of using the waste material for carbon sequestration [56], but the feasibility of this solution depends on having specific minerals present in mine waste and the low conversion have made this solution unattractive thus far.

3.1.2 Sulfide-enriched coal waste

The sulfide-enriched concentrate produced during pre-separation test work at UCT has had a pyrite content of between 2% and 16% [57], [58], [59] and has been consistently potentially acid generating [41], [42], [40], [45]. In terms of minor and trace elements, however, the material has thus far shown to be relatively benign [60]. For the coarse sulfide-enriched fraction, a pyrite content as high as 62% has been obtained [43]. The high sulfur content and risk of acid generation limits application of the stream for several of the

large-volume uses mentioned in Section 3.1.1. and uses appropriate for material with a high pyrite content have been identified, as shown in Fig. **4**.

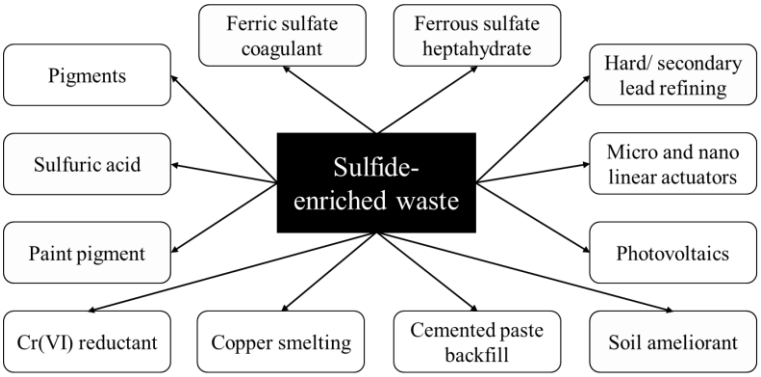

Fig. 4 Alternative options for repurposing sulfide-enriched coal waste.

Sulfuric acid production by roasting pyrite is one of the most mature technologies considered here and has been commercially applied in many locations [61]. The solid waste by-product also has potential application as iron pigments [62]. Pyrite is directly used as a pigment for glass [63] but this application requires relatively pure pyrite. Other repurposing options that require pure pyrite include copper smelting [64], [65], hard/ secondary lead refining [66], producing micro and nano linear actuators [67] and producing photovoltaics [68]. The metal refining applications require pure pyrite to avoid product contamination, and the electronic applications require purity for the technology to function properly. Ferric sulfate, used as a coagulant in waste water treatment, can be produced by bioleaching of pyrite [44], [69]. Bioleaching can either be done in a heap leaching setup, which is not mature, or in a tank leach, which requires long residence times. Ferrous sulfate can be similarly produced but requires that the ferrous iron be precipitated before it is oxidised to ferric sulfate [44]. It will also require the neutralisation of a highly acidic effluent (pH <2), potentially leading to the production of a significant volume of low-quality gypsum, which will require additional waste management. Pyrite-rich material has also been used in cemented paste backfill (CPB) [70], but it has been shown to impact strength development [71] in the material and be susceptible to sulphate attack [72]. CPB has also been shown to have the potential to leach metal ions [73]. Certain design decisions, such as cement content, addition of hydrophobic add-mixtures [72] can improve the environmental characteristics, but risks remain.

Amelioration of alkaline sodic or sulfur-poor soils is another option that is available for repurposing sulfide-enriched coal waste [74], [75]. It is technically simple but requires careful analysis of soil and waste characteristics to ensure that the solution is beneficial and no components become available at harmful concentrations. There are some Calcic and Vertic soils located in Mpumalanga that can potentially benefit from application of sulfide-enriched coal waste [76]. Lastly, pyrite can be used to reduce Cr(VI), a known carcinogen and priority pollutant, to the more benign Cr(III) [77], [78], [79]. The solution is not yet mature, however, and the current approach of using ferrous sulfate for Cr(VI) reduction is effective.

3.2 Fly-ash

Fly ash has several potential repurposing options, as shown in Fig. **5**. Given that South African fly ash is often alkaline, this material has been proposed as a potential neutralising agent for AMD [29], [80]. This solution is at least at a pilot scale [81] and should be cost-effective, since the fly ash, which is produced by burning coal, is generated in the same region as the AMD emanating from coal mines and waste facilities.

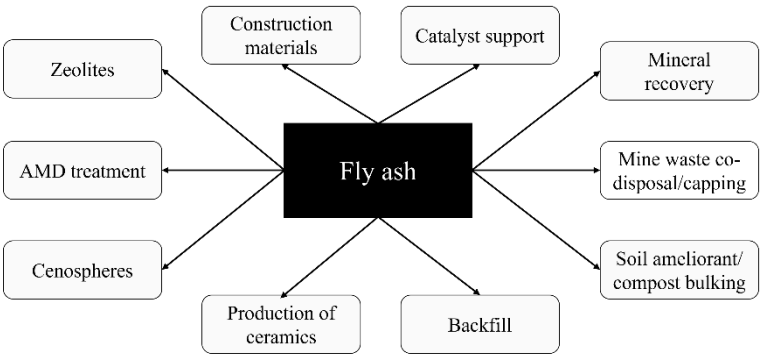

Fig. 5 Alternative options for repurposing fly ash.

Fly ash can also be used in the production of zeolites or as catalyst supports [22], [82]. Both applications make use of the high surface area and zeolites additionally make use of the relatively high ratio of aluminium to silica in many fly ashes [80], [82]. While zeolite technology has been piloted, commercial implementation has been lagging [82], [83]. Another application that makes use of the Al/Si ratio in fly ash is the production of ceramics and bricks, and addition to concrete as a cement extender (pozzolan) and additive to improve concrete properties [22], [82]. Fly ash is already commercially used as concrete additive and pozzolan, and in brick and ceramic tile production [84], [85]. Its pozzolanic properties and small particle size also make it potentially useful as an additive to CPB. While a large proportion of fly ash particles are spherical, some are also hollow, [86] which makes them particularly useful as additives in low-weight cement, ceramics and coatings [84]. This technology is already commercially applied in South Africa, but relatively small volumes are used [84]. Fly ash also contain residual minerals, such as iron and rare earth elements, and some research has focused on finding solutions for recovery [82]. Fly ash composition, however, can be heterogeneous [5], [22] and metal recovery must be assessed on a case-by-case basis. Fly ash has also been proposed a suitable material for co-disposing with acid-generating mine waste or capping such wastes, due to their alkalinity and fine particle size which may effectively slow or prevent water and oxygen ingress into a waste facility [29]. While initial results are encouraging, questions about long-term acidification and mobilisation of toxic elements remain.

The last option for utilising fly ash is use as a soil ameliorant or bulking agent for compost [22], [82]. The alkalinity, high cation exchange capacity and high water holding capacity can improve the characteristics of acidic sandy soils while inherent elements may add soil nutrients [82]. High metal mobilisation and salinisation are, however, some of the potential negative consequences of applying fly ash to soil [82] and this must be assessed on a case-by-case basis.

3.3 Acid mine drainage

In this section, options to repurpose AMD were grouped for simplicity (Fig. **6**). The first and most obvious repurposing option for AMD is recovering the water content. This can be upgraded to potable water, as in the case of the eMalahleni water reclamation plant [87] or remain lower quality water for irrigation [88] or process water [89]. When large volumes of water must be treated to a high standard, many active treatment technologies are mature and dependable [90], but these can be expensive and may produce large volumes of waste. Passive treatment is cheaper and can be used for small to medium acid point sources located in rural settings that are hard to service [90] but can be less effective and still requires monitoring. A combination of both is a mature solution and is likely to be most cost-effective but hazardous waste production and system complexity remain problems [90].

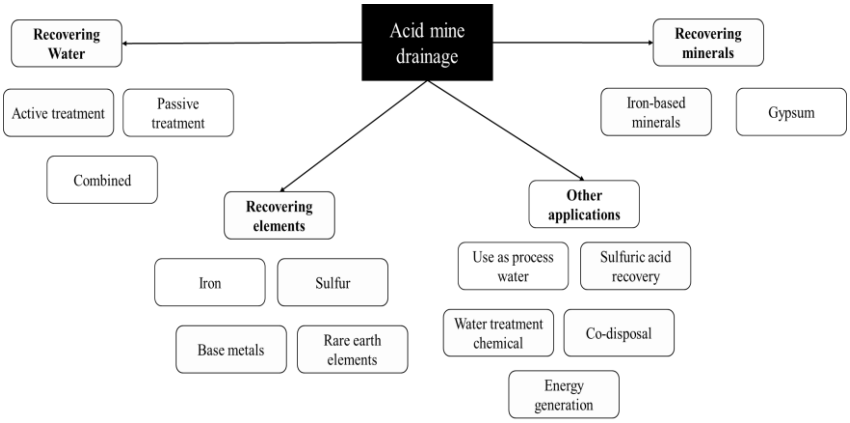

Fig. 6 Alternative options for repurposing acid mine drainage.

AMD is metal-rich and several elements can be recovered from it. Iron [89], [91], [92], sulfur [88], base metals [89], [92] and rare earth elements [92] are all elements that can potentially be recovered. These technologies, however, present difficulties with product contamination by other AMD constituents, process complexity, and they are relatively immature (TRL4-5) [89], [92]. Rather than recovering elements, iron minerals or gypsum can be recovered. Iron minerals can be high-value products, but the technology for producing them are relatively immature and the processes tend to produce contaminated brines as by-product [90]. Gypsum will be discussed in the next section.

The other technologies for AMD repurposing are all relatively immature. Sulfuric acid production achieved good quality product, but the technology is expensive and complex [89], [92]. AMD can also be used directly as a cost-competitive process chemical in cases where the purity of the final product will not be negatively impacted [89]. It can also be directly used as a water treatment coagulant, but trace metals are sometimes found in the treatment discharge and the two waste streams must be located near each other to reduce the cost of the solution [89], [93]. The use of the sludge produced when treating AMD to potable water has been suggested as a suitable material for blinding acid-generating mine waste heaps from contact with water and oxygen [94]. Lastly, it has been suggested that

energy might be recovered during AMD treatment and metal recovery in microbial fuels cells [95].

3.4 Gypsum

There are several potential industries that use gypsum in South Africa (Fig. **7**), but the three largest are the wallboard industry (purity >95%), the cement industry (purity >82%) and agriculture (purity >70%) [5]. Gypsum is also commercially used on a smaller scale as coagulant (Kuit, 2018), industrial filler material [5], [96], in mould-making, in pharmaceuticals, and as a flocculant [96]. Many of these applications do, however, require high purity gypsum to be effective [96].

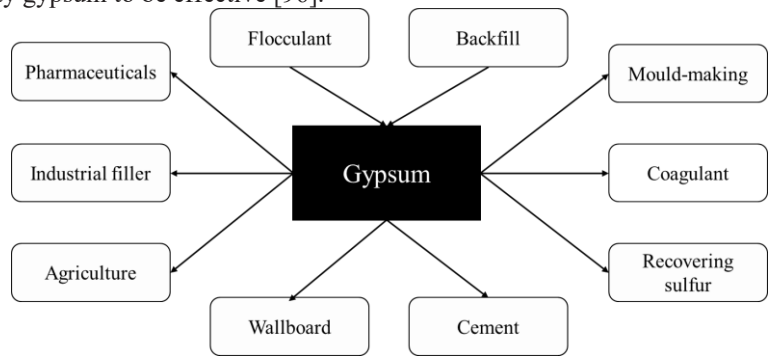

Fig. 7 Alternative options for repurposing gypsum.

Gypsum from acid mine drainage treatment has been processed on a pilot scale to produce elemental sulfur [97], which is a widely used industrial chemical. Recovery of other valuable materials such as calcium carbonate is also a potential option, which can improve the economics of the solution [97]. Kumar Vadapalli et al. (2008) have investigated using AMD-derived gypsum as backfill material and found that while it still contained some acid neutralisation capacity, it did not have the structural integrity required for structural backfill. It could, however, potentially be used in conjunction with a structural backfill to protect it from acid attack.

4 Conceptual approach for integrated reuse of coal mining-related waste

The previous section identified technologies that could potentially be used to repurpose various coal value-chain waste streams. However, in many cases, particularly in the production of saleable products, commercial application has been constrained. Whilst several constraining factors have been identified, key barriers include the lack of economies of scale [14] on a single site and the expenses associated with long transport distances of bulk material by truck [76]. It is postulated that many of the barriers to commercial implementation of waste repurposing options could be overcome and further benefits realised by adopting a more holistic and integrated approach. Such an approach would repurpose current arisings of large-volume wastes across the coal value chain and concurrently rehabilitate mine sites by applying wastes to regenerate soil productivity and backfill mine voids. This will enable future economic development of the land post-mining, rather than being constrained by the long-term maintenance of risk-bearing fixtures left behind by mining. Land rehabilitation therefore aims to safeguard long-term economic

opportunities rather than aiming towards short-term financial gain. Additional economic benefits could be gained through the simultaneous recovery of products that have local market application.

Options were therefore screened based on the following criteria (**Table 1**): potential technical feasibility, based on the current literature and technology information, particularly as it pertains to maturity, robustness, simplicity and affordability; land rehabilitation potential which is aimed at ensuring that as much of the land as possible can be returned to productive use; and applicability of the solution to the Mpumalanga regional context since long-distance transport is likely to be cost prohibitive [76]. The potential for creating secondary revenue streams is considered once the rehabilitation priorities have been fulfilled but may provide revenue to financially enable the rest of the integrated solution.

Table 1. Priorities for repurposing coal mine value chain waste in Mpumalanga

Screening criteria	**Indicators for criteria**
Land rehabilitation: ensuring that the land retains as many potential uses as possible	Acid mine drainage abatement Regenerating soil productivity Ensuring surface stability/land subsidence treatment Recovering land availability Avoiding long-term risk and liability
Potential technical feasibility	Proven and relatively robust technologies Technological simplicity and affordability
Regional appropriateness	Plausible market/application in Mpumalanga Opportunities to simultaneously create value

Table 2 shows the screened options for repurposing coal value-chain waste, based on the criteria outlined above and currently available information as considered in the previous section. **Fig. 8** presents the integrated approach for repurposing these alternatives.

Table 2. Repurposing options for different mine wastes.

Waste stream	**Repurposing options**
Recovered fine coal	combustion at ESKOM
Sulfide-lean waste	Construction applications Mine void backfill Soil fabrication
Sulfide-rich waste	Soil ameliorant for sodic alkaline soils in Mpumalanga Sulfuric acid production Iron chemicals for soil and/or water treatment
Fly ash	Acid mine drainage neutralisation Construction applications Soil amelioration/ additive for soil fabrication
Acid mine drainage	Water and gypsum recovery Nano-iron recovery for water treatment
Gypsum	Cement additive (construction) Soil amelioration/ additive for soil fabrication

Based on Sections 3.1.2 and 3.3, the options for repurposing sulfide-enriched waste and AMD are relatively constrained, and these are the waste streams with the highest long-term

risk of damage to land resources. Their repurposing and rehabilitation is therefore a matter of priority. Section 3.1.2 showed that the sulfide-rich coal waste can be used for ameliorating alkaline soils in the case of fine and ultra-fine components. The pyrite content of separated discards is high enough to be a credible feed stream for a sulfuric acid plant with associated iron oxide production plant [43], [61] if economies of scale can be achieved. This consumes the high-risk material and adds a profit stream to offset some of the rehabilitation costs. The waste ash from the roasting step can be used in construction, steel making or backfill applications [61]. Production of ferrous sulfate heptahydrate, a fertiliser and water treatment chemical, using the bioleaching route could also be a potential application for high sulfur coal waste. The process produces large volumes of sulfate-rich acid, however, and so this option will only be feasible if there is excess capacity on the AMD treatment infrastructure.

AMD must be treated to produce fit-for-purpose water quality. Using locally-produced fly-ash from the local power plants as a neutralisation agent for AMD avoids the use of virgin resources, such as lime and limestone, and is likely to present a saving in terms of transport and feed chemical cost [76]. AMD neutralisation with fly-ash produces a gypsum-laden by-product with residual neutralisation capacity [29]. While this material's uniaxial compressive strength is not high enough to provide structural support as backfill (0.3 MPa [29] vs the 5 MPa recommended by Belem and Benzaazoua (2004)), it might be effective in neutralising residual acidic groundwater in mines and protect structural cemented paste backfill from acid attack in the short to medium term [29]. Long-term leaching behaviour must be investigated, however. If more fly-ash is generated than needed for the neutralisation of AMD, the excess can be used in producing construction materials such as bricks or road paving.

The sulfide-lean coal waste is another material stream with several uses due to its low potential for acid generation. To prioritise land rehabilitation, however, the fabrication of soil for re-establishing soil fertility and agricultural potential is a preferred repurposing option. This is necessary because the lack of topsoil for land rehabilitation has been identified as a key barrier to effective mine rehabilitation in Mpumalanga [12]. When this need is met, any sulfide-lean material that remains can be used as backfill for preventing land subsidence and rehabilitating land subsidence that has already occurred. These are also problems associated with derelict coal mines in Mpumalanga [8]. Gypsum can be used as construction applications, if the quality of the material is good enough, or in soil fabrication or amelioration.

There are several credible ways to integrate these options into a cohesive, mutually supporting regional waste valorisation hub. Fig. **8** shows the integration of likely technically feasible regionally applicable repurposing options for coal value chain wastes to support the rehabilitation of coal mines to enable post-mining land uses. This is designed to lead to a low-waste or no-waste scenario, freeing up land for a variety of post-closure uses.

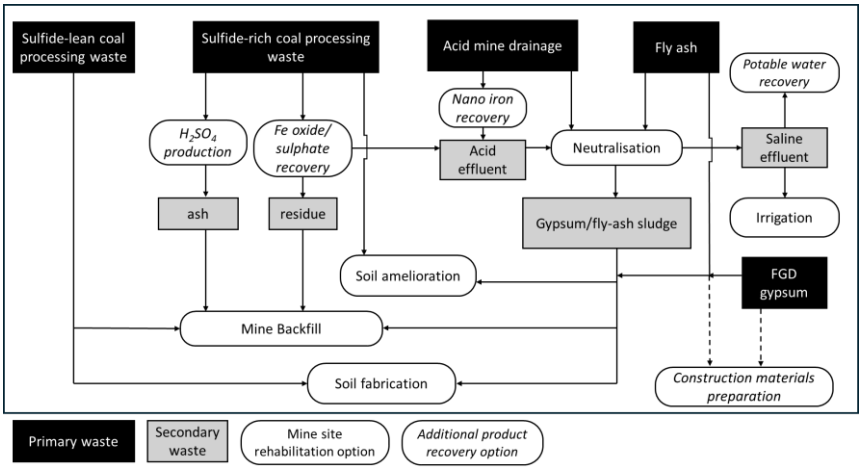

Fig. 8 An integrated approach for repurposing of coal mine-to-power value chain waste on a regional basis.

5 Conclusions

The rehabilitation of regions of coal mining are important priorities for ensuring that a just transition away from fossil fuels will be possible in Mpumalanga. Circular economy principles, eliminating waste and keeping materials in use [100], have been identified as some of the emerging paradigms that can drive the multi-dimensional aspects of sustainability in the mining and metal extraction industries. Repurposing of the wastes presents an opportunity to do this, while simultaneously creating economic opportunities in the region. This paper presents repurposing opportunities and combines them at a regional scale that ensures environmental rehabilitation as a first priority, with the recovery of marketable products generating additional economic value.

Whilst multiple opportunities for integrating downstream application of wastes from coal production, coal AMD treatment and coal combustion have been proposed here, in most cases technical feasibility of the technologies and their integrated application still needs to be demonstrated, either at the laboratory or pilot scale. Even in cases where these technologies are demonstrated, commercial implementation will require the development of a more rigorous business case, which considers the environmental, economic, socio-technical, and regulatory aspects of the proposed options. Such a business case will also need to be based on a comprehensive understanding of the characteristics of the different wastes, and their variability across the region.

This paper was made possible in part by a grant from Carnegie Corporation of New York. Funding from the University of Cape Town as part of the Grand Challenges Initiative is also gratefully acknowledged. The statements made and views expressed are solely the responsibility of the authors.

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