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THE BENEFICIATION AND UTILIZATION OF COAL FINES – A CASE OF HWANGE COLLIERY COMPANY

By

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(C15126014J)

A DISSERTATION

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Declaration

I, Lesley Chioneso Mutyavaviri, hereby declare that this dissertation is my work, except for what is noted in the acknowledgements, references and comments cited in this dissertation body. This work has not been submitted in part or in whole for another degree in any other university.

The undersigned hereby agree that they have read and agreed to submit this final version of the dissertation as the official submission.

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Dedication

I dedicate this work to the loved ones that I lost during the study, my father and grandfather. I wish they were here to celebrate this achievement with me.

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1. Mutyavaviri, L. C., Chihobo, C. H., Makepa, D. C. (2024) The Ecological Effects and valorization of Coal Fines – A Review. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-024-34620-z. **(Published online).**
2. Mutyavaviri, L.C., Makepa, D.C., Chihobo, C.H. (2024). The Characteristics and Environmental Implications of Coal Fines at Hwange Colliery Company. Results in Engineering. http://dx.doi.org/10.1016/j.rineng.2024.102743. **(Published online).**

ABSTRACT

Fine coal waste management has been a great challenge in the coal mining industry as little attention is given to its management and the fines are dumped as heaps on open sites. The characteristics of the coal fines at Hwange Colliery Company were analysed through particle size distribution and proximate and elemental analysis. Approximately 80% of the coal fines passed through the 2mm sieve. The coal fines had an average gross calorific value of 17.43 MJ\kg which has notable potential for energy extraction. Elemental analysis uncovered traces of heavy metals such as Fe, Co, Ni, and Cu, a potential environmental hazard. The potential environmental implications were assessed through water and soil quality analysis which revealed generally low turbidity levels in groundwater with readings ranging from 0.34 to 0.55 NTU. However, elevated sulfite concentrations averaging from 113.68mg/l and traces of nickel of up to 0.07mg/l, warrant continuous monitoring to ensure compliance with safety standards. Soil analysis indicated the presence of heavy metals near coal fines dump sites with lead levels reaching up to 52.32 mg/l, nickel at 36.17mg/l, and copper at 53.70mg/l which impact soil enzyme activity and agricultural productivity. A cleaner production assessment was done to determine the best coal fines utilization options. A feasibility analysis was done using a literature review and brickmaking, pelletization and briquetting were chosen to undergo cost-benefit analysis. Briquetting showed greater profitmaking potential with a payback period of 13 months, a net present value of $1 771 493.18 and an internal rate of return of 90%. Further analysis was done to assess the practicality of briquetting and the binder and binding ratio. The briquettes were produced at varying coal fines and binder ratios using molasses and kaolin clay as binders. Physical strength analysis results show that the briquettes that were produced using 20% molasses were stronger therefore the optimum. The high heating value for the optimum was 21.59MJ/kg which shows the binder did not reduce the energy potential of the coal fines. Thermogravimetric analysis showed that the addition of the binder had no significant effect on the combustion patterns of the briquettes. Therefore, briquetting was proposed to be the best beneficiation and value-addition technique for the coal fines that are being produced at Hwange Colliery Company.

CHAPTER 1: INTRODUCTION

1.1 Chapter overview

The chapter introduces the study giving the background and importance of the research. The general characteristics and behavior of the coal fines that have been studied by other researchers are provided as well as the challenges that emanate from the current disposal and utilization of coal fines are clearly outlined. The importance of the research is also given clearly focusing on the knowledge gap that the research is going to cover.

1.2 Background

Coal fines are coal particles that have a particle size of less than 5mm. The coal industry discards coal of this size due to the high moisture content and handling problems which make the usage of the coal fine unfavorable (Honaker et al., 2005)(Lewitt, 2011). Coal fines are also characterized by an ash content of approximately 45% and a net calorific value that ranges between 2 – 14.6 MJ/kg (Muzenda, 2014). Fine-grained waste coal is a great challenge for various coal producing companies worldwide as it is difficult to utilize due to its size and high moisture content which results in a significant proportion of the output coal being rejected due to its difficulty in storing or utilization (Lewitt, 2011). Despite the large quantities of fine coal waste that is being produced, a small quantity is being reused for other purposes as most of it is disposed into the environment.

Approximately 10 – 20% of the feed coal in most processing plants has particle sizes of less than 0.6mm. The coal fines are then treated by the froth floatation method. However, it is said to be more economical to discard the coal fines as tailings due to the high content of mineral matter that is common in the coal fines. The coal fines have a high surface area with an increased presence of clay minerals which results in them having a higher moisture content than the coarser size fraction (Y.-M. Zhang, 2019).

Over 30 billion metric tonnes of coal can be accessed in the 10 highest coal producing countries. Approximately 10% of the production quantities end up becoming coal fines. The total quantity of the resources that the coal fines represent at global and national levels should be assessed taking into consideration the quantities in existing piles and the generation rates (Lewitt, 2011). This information is important in decision making and evaluation of the economic and environmental sustainability of the methods of treatment that are given to the coal fines.

The projection of coal consumption states that coal extraction will increase at a rate of 0.6% per annum up to 2040 (US Energy Information Administration, 2021)(Adiansyah et al., 2017). The increase in coal consumption automatically leads to an increase in coal fines production. Therefore, as the predictions for increasing coal consumption are being made, quantities of coal fines that may be generated should also be predicted and the measures for management be in place to ensure a reduction in environmental damages that may result from the improper disposal of coal fines.

As energy demands are increasing with time, maximum utilization of energy resources is a global concern and solutions such as waste conversion to energy technologies are being promoted worldwide. The coal fines that are regarded as waste can be utilized through beneficiation and value addition (Ramudzwagi et al., 2020). These options consider the environmental risks that emanate from the fine coal piles and their economic potential as the huge quantities of the fine coal that is disposed of can add millions of metric tonnes of resources into the market per annum(IEA, 2024).

Fine coal beneficiation is a process whereby low-quality coal is turned into a product, size or quality that is suitable for the market. This can be achieved through ash content reduction, removal of mining wastes, and regulation of the product size that is to be formed (Ramudzwagi et al., 2020). This is being done mainly due to the rising environmental concerns relating to the extraction and utilization of coal as an energy source. Maximum utilization of the coal that would have been extracted is required therefore fine coal which was usually dumped has to be utilized through beneficiation.

The beneficiation and utilization of waste is of paramount importance as it saves space. After energy recovery activities, the cumulative waste produced represents only about 10% of the initial waste volume. This is a significant advantage because it preserves land value and minimizes harm to the environment. However, it has been noted that Africa is lagging in terms of commitment towards resource recovery from waste (Baruya & Kessels, 2013).

Energy recovery technologies are being adopted by industries as they are an effective way of waste management while producing productive outputs from them. Materials recovery may also be done through producing value-added products which may be used for other purposes that are not energy extraction. However, the adoption of these technologies has been greatly noticed in developed countries compared to developing countries due to their demand for capital input (IEA, 2024)(Mancini et al., 2024).

Efficient dewatering has been done as a solution working towards meeting the sales revenues and the environmental norms that facilitate the handling of coal fines. However, the challenges that have been faced with dewatering are that the coal fines come in various particle sizes, shapes, specific gravities, and surface area and their behavior in the aqueous environment differ (Hansdah et al., 2017). This has resulted in the dewatering process becoming less effective and requiring technical improvements for better efficiency in dewatering the coal fines.

The briquetting of coal fines has been acknowledged as one of the best methods for coal fines utilization as it allows for the integration of recycling within the existing production units. The application of briquetting has been done since the 19th century and has proven to be useful. Constant further development has been done to improve the quality of the briquettes and pellets through the use of various binders and improvement of machinery for efficiency (Schwelberger et al., 2018).

The use of coal water slurry for energy extraction has been studied to determine its potential efficiency in industries. It has been noted that coal particle size distribution has a great effect on the physical properties of coal water slurry (Nunes, 2020)(Y.-M. Zhang, 2019). This clearly shows that the properties of the coal fines should be analyzed before choosing a method for utilization to ensure that the properties of the coal fines match with the required properties for the given coal fines utilization technology.

The determination of the beneficiation potential of the coal fines is an important aspect in determining the way forward with coal fines management. It is vital to understand the value that the coal fines have as this will assist in decision making which determines the best way which may be used to handle the coal fines. The determination of the beneficiation potential requires knowledge of the physical and chemical characteristics of the coal fines which reflect the quality of the coal fines. The coal fines with high ash and moisture content are regarded as low quality

(Chen et al., 2021). Therefore, the method that may be used to deal with these may differ from the method that may be used to deal with high quality coal fines with low moisture and ash content.

The assessment of the ecological impacts should be done to determine if the coal fines may have a footprint on the environment. This may be done through experimental analysis of ecological aspects such as soil and water to determine their quality through parameters such as pH, soil organic matter content and elemental analysis to determine the presence of heavy metals and other harmful elements that may migrate from the coal fines (Rouhani et al., 2023).

The results of the quality of coal fines and their potential effect on the surrounding environment will help in determining the best method for utilizing the coal fines in a way that does not further the effects that the ecosystem is already facing. Through literature review, the methods for coal fines utilization may be determined and assessed for their technical feasibility depending on the past experiments and experiences that are found from previous research. A cost-benefit analysis may also be done to determine the costs that may be incurred in setting up a plant for coal fines utilization as well as the benefits that come thereof (Havard Business School, 2024). It is important to note that some techniques for coal fines utilization may seem feasible through literature but fail practically. Therefore, practical experiments may also be done to sample the products that may be produced and determine if the quality of the products is practically sustainable.

Following the steps from determining the quality of the coal fines to the practical application of the chosen technique gives a more accurate prediction of the potential that the coal fines may have in developing marketable value-added products via sustainable and lucrative projects (Lino, 2015). This gives the improved management of coal fines a better chance as business people may want to invest in the coal fines beneficiation projects as the financial and economic benefits would have been outlined.

Fine coal waste management has been generally difficult for many countries worldwide. This is evidenced by some companies in the USA which dispose of the fine coal waste that they produce from their operations (Rashid et al., 2023). It is estimated that over 500 million tonnes of coal fines are being stored in refuse ponds in the state of Kentucky and 3 million tonnes of coal fines are being lost to the reject stream annually (Honaker et al., 2005). Poor coal waste management has been largely due to a lack of technologies that are suitable for the proper treatment of fine coal.

However, efforts have been made in the coal industry to find ways to utilize the fine coal that has always been a problem in the coal mining industry. Coal tar pitch and molasses blend has been once used as a binder to form coal briquettes from highly volatile coal (Borowski & Hycnar, 2013). Pellets, coal water slurry and fluidized bed technology are techniques that have also been useful in the beneficiation and value addition of fine coal (Kozicki, 2023)(Nunes, 2020)(Muzenda, 2014).

Coal production has been generally high in Zimbabwe due to the increased energy demands that hydroelectricity fails to sustain due to the reduced rainfall received over the years in Zimbabwe (Baruya & Kessels, 2013). The increase in coal mining leads to the production of large quantities of coal fines which are disposed of on open dump sites. Fine coal waste management has been a challenge in developing Countries such as Zimbabwe. Fine coal waste piles within the major coal mining towns such as Hwange have posed major problems to humans and the environment in Zimbabwe. In as much as they cause environmental problems such as air and water pollution, they have been a serious accidental hazard for the communities (Mlevu, 2019). The potential for energy production from the fine coal waste poses a great need for utilization of the waste instead of it just being idle in the environment. This can be achieved through the beneficiation of the fine coal waste to produce highly marketable products (Muzenda, 2014).

Hwange Colliery Company had been accumulating coal fines over the years until the year 2009 when an active market was discovered. The company has been inviting tenders for coal fines beneficiation or the purchase of large volumes on a prepaid basis to increase the rate of removal of the coal fines from the environment. However, despite these efforts being made, large quantities of coal fines remain, posing various environmental hazards which calls for improved management of the coal fines (Mlevu, 2019).

The scenario of the disposal and utilization of coal fines at Hwange Colliery Company warrants special consideration because the existing efforts to utilize the coal fines that are being produced and the ones that have already been deposited are not performing well. Therefore, the development of this project is aimed at assisting in determining ways to reduce environmental damage and the occurrence of accidents due to the improperly disposed of fine coal at Hwange Colliery Company through the beneficiation of fine coal to produce highly marketable products.

1.3 Problem Statement

Hwange Colliery Company is a coal producing company that faces the challenge of large quantities of fine coal waste that remains after the larger particles have been selected for use. Currently, fewer strategies have been developed for the utilisation of the coal waste that is being produced (Baruya & Kessels, 201 (CNRM, 2016) 3). The fine coal waste is left on the ground which increases levels of dust and air pollutants such as sulphur oxides, nitrogen oxides and carbon monoxide. These pollutants negatively impact the environment through a reduction of air quality (Wahyudi et al., 2022). The dust and air pollutants cause various respiratory diseases in humans such as pneumoconiosis, lung cancer, dust allergies and asthma (CNRM, 2016). The flora and fauna in the surrounding areas where the fine coal waste is deposited suffer stunted growth as the soil properties are negatively altered by the fine coal waste (B. Zhang et al., 2018). The fine coal waste piles have posed a threat to the surrounding communities as people get hurt if the pile is subjected to heat. A case of a young boy aged 13 who was exposed to hot coal dust and injured in 2016 was reported in the Standard which has negatively impacted his life. There are various coal waste dumpsites in Hwange in villages such as Cinderella and Lwendulu villages and the company puts danger warning signs yet these piles remain a threat to the communities (Mlevu, 2019). Most residents in Hwange live in the compounds that were initially built for the mine workers. These houses are near coal waste dumps which leave people exposed to air pollution from dust and underground fires which are also a major fire accident risk (Di et al., 2021).

1.4 Aim

- The study aims to determine the beneficiation potential of the fine coal waste that is being produced at Hwange Colliery Company.

1.5 Objectives

1. To characterize the coal fines that are being produced at Hwange Colliery Company (Physical and Chemical properties).
2. To determine the environmental implications of fine coal waste disposal in Hwange.

3. To assess the cleaner production options for the coal fines that are generated at Hwange Colliery Company.

1.6 Research Questions

1. What are the physical and chemical properties of the fine coal waste that is being produced at Hwange Colliery Company?
2. What are the environmental implications of fine coal waste disposal?
3. What are the various techniques that can be used for value addition for the fine coal waste being produced at Hwange?
4. What is the most appropriate technique that can be used for beneficiation and value addition of the fine coal waste?
5. Are the techniques chosen for value addition for the coal fines at Hwange Colliery Company practically feasible?

1.7 Practical Significance of the Research

The study of the utilization of coal fines is an area of significance as it contributes to waste management and economic gain for the companies that produce coal fines. The utilization of coal fines has several advantages compared to dumping on open dump sites as it reduces the potential for the coal fines to cause accidents. Coal fines are prone to combustion which in most cases is not visible thereby making them a fire hazard for surrounding communities. Therefore, the utilization of coal fines reduces the occurrence of fire accidents due to the open dumping of coal fines.

Land value is also preserved as there will be no need for a large vast of land for coal fines disposal. This allows for the land to be put to better use and also preserves the flora and fauna that may be residing on the site where the coal fines are placed. The industries that produce coal fines get economic benefits from the utilization of coal fines as they are of no value when they are disposed of but can be put on the market and fetch profits after beneficiation and value addition. This also enhances the companies' reputation in the public eye as they appear to be responsible stewards of the environment, making the industries more attractive to investors.

The characterization of the coal fines is important as it aids in understanding the chemical and physical characteristics of coal fines. This study focused on determining the quality of coal fines that are being disposed of in Hwange and their potential impacts on the surrounding environment. A clear understanding of the quality of the coal fines and their impact on the environment was then used to evaluate the available methods for coal fines beneficiation and determine the best method that could be used for the beneficiation of coal fines that are being produced at Hwange Colliery Company.

Water and soil quality analysis in Hwange is also an important contribution to the field of study. The soil and water quality analysis indicate the ecological impacts that may arise from the open dumping of coal fines. They also indicate the severity of the impacts that the coal fines have on the environment which helps in decision making to determine the best method to deal with them.

The characteristics of the coal fines and their impact on the environment give a clear understanding of the methods that may be suitable for the utilization of the coal fines. Cleaner production assessment is also another contribution to the field of study. It gives decision makers clear facts regarding the advantages and disadvantages through techno-economic analysis and environmental analysis of the coal fines utilization methods. An experimental analysis to determine the practical feasibility of the coal fines utilization option is of great importance as companies which produce coal fines of the same properties as those of Hwange Colliery Company may adopt the research so that they utilize the coal fines that they produce.

Therefore, the findings of this study give a roadmap for determining the methods for utilization of coal fines which guarantees positive results as the methods for coal fines utilization are thoroughly reviewed and experimentally assessed to provide valid information on their potential for use as beneficiation options for the coal fines. Justification

The utilisation of the fine coal waste from Hwange Colliery Company will help to reduce pollution that emanates from the fine coal waste piles that await disposal at the site. The disposal of coal fines on open stockpiles contributes to air pollution as the dust that is emitted from the coal fines may contain NOx and Sox elements that contribute to air pollution. Settling dust from coal fines on the ground has the potential to contribute to soil pollution. Water pollution may also occur through the leaching of chemicals from the stockpiles. Air, water and soil pollution has negative impacts on plant and livestock growth and productivity (CNRM, 2016).

The adoption of the study through coal fines beneficiation may reduce the occurrence of respiratory diseases among the employees and community members who live close to the area where the piles of fine coal are placed. This is because as the coal fines are utilized, the generation of stockpiles is limited which directly reduces the negative effects that emanate from the open dumping of coal fines that is the status quo.

The beneficiation process produces marketable products which may be income generating or may reduce cost of production for the company which may have a positive effect on the company's profits (Lewitt, 2011). Coal fines beneficiation through the production of products such as pellets, briquettes and bricks may be economic for Hwange Colliery company as they can sell these products for income generation or harness energy back into their system through the combustion of briquettes and pellets to ensure maximum utilization of resources.

Waste utilization technologies will also assist in fulfilling the Zimbabwe National Climate Policy requirements which are to promote the utilization of waste and the improved management of the existing waste disposal facilities to control greenhouse gas emissions (Zimbabwe Ministry of Environment, Water and Climate, 2017). The use of coal fines allows for an improved waste management system which is a major step towards working to reduce emissions that contribute to climate change.

The beneficiation of coal fines through value addition helps fulfil the sustainable development goals as waste management helps in safeguarding the environment ensuring a clean and safe environment for both workers and the community as well as clean water and air which promotes good health. Therefore, the use of coal fines should be prioritized as part of the mission to fulfil the SDGs.

1.8 Description of the Study Area

Hwange Colliery Company is located in the western part of Zimbabwe about 100 km from Victoria Falls. The mining division incorporates opencast mining, underground mining, coal processing and coke production operations (Hwange Colliery Company, 2020). Coal fines are produced in the mining and product formation processes. Hwange Colliery Company is located in Hwange town which is a self-contained town with almost all services relating to local and central governance being run by the company. The town has a population of approximately 55,000 people as of 2017 (CNRM, 2016). The map of the study area is shown in Figure 1.

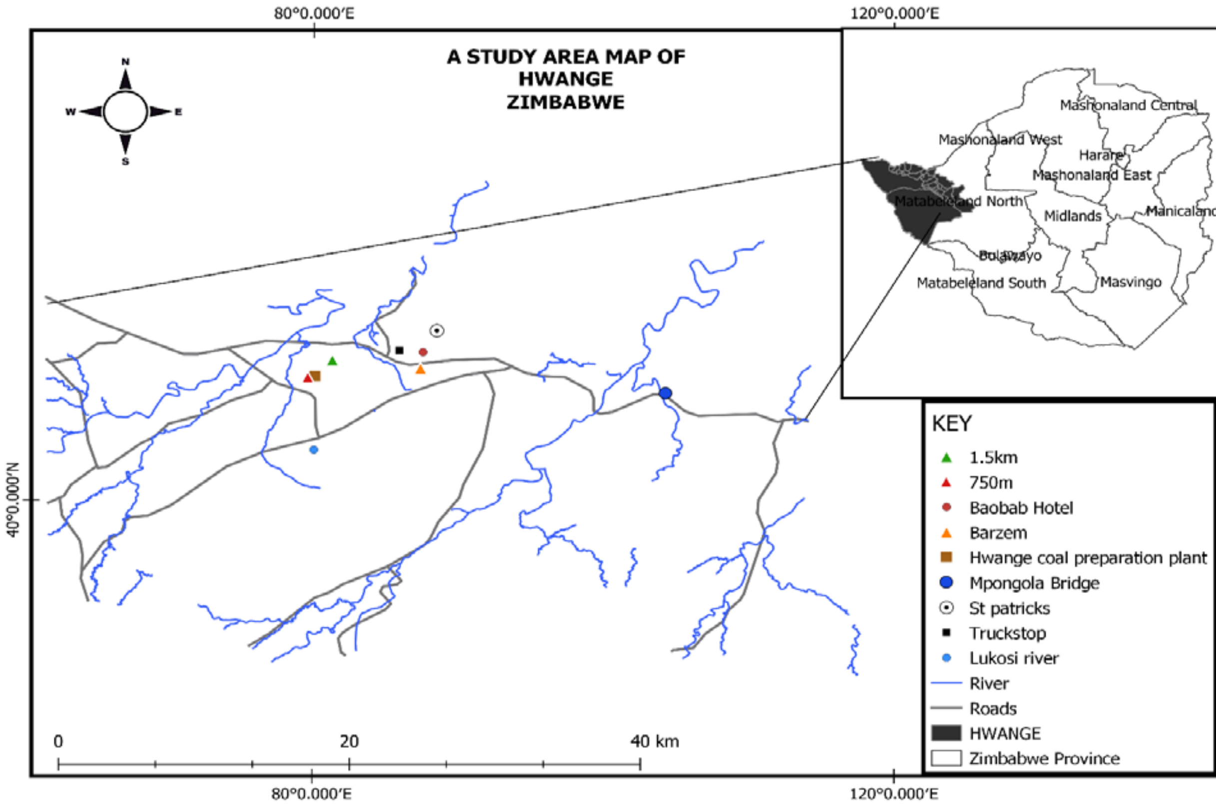


Figure 1.1. Map of the Study Area

1.9 Overview of the Study

The dissertation is composed of 6 chapters. Chapter 1 is an introduction to the research. It gives a clear background of the study, justification and research contribution to the body of knowledge. The objectives of the study which briefly outlines what the researcher intends to achieve with the study are also described in this chapter.

Chapter 2 is a literature review which thoroughly reviews the literature on topics such as the ecological impacts of coal fines, methods of coal fines valorization, cleaner production in the mining industry and the cost-benefit analysis of cleaner production through coal fines beneficiation. The literature review also clearly outlines how the coal fines are produced within the mining processes.

Chapter 3 is the methodology section that outlines the procedures by which the experiments were done. It clearly states how the samples were collected, stored and analysed in the laboratory to obtain the results that were presented in the results and discussion section.

Chapter 4 presents the results of the data collection and experiments that were done. The results are presented using tables and graphics which aid in clear analysis to determine what the results mean.

Chapter 5 is the discussion of the trends of the data that was observed.

Chapter 6 is the conclusion which summarizes the outcomes of the project. Recommendations for further study were also presented in this chapter and areas where further work may be done were also discussed.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter thoroughly assesses the methods that are used for the utilization of coal fines that are produced within the coal mining processes. The production patterns of coal globally are reviewed as these determine the quantities of coal fines that are produced. The ecological impacts of the disposal of coal fines on open dump sites were also reviewed to determine the extent to which these coal fines have affected the environment with the evidence of published research. Evidence of the utilization of coal fines is also noted through various research in working towards the reduction of the generation of coal fines and the utilization of the coal fines that have already been deposited in the environment.

2.2 The Production of Coal

Coal has been used as a major source of energy worldwide. Coal is a combustible sedimentary rock with a high carbon and hydrocarbon content. This makes it a non-renewable energy source due to its formation over millions of years (Gasparotto & Da Boit Martinello, 2021). Coal has been generally used in industries as a heat source which has rendered its importance over the years. However, concerns have been raised regarding its polluting effects and contribution to climate change, which has reduced its usage over time.

Coal may be found relatively near the earth’s surface or deep underground which results in different ways of extraction being used for coal mining. The two major types of mining that are used for coal are surface mining and underground mining (Viney et al., 2021). Surface mining is commonly employed when coal is less than 200 feet underground. In this method, large machines are used to remove the topsoil and layers of rock, also known as overburden, to expose coal seams. Once the coal is extracted, the disturbed area may be restored by covering it with topsoil to facilitate the growth of grass and trees Around two-thirds of coal production in the U.S. comes from surface mines due to the lower costs associated with this method compared to underground mining. (US Energy Information Administration, 2024)

Underground mining, also known as deep mining, is employed when the coal is located more than 200 feet below the surface. Some underground mines are thousands of feet deep, with tunnels that may extend out for miles from the vertical mine shafts. Miners ride elevators down the deep mine shafts and travel on small trains through long tunnels to reach the coal. Heavy machinery is required for underground coal mining (US Energy Information Administration, 2024).

Coal will continue to serve as an abundant and affordable basis for economic and social development. With its extensive and well-distributed resources, coal will play a significant role in eliminating energy challenges. Additionally, coal can and will become increasingly clean with manageable costs in terms of technological advancement, international technology transfer, and research and development in CO2 sequestration. Unbiased energy and environmental policies are required for the utilization of coal in an environmentally friendly manner. Furthermore, a more proactive engagement from the coal and power industries is essential for promoting the global adoption of best technical and managerial practices and highlighting coal's positive attributes (World Coal Association, 2012).

Figure 2.1 gives a clear outline of the processes of coal mining and the machinery that is required for each stage for both opencast and underground mining. It is also important to note that waste material is produced in the processes of coal mining and may be disposed of or treated and reused in the factory or other industries.

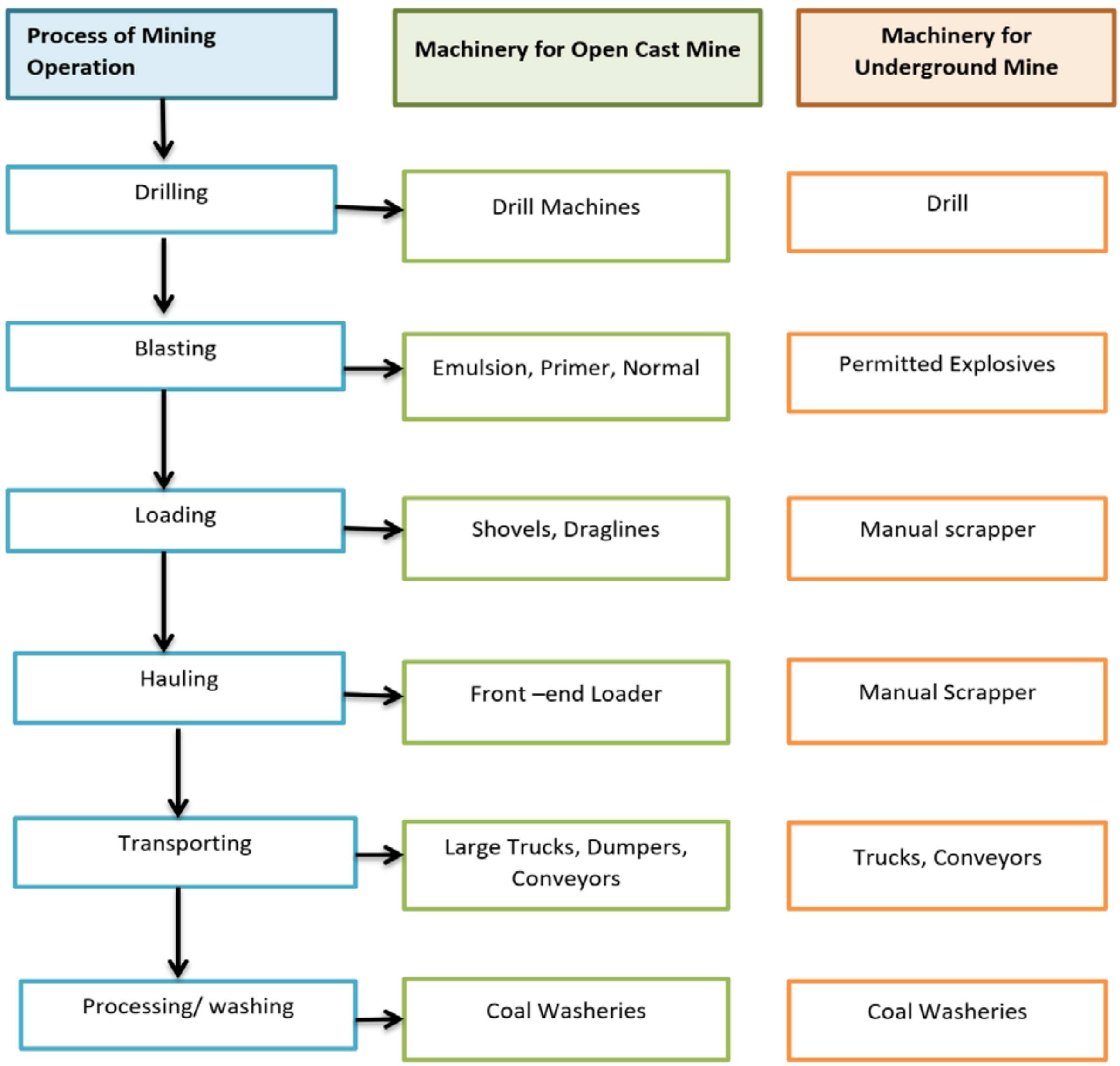


Fig 2.1. Flow Chart Showing the Mining Process and Corresponding Machinery (Mandal, Maity, Chaulya, Prasad, & Verma, 2016).

Typical coal production and coal mining wastes are shown in Figure 2.2. The different types of waste that are produced depend on the amount and the type of coal that is available in an area (Vo et al., 2022). The latest estimates indicate that the current annual global coal production has increased by 120 million tonnes in 2023 (Agnolucci & Temaj, 2024). The total global coal reserve is 1.14 trillion tons, enough to last another 132 years at the current production rate (IEA, 2024).

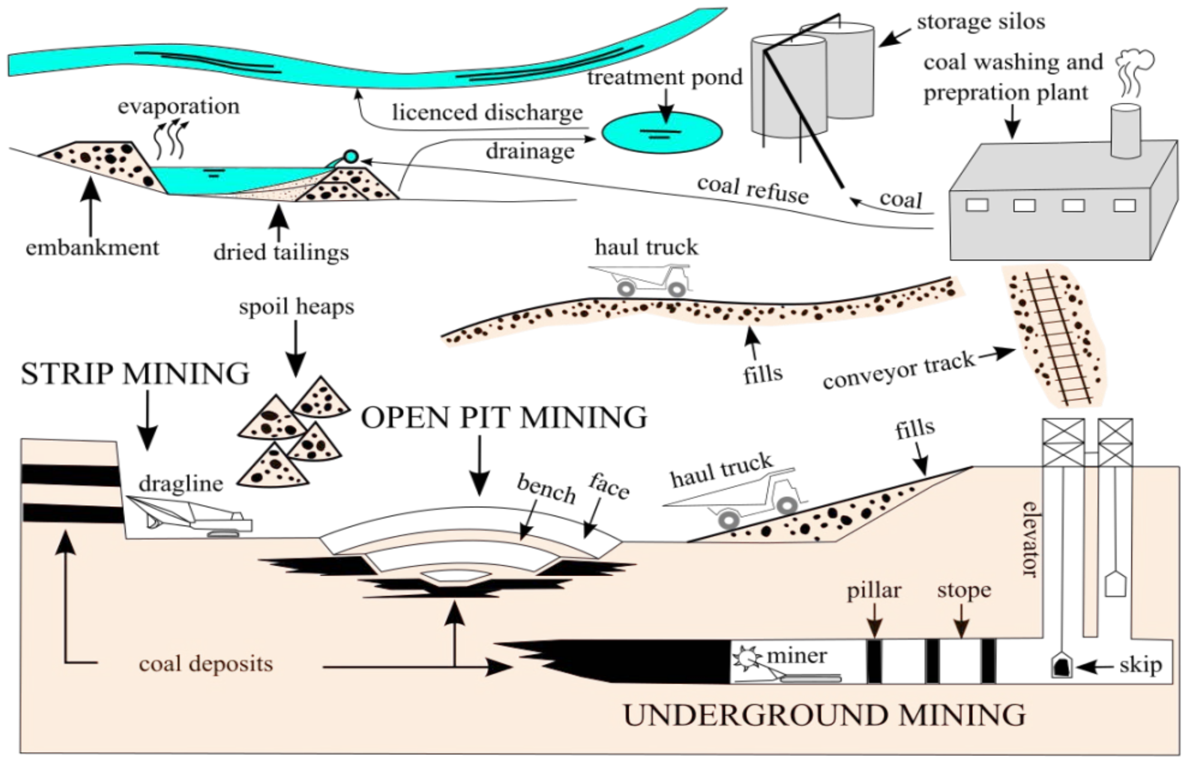


Fig 2.2 A Diagram Showing the Typical Coal Production and Coal Mining Waste Produced (Vo et al., 2022)

In the past, coal mining wastes have been considered problematic geomaterials. They have varied chemical composition, are prone to particle breakage through compaction, degrade quickly through wetting-drying cycles, and can liquefy when loosely deposited. Additionally, they pose challenges such as spontaneous combustion and the leaching of acidic water into the surrounding environment. These issues are linked to specific properties of coal and coal-bearing geomaterials within the wastes (Vo et al., 2022).

2.2.1 Coal Production – A World Overview

Coal still accounts for just over a third of global electricity generation, despite it being the most carbon-intensive fossil fuel. (Eskom, 2021)states that coal is the most widely used primary fuel globally. Approximately 36% of the total fuel consumption for electricity generation comes from coal. Although most countries are gradually transitioning away from coal for power generation, it will remain crucial for iron and steel production until newer technologies become available. Given the increasing energy demands, many countries are left with no option but to keep using coal to generate power. Additionally, some industrial processes rely on coal's carbon content. Therefore, to position coal as a cleaner energy source in the future, governments and the coal industry must work together to develop and implement more efficient and less polluting technologies. This may include but is not limited to, carbon capture, utilization, and storage (U S Energy Information Administration, 2023).

Approximately 82% of the global coal that is produced annually is used by the five major coal using countries which are China, the USA, India, Japan and South Africa (Eskom, 2021). In 2019, coal production in Europe, North America, and Asia Pacific amounted to 557.4 million tonnes (Mt), 701.5 Mt and 5 911.8 Mt respectively (British Petroleum, 2020). Given the concerning state of the global climate (Abbass et al., 2022), the environmental impacts of coal extraction and production activities are rapidly becoming a focus for researchers at a global scale. To address the significant challenges posed by coal mining in Europe and globally, innovative concepts are being developed to manage, recycle, and upcycle waste materials that are generated by coal mining activities (Vo et al., 2022).

In 2022, global coal consumption reached a record high amid the global energy crisis, rising by 4% year-on-year to 8.42 billion tonnes. However, it is expected that in 2023, coal demand will fall in the most advanced economies, with record annual declines of around 20% expected in the European Union and the United States. Other advanced economies such as Korea, Japan, Canada, and Australia are expected to see lower rates of decline. Nevertheless, the growth in China (around 5%) and India (over 8%), as well as Indonesia, Vietnam, and the Philippines, which together represent more than 70% of global coal demands, will offset these decreases on a global level. (IEA, 2024).

Table 2.1 World Coal Production from 2010 to 2020 (IEA, 2024)

	Production volume, million tons	**Growth rate %**
2010	7479	--
2011	7975	6.63
2012	8203	2.86
2013	8270	0.82

2014	8195	(0.91)
2015	7917	(3.40)
2016	7402	(6.50)
2017	7666	3.57
2018	7789	0.30
2019	7906	1.50
2020	7438	(5.92)

Table 2.1 shows the growth rate for global coal production from 2010 to 2020. The table shows a general decrease in coal production which may mainly be due to the increased emissions that are associated with the utilisation of coal and their impacts on the environment.

Table 2.2 shows the global coal production percentages by region. Asia Pacific generally produces more coal compared to all the other regions. Africa produces less coal despite the increase in population which also means increased energy demands.

Table 2.2 Global Coal Production by Region (IEA, 2024)

	2010	**2015**	**2019**	**2020**
Total North America	14.3	11.2	8.6	6.9
Total South & Central America	1.1	1.2	1.1	0.8
Total Europe	10.2	8.6	7.0	6.2
Total Commonwealth of Independent States	5.9	6.1	7.0	6.8
Total Middle East	0.0	0.0	0.0	0.0
Total Africa	3.5	3.3	3.5	3.5
Total Asia Pacific	65.0	69.5	72.8	75.9

Total World	100.0	100.0	100.0	100.0

2.2.2 Coal Production in Africa

Africa is expected to be home to one-fifth of the world's population by 2030 and will play a more significant role in the global energy ecosystem. Although there is a growing demand for energy across the region, the modern energy usage per capita remains among the lowest in the world, despite the continent having ample energy resources. Currently, Africa accounts for only 6% of global energy use and less than 3% of global energy-related carbon dioxide (CO_2) emissions (IEA, 2024). 12.3% of the total energy supply in Africa comes from coal. Therefore, coal is a major part of energy generation and requirements in Africa.

South Africa is the major coal producer in Africa with coal production ranging at approximately 224 million tonnes of marketable coal annually as of 2020. Approximately 72.1% of the country's energy needs are supplied by coal (Eskom, 2021). This makes it difficult to reduce the quantities of coal production due to environmental issues as the economic balance relies mostly on coal utilization. Therefore, clean coal utilization technologies should be employed to ensure a balance between economic production and environmental management.

Countries such as Mozambique, Botswana, Zambia, Namibia and Zimbabwe are in the early stages of growth in the coal industries. However, coal plays a major role in the energy production sector in these countries. Table 2.3 gives a clear presentation of the coal resources in Mozambique as of 2012. If these coal fields are fully exploited, the production of waste that results from coal mining and production is inevitable, which calls for the need for proper waste management systems to be put in place to ensure a smooth flow of operations without major polluting effects on the environment and the surrounding communities (Baruya & Kessels, 2013).

Table 2.3 Major Coal Projects in Mozambique (Mozambi, 2012)

Significant projects	Data
Vale	1.4 Gt
	Mining licence granted
	Production commenced 1H2012
	Target 22 Mt/y from 2H2014
Rio Tinto	13 Gt JORC resource
	20 Mt/y mining licence granted
Jindal Steel & Power	700 Mt resource
	Mining licence granted
	10 Mt/y production from 2012
ENRC	1.3 Gt resources
Minas de Revuboe	1.4 Gt JORC resources
Ncondezi Coal	1.8 Gt JORC resources
ETA star	1.9 Gt resources

2.2.3 The Production of Coal in Zimbabwe

Coal resources are widespread throughout Zimbabwe, with significant reserves in the mid-Zambezi region in the northwest, which is the primary area for current production. Additionally, large deposits are found in the southern region of the country in the Save-Limpopo basin (Baruya & Kessels, 2013). The richest resources are found in the Zambezi area, with 2101 Mt in the Hwange area and an additional 4497 Mt in other regions of the Zambezi. The Hwange coal deposit holds substantial reserves of both coking and thermal coal (Baruya & Kessels, 2013). Presently, Hwange mines one seam at depths ranging from outcrops to 360 m below ground, with seam thicknesses of 10–12 m.

Six coal producers were operating which resulted in a total production of 4.2 million tons during the year 2022, as compared to 3.3 million tons in 2021 (Zimbabwe Chamber of Mines, 2021). Figure 2.3 shows the production patterns of coal from 2014 to 2022. The decrease in coal production during the years was mainly due to shortfalls in foreign exchange for maintaining production capacity, delayed payments for delivered coal to the national power utility, and low coal prices. This clearly shows the impact of the economic setup on energy production and availability which in turn affects Industrial activity. If the industries are not economically stable, less attention will be given to issues regarding proper environmental management, which negatively affects the communities and the ecosystem.

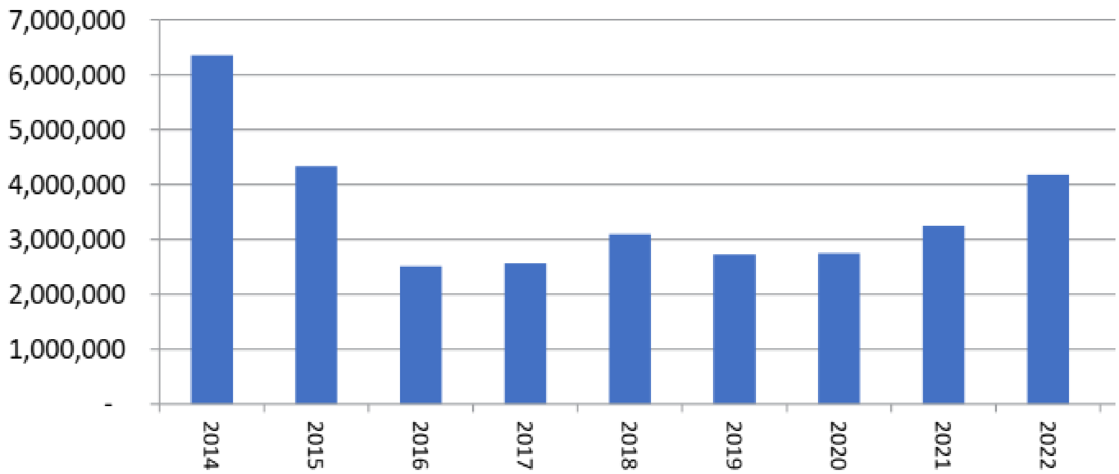


Figure 2.3 Coal Production in Zimbabwe (Zimbabwe Chamber of Mines, 2021)

In the past, coal mining in Zimbabwe was mainly done by Hwange Colliery Company Limited (HCCL). However, the economy's liberalization led to the entry of more players, increasing demand for transportation from the mining fields. Currently, the coal companies have been divided into coal mining companies and coke making companies. The coal mining companies include HCCL, WK Blasting (WK), Makomo Resources, Clidder, and Liberation, while the coke making companies are HCCL, Hwange Gasification, and South Mining. The increase in demand for coal has primarily been driven by the need for electricity generation. The need for more electricity was identified as early as 2000, and plans for the coming decade were set (Mhlanga et al., 2013).

The Hwange Colliery Company Ltd mines a range of coal qualities, from steam quality to coking coal (Hwange Colliery Company, 2024). The coal produced at the base of the seam is lower in ash and volatile content, making it suitable for coking markets, with ash content not exceeding 15% and volatile content over 23.5%. The rest of the seam is marketed as steam coal, containing ash levels up to 24% and has a respectable heating value of 24–26 MJ/kg. The metallurgical coal qualities are detailed in Table 8. These coal qualities are akin to coals found in Waterberg and

Botswanan regions. The run-of-mine coal can have ash contents as high as 50%(Hwange Colliery Company, 2024).

Apart from the Hwange power station, the heavy industry sector, mainly cement production, utilizes coal. Additionally, there is a small overland export market for coal fines to Zambia. The agriculture sector also provides a valuable market for coal such as the tobacco industry which requires heat for curing from coal-fired industrial boilers. (Matyanga, 2012).

The rapid expansion of coal mining in Zimbabwe is a result of the government's 12-billion-dollar mining roadmap, which expects the coal mining industry to contribute about USD 1 billion (Ncube-Phiri et al., 2015). However, alongside the positive benefits of coal mining, there are also several negative impacts on the environment which include greenhouse gas emissions, deforestation, climate change, as well as the deterioration of local ecosystems, and the health of local communities and workers (Matyanga, 2012).

Table 2.4 The Representative of Coal Qualities for Zimbabwe (Baruya & Kessels, 2013)

Coal properties air-dried basis	**Composition**
Calorific value, MJ/kg	29.8
Inherent moisture, %	0.8
Ash, %	9.8
Volatile matter, %	23.4
Fixed carbon, %	64
Volatile matter, % (daf)	26.3
Sulphur, %	1.3
Free swelling index, %	2.0

Table 2.4 shows the general properties of coal that is found in Zimbabwe. The characteristics show that coal has great potential for use in the industry for heating purposes. However, the generation

of waste has to be properly managed to ensure that the coal is used in a sustainable manner taking into consideration the environmental implications that may be associated with the mining and utilization of coal.

2.3 Coal Fines Production

Coal fines are divided into two parts depending on the generation mechanism, and they are primary and secondary coal fines. Primary coal fines are the coal fines that have always existed in the coal reservoir and are produced under coalification and structural deformation. This occurs before the development of coal bed methane. The primary coal fines are found in fault planes, coal pores and interlaying sliding planes. Secondary coal fines are produced during the development of coal bed methane, and these are divided into two types where one is formed by the deformation, crushing and compression of coal and rock. This type of secondary coal fines is produced during drilling and fracturing. The other type of coal fines is produced due to factors such as hydrodynamic denudation and coal destruction. The mechanical differences in the coal and rock components also contribute to the production of coal fines (Chen et al., 2021). Lyu et al, 2024 States that secondary coal fines are produced by the grinding action of drilling tools and also due to the pressure disturbances that are caused by fluids whereas primary coal fines are the aggregates of the crushed micro components that are formed within the structural fracture surfaces which are squeezed to form tectonic coal aggregates which are tightly compressed coal fines that are found along fault planes and internship surfaces (X. Zhang et al., 2021).

The generation of coal fines has also been attributed to mechanised mining. It is estimated that 6% of the run of mine produces are coal fines of less than 200 micrometres (Venter & Naude, 2015). Transfer points with greater distances tend to produce more coal fines compared to shorter distance transfer points. This is a minor technical issue that may be addressed within the plant to ensure that transfer points have shorter distances to reduce crash impact of the coal which produces coal fines. Coal fines production may also increase due to the increased amount of time that the coal takes on the feeder breaker, which is an underground primary coal crusher which reduces coal sizes before it is loaded on the conveyor belt. High speed conveyor belts also produce larger quantities of coal fines due to abrasion. The cutting of coal with a continuous miner may also lead to the production of coal fines. The efficiency of the cutter depends on several factors such as the type of drum and operator's skill since important aspects such as the interaction between the cutter head and the coal face are important. The other parameters that also influence the cutting efficiency are line spacing, angle of attack, back clearance angle and rake angle (Saubi et al., 2023).

Careful consideration should be done to ensure the efficiency of the machinery that is used in coal mining to ensure that minimum coal fines are produced. This is the first step towards coal fines waste management that takes cleaner production into practice. If properly done, less coal fines will be produced and it becomes a lesser problem to manage the coal fines in smaller quantities.

2.3.1 Coal Fines Production – A World Overview

Globally, countries that produce coal have accumulated vast amounts of coal fines stockpiles over the years. The processing, handling and transportation of the coal fines is the major challenge for the mining industry. Therefore, coal fines utilization by the coal industry is largely dependent on economic demand and market fundamentals which advocate for new technologies that increase the productivity of the coal producers. The abundant amounts of unutilized coal fines reflect the potential that the coal industry has of taping into and adding millions of metric tonnes of coal into the market every year (CoalTech Energy, 2021).

The Table below shows the Quantities of coal fines that are available in stockpiles and ready for use to harness energy. China, being the largest producer of coal has the highest quantities of coal fines that are available in stockpiles of approximately 9 500(Million Metric Tonnes). China is followed by India, the United States of America, Indonesia, South Africa, Australia, Germany, Russia, Poland and the least being Kazakhstan with Approximately 700 MMt (CoalTech Energy, 2021). This shows that there are abundant resources that are being disposed of in coal fines and there is a need for advocacy for industries to take part in the technologies that produce marketable products from coal fines which may be lucrative for the businesses.

Table 2.5. Coal Fines Stockpiles in the Top 10 Coal-Producing Countries (CoalTech Energy, 2021)

Country	**Stockpile (Million Metric Tonnes)**
China	9 500
India	4 500
United States of America	3 000
Indonesia	2 500
South Africa	2 400
Australia	1 500
Germany	1 300
Russia	900
Poland	750
Kazakhstan	700

2.3.2 Coal Fines Production in Africa

South Africa is the major coal mining country in Africa, with the mining operations producing approximately 224 million tonnes of marketable coal annually. It is the 5th largest coal producing country in the world. 25% of the coal that is produced in South Africa is exported, making it one of the largest coal exporting countries globally (Eskom, 2021). As of 2021, approximately 72.1% of South Africa's primary energy needs were provided for by coal. This is unlikely to change in the coming years as there are no suitable alternatives to coal that can cover the gap in energy production if coal utilization is ceased.

The high demand for energy in South Africa has led to the extraction of low-quality coal from coal mines. These will require efficient coal processing equipment which eventually leads to increased coal fine production (de Korte, 2015). South Africa produces over 10 million tonnes of coal fines annually (Reddick et al., 2007). The coal fines have high sulfur content which contributes to various environmental problems such as acid mine drainage, dust and spontaneous combustion which is an accident hazard. Improved coal fines beneficiation techniques will be required to cater for the large quantities of coal fines in the run-of-mine coal(de Korte, 2015) .

Until recently, billions of tonnes of coal fines from coal mining operations have been discarded into slime dams, landfills and open dump sites which produce acid mine drainage during the rainy season. Self-ignition is also a major hazard that occurs from the coal fines that have been disposed of in South Africa and fire accidents are bound to happen. The much finer coal (ultra-fine coal) is blown by wind leading to air pollution. Diseases such as asthma, pneumoconiosis and bronchitis may emanate from air pollution by the coal fines (Oluremi & Elsaigh, 2023).

Other African countries are producing smaller quantities of coal. However, countries such as Mozambique are expected to grow their coal mining industry to a production rate of 100 Million tonnes/year. This means that approximately 5% of the total coal produced may come from coal fines (Baruya & Kessels, 2013). Therefore, as the industry grows, measures should be put in place for coal fines utilization to ensure proper coal waste management in the production process.

Zimbabwe has approximately 10.1 – 26 Gt of coal deposits both proven and probable (Baruya & Kessels, 2013). Most of the coal mining in Zimbabwe is done in the Hwange district in the North-western areas of Zimbabwe (CNRM, 2016). Approximately 5% of the coal that is produced at Hwange Colliery Company produces coal fines which accumulated in stockpiles over many years and the company started the process of selling the coal fines for beneficiation in 2009. The company has been inviting tenders for coal fines beneficiation or the purchase of large volumes on a prepaid basis to increase the rate of removal of the coal fines from the environment (Hwange Colliery Company 2017). This however has been less effective as stockpiles with large quantities of coal fines are still present and require immediate attention as they pose threats to the surrounding communities and the environment.

The presence of coal fines on open dump sites in Africa without maximum utilization requires immediate attention. The surrounding communities and the environment face adverse conditions due to the improper disposal of coal fines. Lower-cost cost cleaner production technologies for coal fines may be adopted for the utilization of coal fines to produce marketable goods for energy extraction. Therefore, advocacy and training may be offered to coal mining industries for them to realize the potential that the coal fines have as a resource instead of them being disposed on the environment and causing various challenges to the environment and the surrounding communities. The community may take part too in product development using coal fines as a source of income.

2.3.3 Determination of the Quality of Coal Fines

It is of great importance to understand the quality of the coal fines that are present in an area. This information will aid in determining the best beneficiation option that may be adopted for the coal fines that will not have any challenges when utilizing them. Several methods may be adopted to determine the quality of the coal fines which include particle size analysis, proximate analysis, ultimate analysis and elemental analysis.

2.3.4 Particle Size Distribution in Coal Fines

Generally, particle size distribution of coal fines consists of coal of less than 5mm in size (Oluremi & Elsaigh, 2023). The particle size of coal fines that are produced from coal bed methane was analysed. It was noted that the particle size of the coal fines that are produced from coal bed methane wells range from 1 – 400 micrometres and is generally above 20 mesh (Chen et al., 2021). The coal fines at Pittsburgh have high volatile coal fines with 10 – 80% of the coal fines passing through the 200mesh sieve. The determination of the particle sizes of coal fines is important as some methods of utilization require much finer coal whereas others require coarser coal fines.

Particle size distribution may be assessed through sieve analysis, where two motions are provided in a sonic sieve which are a vertical oscillating column of air and a repetitive mechanical pulse. The sieves should be brushed first to remove clogs so that particles may pass through (Liu, 2009). Laser particle size analysis may also be used for assessing the particle size distribution in coal fines. The major advantage of laser particle size analysis is that it is more efficient and accurate. It also has the potential to produce continuous particle size distribution results. However, laser particle size distribution analysis analyses a relatively limited particle size range of 0.001 – 1 000 micrometres therefore particles greater than 1mm in size require a supplementary method for analysis (Chen et al., 2021). Figure 2.5 shows how the sieve analysis is conducted.

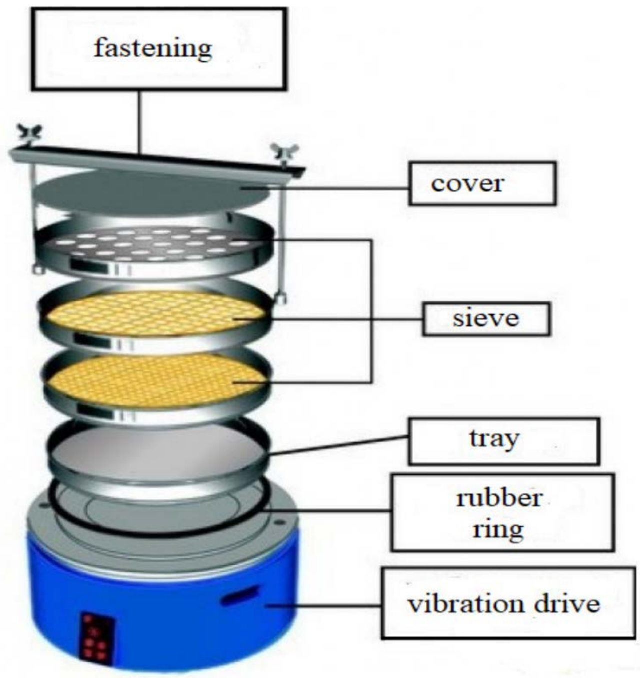


Figure 2.4 Sieve Analysis (Aluikov & Osinstev, 2021)

2.3.5 Proximate Analysis

The proximate analysis measures moisture content, ash content, volatile matter and carbon content by weight percentage. The results from the proximate analysis are used to establish the rank of coal and also to show the ratio of combustible to incombustible elements. Proximate analysis also provides the basis for buying or selling coal and may also be used to evaluate coal for different purposes (Zhu, 2014).

ASTM methods are generally used for proximate analysis of various samples. Table 2.6 below shows the results of the proximate analysis that has been done for different types of coal material.

Table 2.6. Proximate Analysis for Different Coal Types in Varying Areas

Coal sample	Sampling area	Wt%			
		Moisture content	Ash content	Volatile matter	Fixed carbon
(Adeleke et al., 2019)	---	1.37	17.94	13.77	66.92
(Bakri et al., 2022)	Massenreng Pulu Village, Lamuru District, Bone Regency, Indonesia	16.18	4.49	41.86	37.47
(Bakri et al., 2022)	Massenreng Pulu Village, Lamuru District, Bone Regency, Indonesia	15.32	2.48	42.84	38.36
(Cheepurupalli & Anuradha, 2019)	Ethiopia	16.73	21.46	34.22	27.55

2.3.6 Ultimate Analysis

Ultimate analysis determines the weight percentages of carbon, sulfur, nitrogen, hydrogen and oxygen. Trace elements found in coal may also be determined through ultimate analysis (Speight 2015). Carbon and hydrogen are said to be the most important elements in coal and usually account for approximately 70 – 95% of the weight of coal. Ultimate analysis determines carbon and hydrogen as gaseous products in the complete combustion of coal. Nitrogen, sulfur, ash and oxygen are also determined in the process (Cheepurupalli & Anuradha, 2019). The advantage of ultimate analysis is that it is a convenient method that reports coal's major organic elemental compositions (Kentucky geological Survey, 2024).

The ultimate analysis is done using an ultimate analyzer which measures the weight percentage of carbon, hydrogen, sulfur, nitrogen and ash of a coal sample. Oxygen is calculated by subtracting the total percentages of the other elements from 100 (Kentucky Geological Survey, 2024). The ASTM methods are generally used as standard testing methods for the ultimate analysis of coal fines. Table 6 shows the results of elemental analysis that were produced by other researchers.

Table 2.7. Ultimate Analysis of Coal from Different Mining Areas

Reference	Study area	C	H	N	S	O
(Cheepurupalli & Anuradha, 2019)	Ethiopia	63.54	4.96	2.00	1.88	51.90
(Bakri et al., 2022)	Indonesia	66.26	4.62	0.98	-	22.8

2.3.7 XRF analysis

The XRF analysis is a technique that uses the interaction of X-rays with a given sample to determine its elemental composition. The major advantage of XRF is that it is fast, accurate and non-destructive. It also requires minimum sample preparation and it is useful in a variety of industries from food, mining and health (Brouwer, 2010). Table 7 shows the results of an analysis of coal dust from different mining companies in Indonesia.

Table 2.7. XRF analysis of coal dust from different mining companies in Indonesia (Wahyudi et al., 2022)

Element	**PT. A**	**PT. B**	**PT. C**
Mg	0.150	2.196	3.077
Al	23.081	18.056	14.972
Si	46.325	34.203	24.518
P	2.822	5.634	10.160
S	11.652	13.621	9.247

K	1.822	1.382	0.824
Ca	3.761	8.970	15.984
Ti	1.341	1.484	1.642
Fe	7.761	11.629	15.391
Ag	0.825	2.010	2.608
Other	0.460	0.815	1.577

2.3.8 The Ecological Impacts of Coal Fines

The stockpiling of coal has detrimental effects on humans and the environment. Since it is done on the surface, the coal dust gets dispersed into to the atmosphere and it spreads over large areas surrounding the mine. The inhalation of coal dust leads to the occurrence of severe diseases such as black lung and lung cancer (Angulo-Bejarano et al., 2021). The coal dust that emanates from the disposal of coal fines on open dump sites contains heavy metals that may harm humans due to long-term exposure. Elements such as C, H, O, N, cd, Fe, Br, Cu, Ni, Na, Cr, S and Mg and their oxides.

Heavy metals are environmental pollutants that have high toxicity and longevity in the atmosphere. They accumulate in the human body by bioaccumulation and are carcinogenic. The heavy metals can mix with different environmental elements such as water, air and soil. Other organisms are exposed to heavy metals via the food chain where bioaccumulation and biomagnification occur. Chromium is highly carcinogenic and lead poisoning may cause intellectual abnormalities in children (Hou et al., 2013) (Mitra et al., 2022). Cadmium poisoning in humans may occur through the ingestion of food, air or water rich in the metal. Exposure to cadmium may result in damage to the liver, kidneys, skeletal system and cardiovascular system (Genchi et al., 2020). The inhalation of air that is contaminated with nickel may cause allergies, nasal and lung cancer, and kidney and vascular diseases. (Genchi et al., 2020). Figure 2.4 clearly expresses the mechanism of heavy metal toxicity in humans.

The coal dust that is dispersed by wind may settle on water bodies leading to water pollution. The heavy metals may be ingestion by humans and animals through the drinking of polluted water. The effects of the ingestion of heavy metals have been articulated using Figure 2.4. The deposition of coal dust on the water bodies may also negatively impact the aquatic ecosystem. Water pollution that emanates from coal dust settling in water bodies leads to a reduction in fertilization, larval settling, growth and the survival of corals and fish (Benitez-Polo & Velasco, 2020). The aquatic life in Deka River which feeds into Zambezi River has been affected by the coal dust which has led to death and reduction of aquatic life in the river. The valorization of coal fines to produce marketable goods may be one of the major solutions to curb the challenges of air pollution in Hwange Zimbabwe.

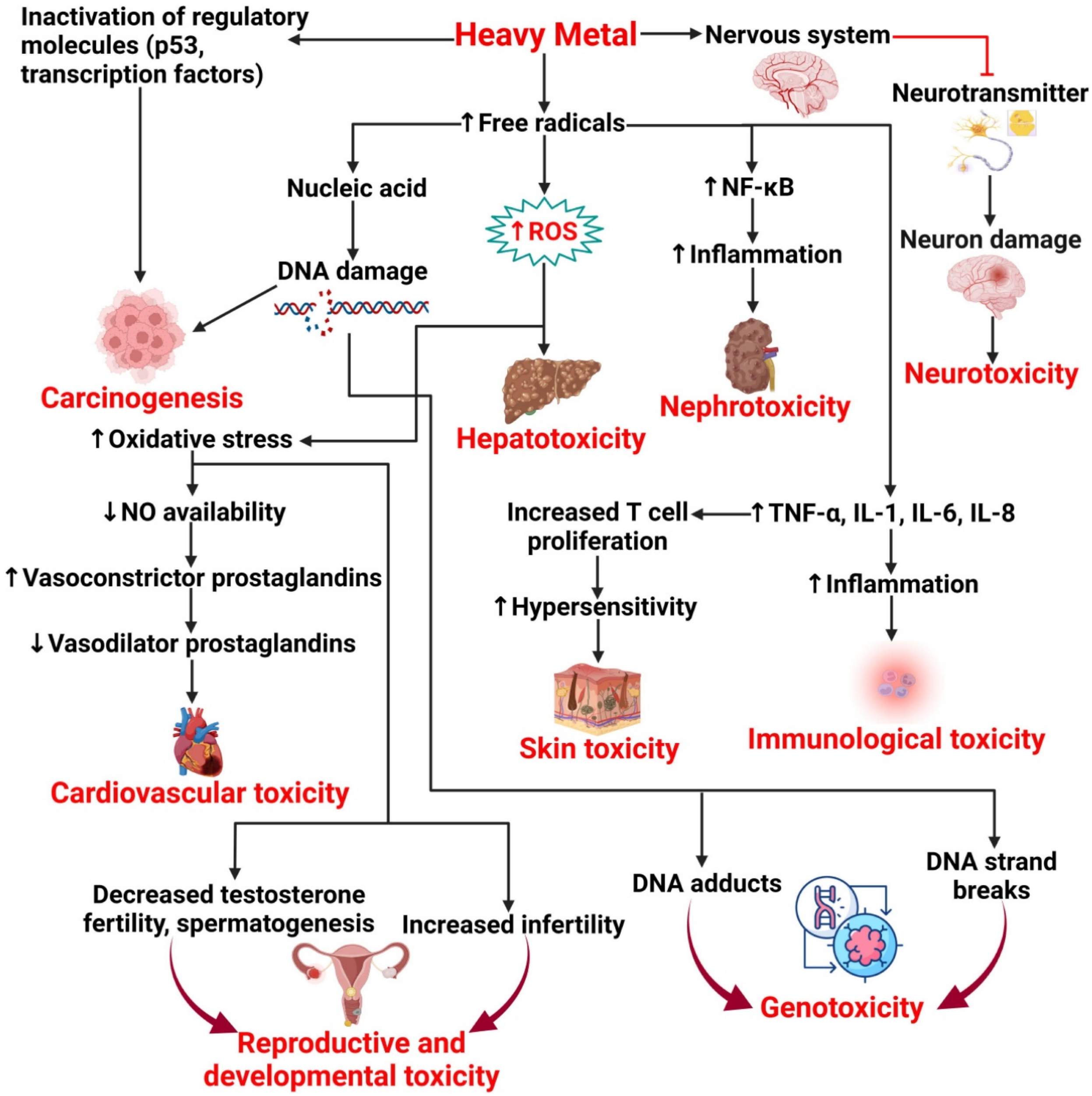


Fig 2.5. The Mechanism of Heavy Metal Toxicity in Humans (Harischandra et al., 2919)

Coal particles may also settle on the soil leading to soil pollution. The heavy metals that would have been deposited may be absorbed by plants and crops, which inhibits their growth due to plant tissue contamination (Rouhani et al., 2023). The heavy metals that would have been absorbed by the plants will eventually affect humans and other living organisms when they ingest the plants. This shows how detrimental the effects of coal dust from coal fines dump sites are. There is a need for proper waste management strategies which reduce the movement of coal dust over large areas which in turn reduces the occurrence of heavy metals in the environment in water, air and soil.

Acid mine drainage may also occur due to the disposal of coal fines on open dump sites. This occurs when sulphide-bearing minerals are exposed to air in the presence of adequate moisture in a microbial environment leading to them becoming oxidized thereby producing acidic conditions (Johnson & Hallberg, 2003)(Kotelo, 2013). The generation of acid from coal fines is dependent on the distribution of acid forming minerals in the coal fines. Therefore, the sulfur that may be present in the coal fines should be analyzed to determine the potential of the coal fines to produce acid (Kotelo, 2013). Generally, coal fines have high sulfur content which shows the high potential that they have for acid mine drainage. The effects of acid mine drainage have been evidenced in Deka River which has been crippled by acid mine drainage. This has led to the death of aquatic life in the river as well as the animals which drink water from the river.

Fire hazard is also a major concern in areas where coal fines are dumped. The spontaneous combustion occurs due to the natural low-temperature oxidation process which will be accompanied by heat generation (Różański, 2018). The fires that occur on coal fines may not be visible to non-experts which increases the risk of fire accidents in the general community as people may fall into the fire without realizing it. This has been evidenced at Hwange where several accidents have occurred due to the spontaneous fires which have crippled some people (Mlevu, 2019). An 8-year-old girl succumbed to the burns she got when she fell waist-deep into a Firehole at an old dump site that is located in Makiwa Village in Hwange. The fires also lead to air pollution as emissions of SOx, COx and NOx happens which affects human health and other living organisms in the area. Diseases such as asthma, pneumoconiosis and lung cancer may occur due to the inhalation of polluted air from the combustion of coal fines (Munawer, 2018).

The severe adverse effects of coal fines on the environment are evidenced by the ecological effects that result from the presence of coal fines on the environment. To alleviate the negative impacts of coal fines, integrated coal waste management should be incorporated into the coal mining production processes. This will assist in the management of coal fines from production to disposal.

2.4 Economic Impacts of Coal Fines

The realization of the economic gains that may be gained from the reduction in coal fines generation as well as the utilization of coal fines to produce marketable goods is an important factor that should be considered in decision making regarding coal fines. the competing social, economic and environmental interests are optimized through the beneficiation of the coal fines to produce high value marketable goods (Muzenda, 2014)

The generation of coal fines may lead to the blockage of the tail end of conveyors, which leads to production losses as operations are forced to stop. Morupule Coal Mine in Botswana faces the challenge of conveyor belt blockage and it was noted as the major cause of delay compared to any other conveyor belt problem. The cumulative delay that occurs due to the blockages is 77.57 hours every month, which is approximately 3.37 hours/shift. It was also pointed out that the delays that occur due to the conveyor belt blockages lead to a production loss of about 575 tonnes per shift as the average coal production at Morupule Coal Mine amounts to 4 100 tonnes per shift (Saubi et al., 2023). The economic losses that occur at Morupule coal Mine are a clear indication of the need for improved efficiency in coal mining processes to reduce coal fines generation to limit the occurrence of production losses.

A cleaner production assessment was done for the coal fines that are generated in South Africa to determine the economic, environmental and technical feasibility of the utilization of coal fines to produce value-added products. It was noted that the production of coal fines and the occurrence of coarser coal on the coal fines dump site could be reduced at a lower cost by optimizing the crusher performance. The coal fines may also be economically upgraded, recovered or sold which may be lucrative for the coal mining industry. However, careful considerations should be made when determining the method for beneficiation as the different types and quality of coal fines may require different cleaner production options (Reddick et al., 2007). The beneficiation and utilization of coal fines offer a realistic approach towards the management of coal fines with both economic and environmental benefits.

2.5 Cleaner Production

Cleaner production aims to reduce the negative effects of production on the environment and operating costs. Process-integrated methods are put in place as cleaner production is a conceptual and procedural approach to production which demands that all phases within the life cycle of a process or product be addressed with the objective of prevention and minimization of the short and long-term risks to humans and the environment (de Oliveira Santos et al., 2020). Cleaner production conserves raw materials and energy in the production process. It also focuses on removing toxic raw materials and the reduction of the amount and toxicity of waste material (Aziz et al., 2011). Cleaner production has been internationally implemented as it is an integral component of international conventions such as the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) (Kusena et al., 2014).

Fig 5 clearly shows the elements which industries can look into as part of cleaner production which increases their efficiency whilst protecting the environment. These may be targeted as areas for improvement within the production processes in industries. The production of useful by-products from coal fines which are regarded as waste from coal mining and utilization can be done as part of the cleaner production mechanism for the coal-producing industries.

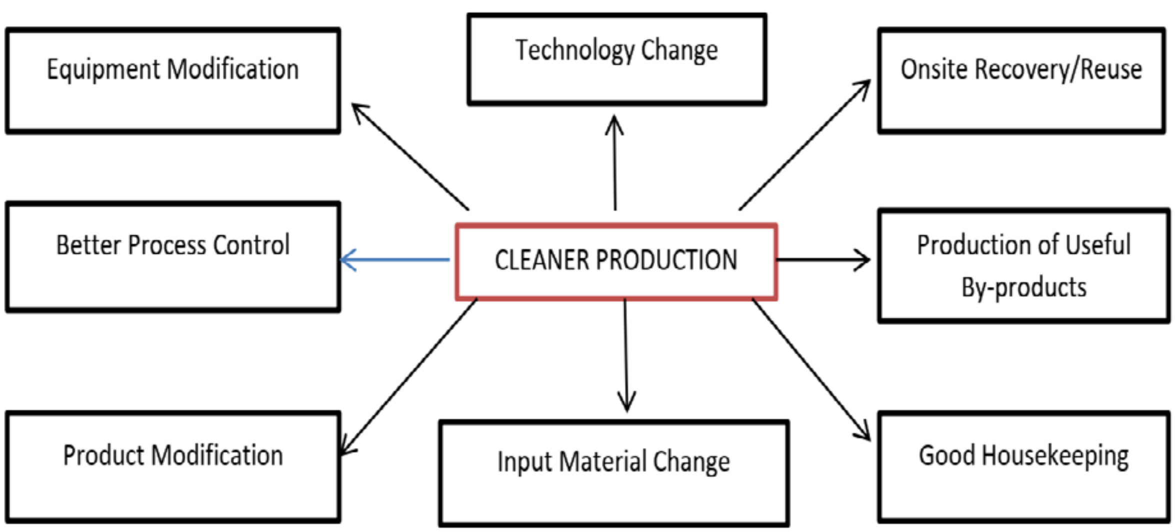


Fig 2.6. The Strategic Model of Cleaner Production

The elements of cleaner production are clearly explained (Nilsson et al., 2007)

Equipment Modification – modify the existing equipment to improve efficiency and reduce waste and emissions generation. This may be achieved through improved equipment layout and increased automation.

Onsite recovery/ reuse – focuses on the reuse of waste materials within the same production process or for other uses within the same organization.

Technology change – the use of newer technology to minimize waste production, and emissions generation and improve efficiency.

Product modification – the characteristics of the product are modified to minimize the environmental impacts of the product during and after its use. The environmental impacts of its production may also be modified. Product modification comes through eco-design, product life extension and environmentally friendly packaging.

Input material change – focuses on changing the input materials of the production process by replacing toxic materials with less toxic or non-toxic materials, using renewable materials for production processes and material purification.

Good housekeeping – may be achieved through prevention of leaks and spills and enforcement of the existing operation instructions. An efficient production plan and a well-planned maintenance program for all equipment and facilities may reduce waste generation by up to 50%.

Better process control – focuses on modification of operational procedures such as pH, temperature and pressure and equipment instructions in order to run the process more efficiently with lower waste and emission generation rates.

Production of useful by-products – waste is transformed to produce useful by-products that may be considered as input material for other companies or other business sectors.

Fig 2.7 clearly illustrates how cleaner production fit in the integrated waste management system. This clearly shows how they are interconnected to ensure environmental sustainability as cleaner production requires integrated waste management for its goals to be met and integrated waste management is achieved through cleaner production.

Fig 2.7 An Integrated Approach to Cleaner Production (Gavrilescu, 2003)

Cleaner production strategies were implemented in Indonesia to improve the environmental performance of the small-scale cracker production industry. It was noted that good housekeeping alternatives such as improving worker thoroughness and the scrapping of production tools before the washing process reduced the amount of water that was required for washing by 22.04% (Khuriyati & Denok Kumalasari, 2014). This shows that cleaner production may be implemented in any business despite its size such that the initiatives will be part of the production processed as the business grows.

2.5.1 Advantages of Cleaner Production

- Implementing cleaner production strategies reduces long-term liabilities that companies may incur due to pollution or waste disposal at a given site over a long period. Carbon dioxide emissions were reduced by 52 500 tonnes in Eastern Europe due to the implementation of cleaner production. Sulfur dioxide emissions were also reduced by 1 916 tonnes (Johnson & Hallberg, 2003).

- Cleaner production leads to increased profitability due to reduced production costs, enhanced productivity, increased product yields and the efficient use of energy and raw materials. Studies that were carried out in Asia showed that the implementation of cleaner production resulted in a 50 – 70% decrease in emissions, wastewater and solid waste generation. This occurred over a short payback period of less than a year to 3 years maximum (Gunarathne & Sankalpani, 2021).
- The consumer risk is reduced due to the implementation of cleaner production.
- Cleaner production also reduces the risk of environmental accidents as thorough assessment of machinery and production processes are done to reduce chances of high waste production and accidents. In Nairobi, Kenya it was noted that the implementation of cleaner production improved the company’s operations through efficient resource use and improved environmental performance which is vital in sustainable development (Kusena et al., 2014).
- Cleaner production may also be supported by local communities, employees and customers and it promotes good health practices which is an advantage to them.

2.5.2 Disadvantages of Cleaner Production

The major disadvantage of cleaner production is that most of the programs that relate to cleaner production are donor-funded which makes them short lived as the implementation stops once the funding ends. Therefore, cleaner production initiatives should be locally initiated and implemented to ensure their feasibility and ability to be implemented long term (Kusena et al., 2014).

2.5.3 Cleaner Production in the Mining Industry

Cleaner production in the mining industry may be classified into managerial changes, policy changes and physical changes whereby managerial changes are adopted by the top management and policy and physical changes are adopted in the operations through process and equipment modification (Satish G & Nagesha, 2018). The mining industry plays a major role in African countries such as South Africa, Botswana and Zimbabwe. The survival of the industry largely depends on the effectiveness of the measures that are taken to deal with the environmental impacts that are associated with the mining sector. This can only be fully achieved through cleaner production (Trusler & Mzoboshe, 2011).

Coal mining in South Africa is responsible for regional and local environmental pollution. This has resulted in more environmental legislation being put in place and more public concerns which has resulted in companies doing rehabilitation projects which are costly for them. Cleaner production is the solution for the pollution challenges in the coal mining industry in South Africa as it will provide a cost effective approach to minimize its environmental footprint and meet its current and future legislative requirements (Matyanga, 2012)(Trusler & Mzoboshe, 2011)

The disposal of slurry (water and coal fines) was noted at the collieries that were assessed for cleaner production in South Africa. The cleaner production options that were identified after the assessment were (Trusler & Mzoboshe, 2011)

- Good housekeeping by increasing the crusher top size to reduce the quantities of coal fines that are generated and classifying cyclones to perform sharper and more precise operations;
- Technology change and internal recycling through the installation of a flocculent make-up system;
- Technology change and product change through coal fines beneficiation; and
- Product change and resource use optimization through solar drying and selling of the unwashed existing coal fines to local power stations.

Cleaner production is a viable solution to the environmental challenges that are being faced by the mining industry. It allows for sustainable mining in a manner that balances the economic, environmental and social consideration which makes it a perfect solution for the mining sector. However, thorough assessment should be done before proposing any cleaner production options to ensure that they are the right solution for the problem at hand.

The adoption of cleaner production is the solution that should be adopted to curb waste generation at Hwange Colliery company from the production process until disposal. Coal fines are a resource that may be exploited for energy generation. However, careful considerations should be done to ensure the cleaner production solutions are long term and cost effective so that they can be easily adopted by the decision makers.

2.6 Methods of Coal Fines Utilization

The challenges that emanate from the open dumping of coal fines are major environmental and social concerns which require attention. Therefore, the utilization of coal fines to produce marketable value-added products is part of the solution that removes the dumped coal fines from the environment. The coal fines may be utilized for energy extraction or any other purposes through options stated below and these have been thoroughly reviewed in the systematic review paper that is attached as appendix A. The methods that may be used for coal fines utilization are;

- Coal water slurry
- Fluidized bed technology
- Briquetting
- Pelletization
- Brickmaking

2.6.1 Coal Fines in the Agriculture Sector

Apart from the above-mentioned methods for coal fines utilization, it has been noted that coal fines may also be used in the agriculture sector to rehabilitate the topsoil in mining areas which have a thin solum. The topsoil in the mining areas is altered due to the mining activities which leaves a thin solum which cannot sustain plant growth due to low fertility levels, organic matter content and a damaged soil structure (Subowo, 2011). It is necessary to alter the topsoil through the addition of various materials such as mining waste such as coal fines and household waste so that a planting medium can be met (Sriningsih et al., 2022). The use of coal fines for post-mining reclamation may recover valuable resources and prevent environmental issues that may arise from both coal fines dumping and leaving the mining area bare (Saubi et al., 2023).

Filho et al, (2020) carried out a study on the utilization of fine coal on topsoil in South Africa at a ratio of 1:1 with 2% malt waste and 3% compost. This combination provided a good growing medium for tef cereals. Coal fines were also combined with steel slag at a ratio of 19:1 with 2% rice husks and 3% mud sludge in Brazil and a good growing medium for oats was produced (Firpo, 2020). A study was also done in Indonesia to examine the application of fine coal and fly ash-bottom ash as a substitution for topsoil and its effects on the growth of jabon *(Anthocephalus*

Chinensis). The study was conducted under varying coal fines ratios of 0, 10, 20 and 50% and it was noted that up to 50% of coal fines could be used as topsoil substitution. The combination of fly ash-bottom ash of 1000g/15kg of growing media and 50% coal fines were found to be the best treatment for the growth of jabon. (Sriningish

2.6.2 Methane and Polymers Production

Coal fines may also be used in methane and polymer production through the process of solubilization. Coal solubilization is a process by which coal is converted into a solution of macromolecules by microorganisms and enzymes. These can then be converted to various products such as methane and polymers. Lignite coals with low carbon content are more susceptible to solubilization due to their high moisture content, softness and low abrasion index. However, certain microorganisms can also solubilize coal fines with high carbon content (Muzenda, 2014).

The solubilization of coal fines to produce methane and polymers was noted to be a part of the solution which utilizes coal fines and solves the environmental and social challenges that they pose (Reddick et al., 2007). The technology has not been commercially used in South Africa but research is being done to optimize and commercialize methane and polymer production (Muzenda, 2014).

A study was done to produce polymers from raw coal gasification fine slag, which solves secondary pollution issues and provides substantial economic and environmental benefits. The mechanically activated coal gasification fine slag was used as a filter to fill styrene-butadiene rubber-based composites which enables the utilization of coal based solid waste and preparation of polymer composites with an excellent performance (Feng et al., 2024).

2.7 Cost Benefit Analysis

The management of coal fines through beneficiation and value addition requires a balanced strategy that meets both the environmental and economic demands (Moosa, 2016). Therefore, thorough analysis should be done to ensure the costs that should be met and the projected income and profits are known before undertaking the project. This may be done using a cost benefit analysis.

Cost benefit analysis is the process whereby the projected and estimated costs and benefits of a project are given to determine its feasibility from a business perspective. It is an analytical tool that may be used for the assessment of benefits and costs systematically to determine the soundness and viability of a project. It is also an important aspect that aids in decision or policy making hence it focuses on determining the feasibility of a given project (Moosa, 2016).

When conducting a cost benefit analysis, it is important to note how future benefits will be discounted in relation to current costs. This is an important aspect as the choice of the discount rate has an impact on the outcome of the analysis (Koopmans & Mouter, 2020). The cost benefit analysis should consider opportunity costs that consider the costs of the lost opportunities due to the diversion of resources to the current projected use (Havard Business School, 2024). The cost benefit analysis can be done using three elements which are the payback period, net present value and the internal rate of return.

2.7.1 Payback Period

The payback period is the measure of the time that it takes for an investor to recover their initial investment from a project (Dai et al., 2022). It may also be defined as the cash inflow from an investment over time to recover the initial investment (Havard Business School, 2024). The payback period may be used as an indicator of the risk that is inherent in a project as it considers the initial inflows and ignores the cashflows after the point at which the initial investment is recovered. The payback period has been criticized for its inability to account for the project's flows in a present-valued context (Boardman et al., 1982).

2.7.2 Net Present Value

The net present value is the current value of the project's net benefits. The future values are discounted using a given discount rate and if a project has a net present value that is greater than zero, it will show good potential if implemented (Accounting Tools, 2023). The present value of the future cash flow of a project may be determined using the net present value. This makes it easier for decision makers to analyze (Dai et al., 2022) the potential of a project as the monetary value of the project will be of the same time frame.

2.7.3 Internal Rate of Return

The internal rate of return is the maximum interest that could be paid for the project resources while enough money is left to cover investment and operating costs and break even. Therefore, the internal rate of return is the discount rate for which the present value of total benefits is equivalent to the present value of total costs (accounting). For the project to be worthy of an investment, the rate of return must be higher than the maximum opportunity cost of the capital (discount rate).

2.7.4 Advantages of Cost Benefit Analysis

The advantages that are associated with using a cost benefit analysis in a project are;

- It provides a starting point for the evaluation of the monetary value of a project.
- It allows for comparisons to be made between projects as the investments are evaluated using the same methods and the projects with less or no profits are excluded from implementation (Accounting Tools, 2023)(Moosa, 2016).
- Cost benefit analysis provides a straight forward report that simplifies decision making.

2.7.5 Disadvantages of cost benefit analysis

The disadvantages that are associated with using a cost benefit analysis are;

- The results of a cost benefit analysis are sensitive to the choice of a discount rate as the chosen rate affects the entire result of a complex cost benefit analysis which makes the use of the technique in project evaluation controversial.
- It accounts for the known costs and benefits currently which may change. The future costs and benefits cannot be conceived or measured which greatly affects the outcomes of the cost benefit analysis (Koopmans & Mouter, 2020; Moosa, 2016).

The economic impacts of coal fines may be accounted for using the cost benefit analysis. The costs that came with coal fines generation was accounted for at Morupule Coal Mine in Botswana which faced challenges of conveyor belt blockages due to coal fines. It was estimated that approximately BWP 418 284.57 which is equivalent to USD30 975.73 is lost every shift due to conveyor belt blockage (Saubi et al., 2023). Therefore, the ways that may be used to reduce coal fines generation and reduce losses are considered benefits and very useful for the industry as the status quo has both monetary and environmental disadvantages.

Billions of tonnes of coal fines are discarded due to intensive coal mining globally (Oluremi & Elsaigh, 2023). The realization of the economic value that the coal fines have may be done through beneficiation and value addition to produce marketable goods which is a greater benefit as compared to open dumping on coal fine piles which leads to environmental degradation and reduction of land value.

The ecological impacts that emanate from the dumping of coal fines may be curbed by the utilization of the coal fines which leads to them being removed from the environment. Careful considerations should be done to ensure a balance between the environmental benefits that results from reduction in coal fines generation and the utilization of the coal fines that would have been generated with the economic benefits that may be realized from the utilization of the coal fines. The balance between the economic and environmental aspects relating to coal fines is of great importance as it will determine if the concept of coal fines utilization will be accepted by decision makers and this will be easier if profits can result from coal fines utilization.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The chapter clearly outlines the methods that were used to obtain the results of the study. The research focused on the qualitative analysis of coal fines and their ecological impacts to determine their feasibility for beneficiation and utilization as well as their effects on the environment. The most suitable valorization method for the coal fines at Hwange Colliery Company was also determined.

3.2 Coal fines sample size for the study

The researcher used 9 samples from 3 different fine coal piles for the study. According to EPA (2009), the sampling process involves the collection of primary increments which are the smaller sample portions that are collected at varying points on the coal pile where samples are to be collected. These smaller proportions were then homogenized to ensure that the sample was a better representative of the bulk coal fines pile material. The researcher followed the ASTM D 346-75 procedure for coal sample collection and preparation for analysis. The location and sample names for the samples that were collected for analysis are shown in Table 4.1. The samples were put in zip bags for transportation and analysis at the laboratory.

Table 3.1. Basic Information of Coal Fines Samples

Sample number	**Sample name**	**Collection location**
1	Site A sample 1	Coal fines dump site 1 upper section
2	Site A sample 2	Coal fines dump site 1 middle section
3	Site A sample 3	Coal fines dump site 1 lower section
4	Site B sample 1	Coal fines dump site 2 upper section
5	Site B sample 2	Coal fines dump site 2 middle section
6	Site B sample 3	Coal fines dump site 2 lower section
7	Site C sample 1	Coal fines dump site 3 upper section
8	Site C sample 2	Coal fines dump site 3 middle section
9	Site C sample 3	Coal fines dump site 3 lower section

3.3 Experimental Analysis of The Coal Fines

The coal fines quality analysis was done through particle size distribution analysis, proximate analysis and elemental analysis. The particle size distribution was determined through sieve analysis, adhering to the ASTM standard testing methods.

3.3.1 Particle Size Distribution of the Coal Fines

The particle size distribution of the coal fines at Hwange Colliery Company was done through sieve analysis. 500 g of the sample was weighed, and put on a 3mm sieve. The portion of the coal fines for each sieving was limited to ensure that the coal fines were in direct contact with the base of the sieve at the completion of sieving for each sieve. The sample was sieved with a gentle rotary motion until most of the finer coal fines had passed through the sieve and the sample was fairly free of finer particles. The sample was sieved with successive sieves until the smallest sieve was used. The sieve sizes that were used for this study were 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 2.0 and 3.0mm. The samples that were sieved separately were combined with the same sieve size and weighed. The weight percentage of each sieve size was recorded and presented in the results section.

3.3.2 Proximate Analysis of the Coal Fines

The moisture content for the coal fines samples was determined by weighing 6 $\pm$ 1 grams of samples and heating them at 105 degrees Celsius until a constant weight was reached. The moisture content percentage was calculated by finding the difference in weight before and after drying the sample. The moisture percentage was calculated using the formula below:

$$\%\text{ moisture content} = \frac{\text{Weight of wet sample} - \text{weight of dry sample}}{\text{Weight of wet sample}} \times 100$$

Determination of the volatile matter content was done by igniting the coal fines sample at 850 degrees Celsius. The sample that was dried in the process of determination of the moisture content of the sample was closed with a lid and weighed. The initial mass was recorded and the sample was put in a muffle furnace at 850 degrees Celsius for 8 minutes. After the heating process, the sample was left to cool for 15 minutes and the final weight was recorded. The volatile matter percentage content was calculated using the formula below:

$$\% \text{ volatile matter} = \frac{\text{initial mass of sample} - \text{final mass of sample}}{\text{Initial mass of sample}} \times 100$$

The ash content was determined by heating the remaining coal fine sample from volatile matter determination at 750 degrees Celsius for 1 hour. The sample was put in the muffle furnace for one hour. The sample was left to cool for 15 minutes and then the final mass was also determined. The percentage ash content was calculated using the formula below:

$$\% \text{ ash content} = \frac{\text{initial mass of sample} - \text{final mass of sample}}{\text{Initial mass of sample}} \times 100$$

The fixed carbon content was calculated by determining the percentage that is left after removing the percentage of moisture content, volatile matter and ash content. This was calculated using the formula below:

% fixed carbon = 100 – (% moisture content + % volatile matter + % ash content)

3.3.3 Determination of higher heating values

The Higher Heating Value (HHV) was determined using Mendeleev's equation as outlined in Eq. 1(Mendeleev, 1897).

$$\text{HHV} = 0.339\text{C} + 1.256\text{H} - 0.109\text{O} + 0.109\text{S} \qquad (1)$$

An average HHV was determined for the coal fines at Hwange Colliery Company and presented in the results.

3.3.4 Elemental Analysis of Coal Fines

The elemental analysis was conducted following the x-ray fluorescence method. The initial sample was crushed to achieve a particle size below 50 micrometers. Subsequently, the finely ground sample was pressed into pellets of around 3 mm in diameter. These pellets were then subjected to X-ray fluorescence analysis for comprehensive elemental characterization.

3.4 Water Quality Analysis

3.4.1 Water samples collection

The purpose of this analysis was to assess the potential impacts of coal fines on the nearby water bodies. Water samples were collected from the surrounding groundwater bodies at varying distances from the coal fine piles. Sealable polyethylene bottles were used to collect the water samples for analysis in the lab. The water samples were collected from Baobab Hotel, Barzem and St Patricks Pre-School. Three water samples were collected from each site for analysis. The 2 rivers that were targeted for water sampling were dry when the samples were collected therefore river sediments were collected for analysis. The water quality parameters that were used for this study were selected based on the general properties of coal fines which posed a possibility that the coal fines might be affecting the water quality. Table 4.2 presents the parameters that were used for water quality analysis and the method of analysis for each parameter. The methods were conducted according to the ASTM standard methods for examining water and wastewater (Baird & Bridgewater, 2017).

Table 3.2. A Summary of Parameters and Standard Test Methods for Water Quality Testing

Parameter	**Description**	**Test Method**
*Electrical conductivity	An electrical conductivity meter was inserted in the water samples and the results were recorded.	ASTM D1125-23
*pH	A pH meter was inserted in a water sample and the results were recorded.	ASTM D1293-18
*Turbidity	A turbidity meter was inserted in a water sample and the results were recorded.	ASTM D6698-14
Sulfates	Spectrophotometric method	ASTM D516-16
Nitrates	Ultraviolet spectrophotometric method	ASTM D7781-14
Chlorides	Titration with standard silver nitrate and potassium chromate as indicator	ASTM D7781-14

Iron	Atomic absorption spectrophotometry	ASTM D1068-15
Calcium	Atomic absorption spectrophotometry	ASTM D511-14
Copper	Atomic absorption spectrophotometry	ASTM D1688-17
Nickel	Atomic absorption spectrophotometry	ASTM D1886-14

* on site analysis

3.5 Soil quality testing

3.5.1 Soil sample collection

Three sampling areas were chosen for collection of soil samples with increasing distance from the fine coal piles. Samples were collected at 5cm depth for analysis at the dump site, 750m, 1km and 1.5km from the dump site. Soil sediments were also collected from rivers to determine if the water had any pollutants before it dried up. Lukosi River and Mpongola River were used for the study. Samples that were to be tested in the lab were carried using sealable polythene bags to ensure that no further reaction occurred before the tests were conducted.

3.5.2 pH

2g of soil was mixed with 20 ml of deionized water. The solution was stirred for 10 seconds and let to stand for 15 minutes. The pH of the solution was used to determine the pH of the soil sample (Adamchuk & Mulliken, 2005).

3.5.3 Soil organic carbon

A dried and weighed soil sample was placed in a muffle furnace at 450^oC until constant weight was reached. The reduction in weight determines the quantity of organic matter that is present in the soil sample. The weight reduction represented the quantity of organic matter that is present in the soil sample.

3.5.4 Heavy metals (arsenic, copper, lead, nickel, manganese)

Heavy metal testing in soil was done using the atomic absorption spectrometry method. The samples were treated with nitric acid and hydrogen peroxide as they were being prepared for atomic absorption spectrometry and the results were recorded.

3.6 Assessment of cleaner production options for the coal fines

The results from objectives 1 and 2 were used to generate cleaner production options for the coal fines. The methods for the utilization of the coal fines were thoroughly discussed in the literature review. These options were subjected to a feasibility assessment to determine the most feasible intervention which is practical for implementation at Hwange Colliery Company. The feasibility assessment was done focusing on 3 aspects which are technical feasibility, economic feasibility and environmental feasibility. Cost benefit analysis was done for the cleaner production options that were left after the feasibility analysis was done. This was to determine which option would be more favorable and could be the first to be implemented which shows the potential of having more benefits than costs. 2 mutually exclusive options which appeared to be more viable for the coal fines were opted for and recommended to Hwange Colliery Company.

3.7 Cost Benefit Analysis for the cleaner production options for the coal fines

A cost benefit analysis was done to determine the most economically viable option for the coal fines at Hwange Colliery Company. Considering that the status quo for the coal fines which is open dumping has no benefits for the community and environment, a cost benefit analysis for the options that passed the feasibility analysis was done. The analysis determined the net present value, initial rate of return and pay pack period for the cleaner production options that were chosen.

All the construction costs, operation costs and maintenance costs for the cleaner production options were determined the total income was calculated using information from the previous objectives which assisted in giving an estimation of the product quantities that may be produced using the coal fines that are being produced at Hwange Colliery Company.

The researcher assumed that the quantity of products generated was the same for each given period which means the project has the same income for a given time period. The payback period which is the time taken to return the initial capital from the cash flows. (Witt, 2013). The payback period was determined using the formula below.

$$\text{Payback period} = \frac{\text{initial capital investments}}{\text{Cash flow}}$$

The internal rate of return is the rate at which the net present value of a project is zero that is the interest rate which when calculated will give the project a net present value of zero (Watters and Hoare, 2018). It was calculated using the formula below.

IRR = A + [(a / a + b)] [(B - A)]

A is the lower discount rate that produces a positive NPV. a is the NPV resulting from the discount rate of A%. B is the higher discount rate producing a negative NPV and b is the NPV resulting from the discount rate of B%.

Net present value is the growth of a project that is determined by both cash inflows and outflows but calculated to present values (Juhasz, 2011). The initial rate of return that was obtained from the above method was used as the discount rate. The net present value is calculated as shown by the formula below.

$$0 = CF_0 + \frac{CF_1}{(1+IRR)} + \frac{CF_2}{(1+IRR)^2} + \frac{CF_3}{(1+IRR)^3} + \ldots + \frac{CF_n}{(1+IRR)^n}$$

Or

$$0 = NPV = \sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n}$$

Where:
CF_0 = Initial Investment / Outlay
$CF_1, CF_2, CF_3 \ldots CF_n$ = Cash flows
n = Each Period
N = Holding Period
NPV = Net Present Value
IRR = Internal Rate of Return

After the calculations were done, the results were tabulated so as to give a clear comparison of the costs and benefits of cleaner production options for the coal fines and determine the most feasible option that can be recommended for Hwange Colliery Company.

3.8 Experimental Analysis of the Coal Fines Utilization Option for Hwange Colliery Company

The coal fines utilization option that was determined was experimentally assessed to determine its practical feasibility for the coal fines at Hwange Colliery Company. Organic and inorganic binders which are molasses and kaolin clay were used for the briquetting process. The compositions of the binder ratios that were used were;

- 90% coal fines: 10% molasses;
- 80% coal fines: 20% molasses;
- 90% coal fines: 10% kaolin clay;
- 80% coal fines: 20% kaolin clay;
- 90% coal fines: 5% molasses: 5% kaolin clay;
- 80% coal fines: 10% molasses: 10% kaolin clay;

a) Coal Fines b) Molasses c) Kaolin clay

3.9 Physical Strength Analysis of the Briquettes

The briquettes were analysed to determine their physical strength through the water resistance analysis and drop shutter test.

3.9.1 Water Resistance Test

The water resistance test was done by immersing a briquette in a container of water until it disintegrated. The time it took for the briquette to disintegrate was recorded.

3.9.2 Drop Shutter Test

The produced briquettes were dropped at a height of 2m onto a hard surface and the breakage was determined.

The coal fines- binder composition that produced briquettes with the highest strength was considered the optimum and reactivity analysis was done on them in comparison with the coal fines to determine if there would be any change in energy and combustion patterns that may be noted due to the addition of binders. Proximate and ultimate analysis was conducted for the optimum briquettes.

3.9.3 Thermogravimetric Analysis (TGA)

The TGA was performed up to 850^oC since it is the temperature where no further mass loss was obtained. This was determined through preliminary experiments that were conducted for the coal fines. The coal fines and the optimum briquette underwent TGA at three different heating rates which were 10 ^oC/min, 20 ^oC/min and 30 ^oC/min. The analysis was done using air at a gas flow rate of 10mL/min.

3.10 Design Brief for the Briquette Press Machine

3.10.1 Background

The production and disposal of coal fines on open dump sites at Hwange Colliery Company has posed major environmental problems for the Hwange Community. Air, water and soil pollution has occurred due to the coal fines disposal. People and animals are at great risk of fire accidents that may occur from the coal fines which tend to self-ignite. Briquetting of the coal fines to produce combustible fuel was proposed as the solution which incorporates the utilization of coal fines to produce value added marketable products.

3.10.2 Objectives

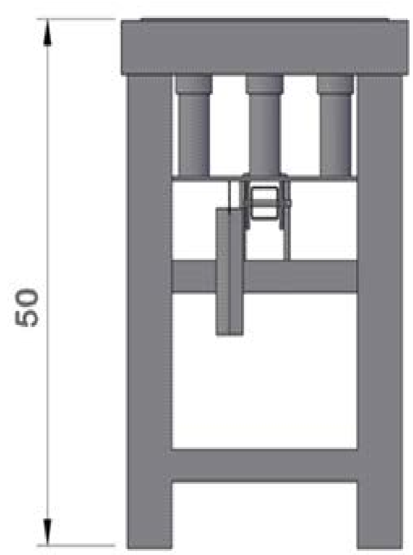
The objective of the design is to produce a simple manual briquette press machine that is easy to operate and produces briquettes for combustion purposes.

3.10.3 Expected Deliverables

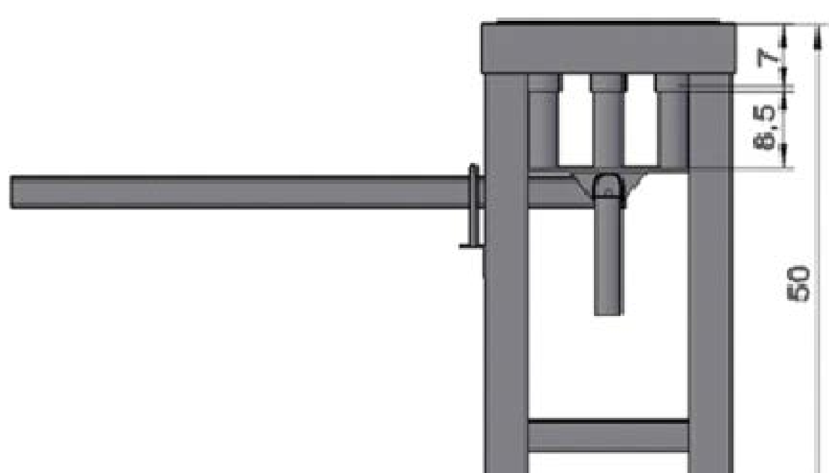
A manual briquette press machine that produces compacted cylindrical briquettes and has the potential for scaling up to develop a larger press machine for mass production.

3.10.4 The Briquette Press Machine Design

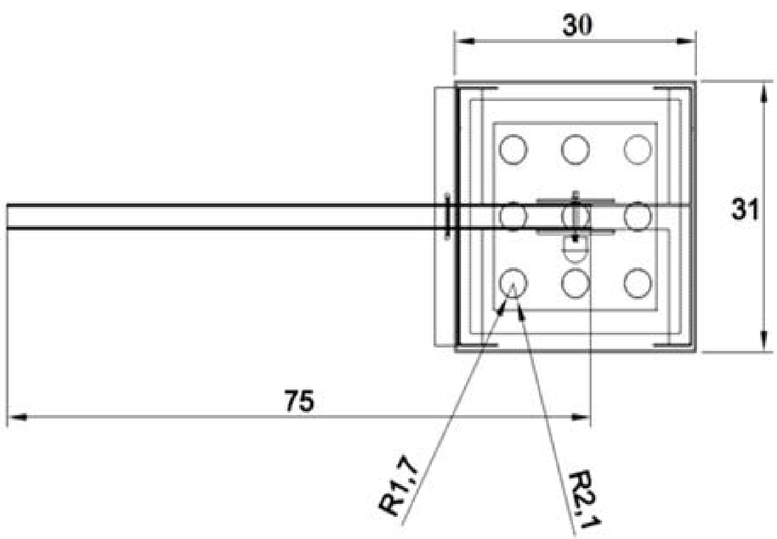
The machine should be constructed using heavy-duty steel that ensures stability and longevity. The machine should produce cylindrical briquettes. The machine must have a lever that is ergonomically designed to simplify the manual operation process. The machine features an adjustable base that allows for the production of various briquette sizes using the same machine which improves the market value of the briquettes as they may be produced according to customer specifications. Safety tests should be done to ensure that the machine will meet all safety standards for users. Figure 4.1 presents the design of the proposed briquette press machine.



a) Front view



b) Side view



c) Top View

Figure 4.1. The Briquette Press Machine Design

CHAPTER FOUR: RESULTS

4.1 Introduction

This chapter presents the results of the experiments and analysis that were carried out in the study. Results for the quality of the coal fines, potential environmental implications through water and soil quality analysis, feasibility assessment of the coal fines utilization options as well as the practical applicability of the coal fines utilization option are presented in this section.

4.2 Particle Size Distribution

Table 4.1. Sieve analysis of the coal fines at Hwange Colliery Company

Sample location	**sieve size (mm)**								SD
	0.2	**0.4**	**0.6**	**0.8**	**1.0**	**1.5**	**2.0**	**3.0**	
Site A (%)	8	5	12	15	19	18	12	11	1.39
Site B (%)	7	6	11	17	15	21	10	13	1.55
Site C (%)	3	5	12	14	15	19	10	15	0.97

Table 4.1 presents the sieve analysis results for coal fines collected from three different sites at Hwange Colliery Company. The table shows the percentage of coal fines passing through various sieve sizes ranging from 0.2 mm to 3.0 mm for each sample location (Site A, Site B, and Site C). The coal fines from Site A exhibited a relatively even distribution across the different sieve sizes. The highest percentage passing was observed at the 1.0 mm sieve size (19%), followed by the 1.5 mm sieve size (18%). The lowest percentage passing was at the 0.4 mm sieve size (5%). The standard deviation for Site A was 1.39, indicating moderate variability in the particle size distribution. The coal fines from Site B showed a slightly different distribution compared to Site A. The highest percentage passing was at the 1.5 mm sieve size (21%), followed by the 0.8 mm sieve size (17%). The lowest percentage passing was at the 0.2 mm sieve size (7%). The standard deviation for Site B was 1.55, suggesting slightly higher variability compared to Site A. The coal fines from Site C displayed a distinct distribution pattern. The highest percentage passing was at the 3.0 mm sieve size (15%) and the 1.5 mm sieve size (19%). The lowest percentage passing was at the 0.2 mm sieve size (3%). The standard deviation for Site C was 0.97, indicating the least

variability among the three sites. The p-value that was obtained from the ANOVA test was 0.924 which shows that there is no statistically significant difference in particle size distribution between the sites. The f-value was 0.079 which showed that the differences between the sites were minimal as compared to the differences within each site which supports the conclusion that the sites have generally similar particle size distributions.

Figure 4.1 shows the results of the particle size distribution of the coal fines from Xinzhi coal mine, Huozhou Coal Electricity group. It was noted that approximately 80% of the coal fines were smaller than 20 micrometres and less than 5% of the coal fines were larger than 30 micrometres. It was concluded that the coal fines were ultra-fine(X. Zhang et al., 2021).

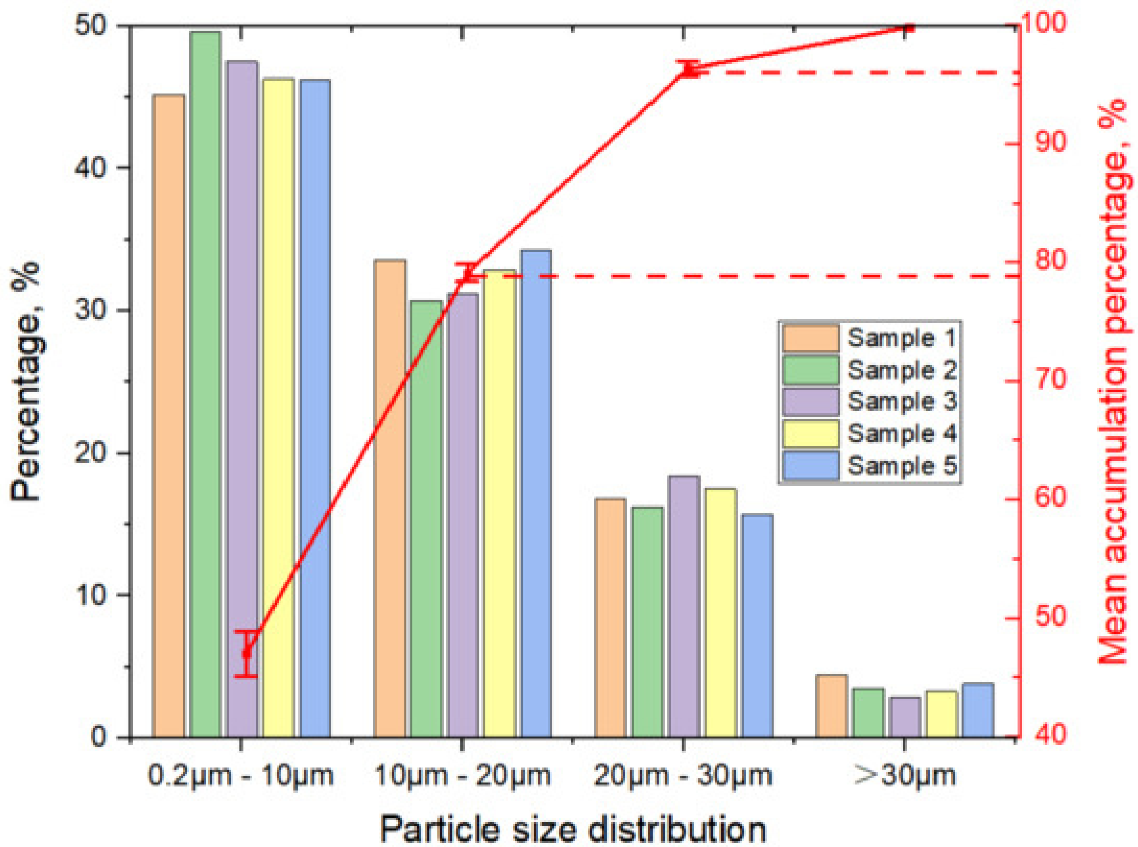


Figure 4.1. Particle size distribution of coal fines at Xinzhi coal mine

4.3 Proximate Analysis

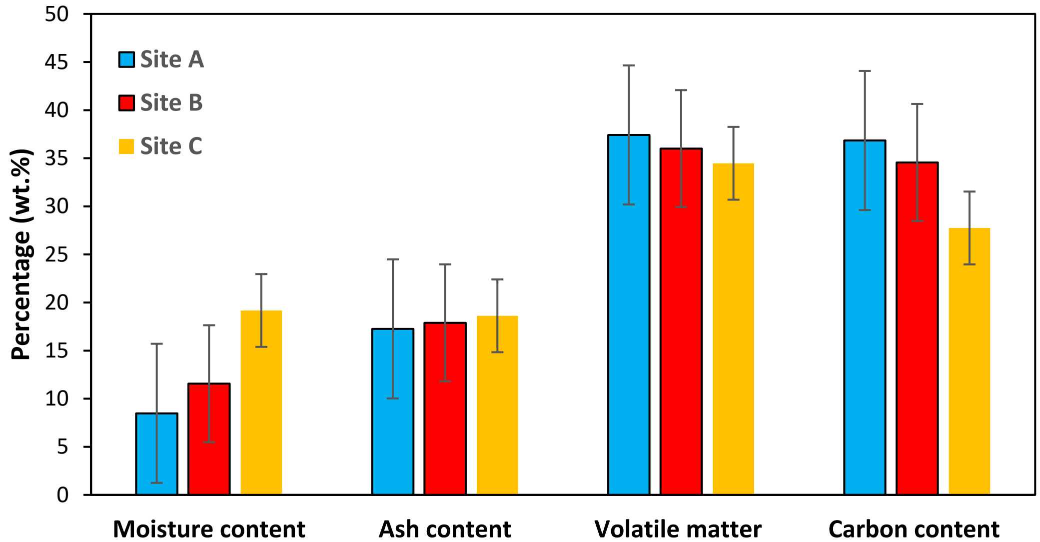


Figure 4.2. Results of Proximate Analysis of Coal Fines at Hwange Colliery Company

Figure 4.2 illustrates the composition of coal fines from three different sites (Site A, Site B, and Site C) at Hwange Colliery Company. Site C exhibits the highest moisture content among the three sites, while Site A has the lowest. In terms of ash content, Site B and Site C show similar levels, both slightly higher than Site A. The volatile matter content is fairly consistent across all three sites, with Site A being marginally higher. Carbon content is highest at Site A, followed by Site B, with Site C having the lowest carbon content. These findings highlight the variability in the composition of coal fines across the three sites. Specifically, Site A generally features higher carbon content and lower moisture content, whereas Site C has the highest moisture content and the lowest carbon content (Di et al., 2021).

4.4 Higher Heating Values for the Coal Fines

Figure 4.3 depicts the HHVs of coal fines from different sites within Hwange Colliery Company. The data reveals notable variations in HHV across the sampled sites. Site A exhibits the highest HHV at 22.72 MJ/kg, indicating a higher energy content per kilogram of coal fines compared to

Sites B and C. Site B follows with an HHV of 21.28 MJ/kg, showing a slightly lower energy content than Site A but still higher than Site C. Site C, with an HHV of 21.05 MJ/kg, demonstrates the lowest energy content among the sampled sites.

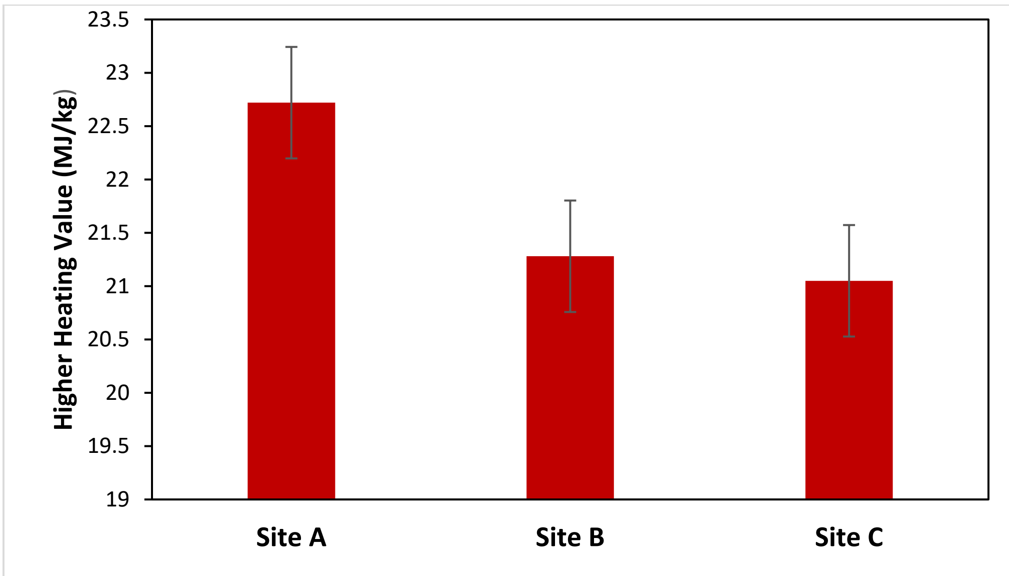
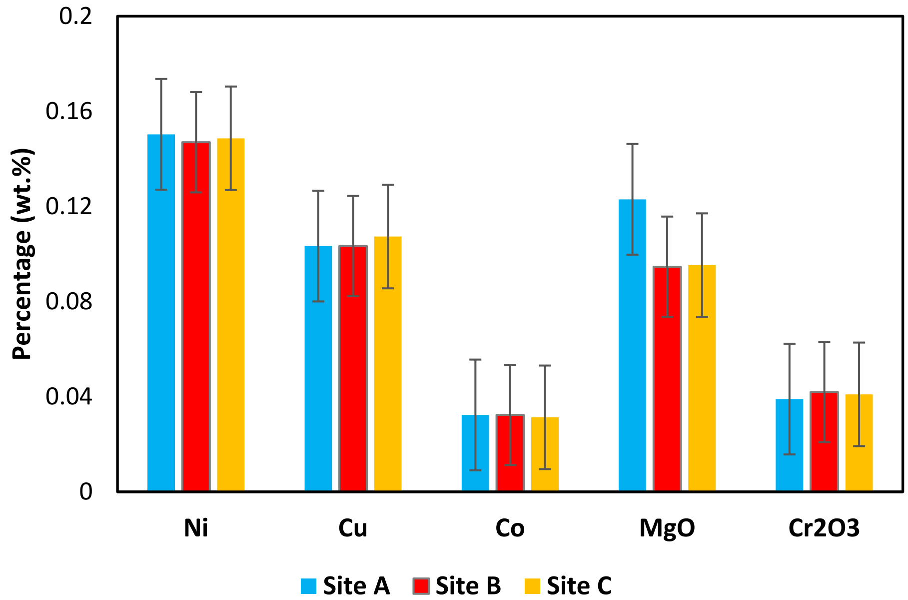
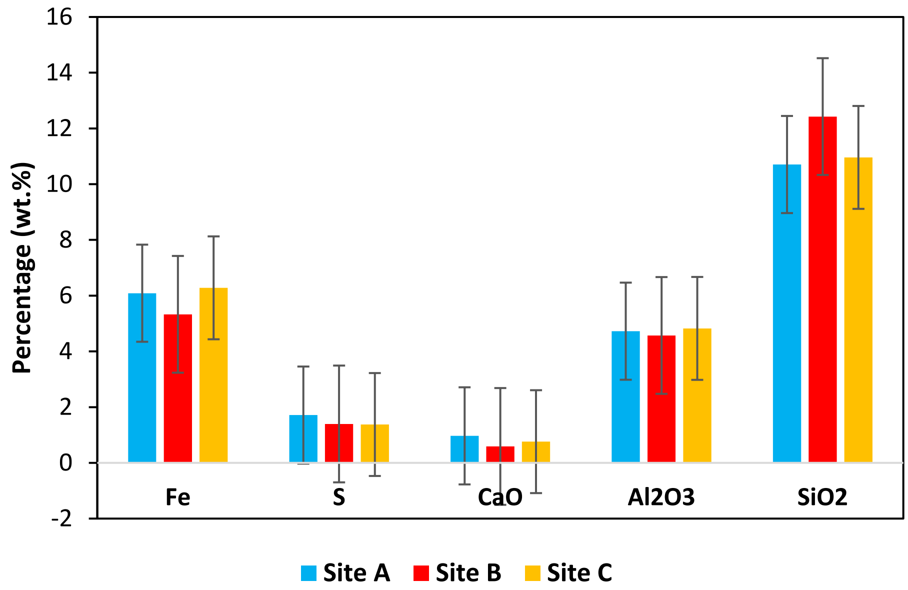


Figure 4.3. HHVs of the Coal Fines at Hwange Colliery Company

4.5 Elemental Analysis of the Coal Fines



(a) Ni, Cu, Co, MgO and Cr_2O_3 Content in the Coal Fines



(b) Fe, S, CaO, Al_2O_3 and SiO_2 Content in the Coal Fines

Figure 4.4. Elemental Analysis Results of the Coal Fines at Hwange Colliery Company

The XRF data can be used to predict the combustion behaviour of the coal (Speight, 2005) Figure 4.4 presents the percentage (wt.%) of various metal oxides and elements in coal fines from three different sites (Site A, Site B, and Site C) at Hwange Colliery Company. As illustrated in Figure .4a, the results indicate that the content of Nickel (Ni) is relatively similar across all three sites, with Site A slightly higher than Sites B and C. Copper (Cu) content is also comparable across the sites, with Site A being slightly higher. Cobalt (Co) content shows minimal variation among the three sites. Magnesium Oxide (MgO) is highest in Site A, followed by Site C, and lowest in Site B. Chromium Oxide (Cr2O3) content is consistent across all three sites with slight variation (Rehman et al., 2019).

As illustrated in Figure 4.4b, Iron (Fe) content is relatively consistent across the sites, with Site C having slightly higher content. Sulfur (S) content shows minor variations, being slightly higher in Site B. Calcium Oxide (CaO) content is minimal across all sites, approximately less than 1%. Aluminum Oxide (Al2O3) content is quite similar across the sites, with all three sites having around an average of 4.6%. Silicon Dioxide (SiO2) content is highest among the elements, particularly in Site B, which is close to 12.42%. These findings indicate that while some elements like Fe and Al2O3 show consistent distributions across the sites, others like SiO2 exhibit more significant variations, highlighting the need to consider these differences in environmental assessments and processing strategies for coal fines at Hwange Colliery Company (Deng et al., 2021).

The ANOVA test showed no statistically significant differences for the elemental compositions across sites with -values ranging from 0.094 to 0.915 for each element that was analyzed.

4.6 Thermograviometric Analysis of the Coal Fines

Figure 4.5 shows the TGA curves for the coal fine at 10, 20 and 30^{o}C/minute heating rates. Moisture loss occurred from approximately 90 to 180 ^{o}C and thereby volatilization started to occur. Rapid decrease in residual mass occurred from 350 $^{-}$ 600 ^{o}C at 10 ^{o}C/minute heating rate, 400 - 650 ^{o}C at 20 ^{o}C/minute heating rate and 450 – 750 ^{o}C at 30 ^{o}C/minute heating rate. No mass loss was observed for all the heating rates from approximately 750 ^{o}C.

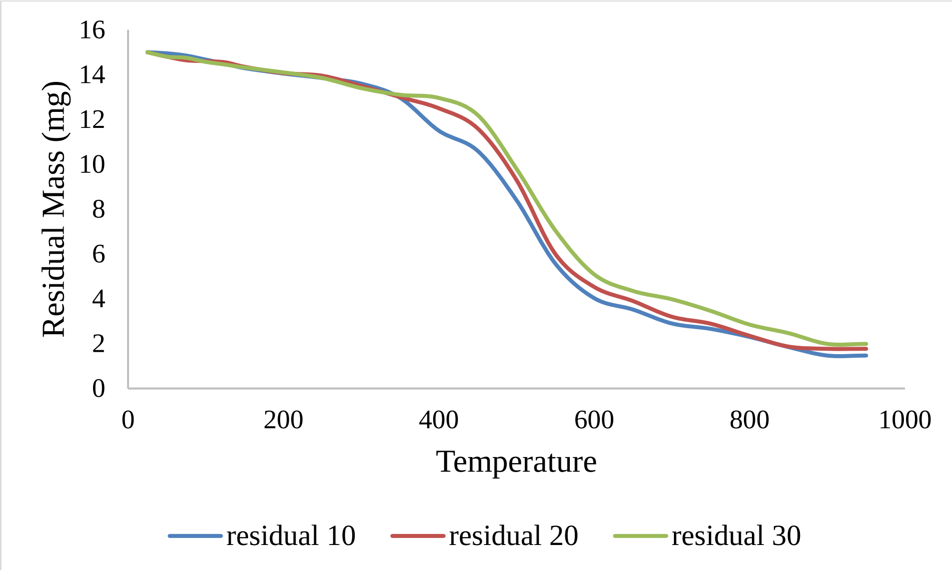


Figure 4.5. TGA for the coal fines being produced at Hwange Colliery Company

Figure 4.5 shows the residual mass loss curve for the optimum briquettes. Gradual mass loss occurred and was followed by rapid mass loss from 13.1mg to 2.66mg at 600 ^{o}C. no further mass loss was observed from approximately 800 ^{o}C at 10 ^{o}C/minute heating rate. Rapid mass loss started at 400 ^{o}C for the 20 ^{o}C/minute heating rate with a mass reduction from 12.5mg to 3.68mg at 700 ^{o}C. no further mass loss was observed from approximately 800 ^{o}C. at 30 ^{o}C/minute heating rate, 12.18 at 400 ^{o}C to 3.68 at 700 ^{o}C. No further mass loss occurred at 850 ^{o}C and above temperatures.

4.7 Water Quality Analysis

Table 4.2. On Site Water Analysis Results

Site	**Sample**	**Parameter**		
		Turbidity (NTU)	**EC (µS/cm)**	**Ph**
Baobab	Sample 1	0.50	2000	8.16
	Sample 2	0.55	2030	8.14
	Sample 3	0.53	2030	8.20
Barzem	Sample 1	0.55	741	6.88
	Sample 2	0.53	742	6.86
	Sample 3	0.44	742	6.89
St Patrick's Pre-School	Sample 1	0.38	880	7.10
	Sample 2	0.34	877	7.14
	Sample 3	0.39	875	7.11

Xinzhi Coal Mine (X. Zhang et al., 2021).	-	-	8.06

The water quality analysis results, presented in Table 4.2, provide insights into the parameters measured at different sites: Baobab, Barzem, and St Patrick’s Pre-School. The water quality analysis across Baobab, Barzem, and St Patrick’s Pre-School sites reveals distinct characteristics. Baobab exhibits relatively clear water with turbidity ranging from 0.50 to 0.55 NTU, moderate electrical conductivity around 2000 µS/cm, and slightly alkaline pH levels ranging from 8.14 to 8.20. Barzem shows lower turbidity levels between 0.44 to 0.55 NTU, lower electrical conductivity around 741 to 742 µS/cm, and mildly acidic pH levels ranging from 6.86 to 6.89. St Patrick’s Pre-School displays consistently low turbidity from 0.34 to 0.39 NTU, moderate electrical conductivity around 875 to 880 µS/cm, and neutral pH levels ranging from 7.10 to 7.14. These findings highlight variations in water clarity, mineral content, and acidity across the sites, crucial for assessing their environmental impact and suitability for various uses (World Health Organization., 2011).

The ANOVA test results for the onsite water parameters showed significant differences between the sites that were tested with p-value being 0.0058, 8.91×10^{-12} and 1.45×10^{-9} for turbidity, EC and pH respectively.

Table 4.3 compares the water quality parameters of St Patrick's Pre-school, Barzem, and Baobab sites with the specifications outlined in ZWS 560:1997 for portable water. St Patrick's Pre-school shows arsenic levels within limits, while Barzem and Baobab do not have data provided. Calcium content is highest at Barzem (58.92 mg/L) and lowest at Baobab (23.40 mg/L), with St Patrick's Pre-school falling in between (48.25 mg/L). Chloride levels are highest at Baobab (92.18 mg/L), within the permissible range, while Barzem and St Patrick's Pre-school fall within the specified limits. Copper and lead are not detected across all sites, meeting standards. Nickel levels are minimal and within acceptable limits at all sites. Nitrates are well below the maximum allowable concentration at all sites. Sulfate levels exceed limits at Baobab (539.10 mg/L), while Barzem and St Patrick's Pre-school are within recommended guidelines. Iron is not detected above permissible levels at any site. These results highlight variations in water quality across the sites, emphasizing compliance or deviations from ZWS 560:1997 standards, crucial for assessing water safety and suitability for consumption and other uses.

The ANOVA results for Ca (0.00028), Ni (0.00036), Cl (0.008) and S (9.76×10^{-10}) showed significant differences across the sites which highlights the distinct variations is water quality across the sites.

Table 4.3. Comparison of Various Parameters in Different Water Sources with ZWS 560:1997 Specifications

Parameter	**St Patricks Pre-school**	**Barzem**	**Baobab**	**Portable Water ZWS 560:1997 Specification Requirements**	**Xinzhi Coal Mine results** et al., 2021)
Arsenic as As, mg/L	-	-	-	0.1 max	-
Calcium as Ca, mg/L	48.25	58.92	23.40	-	-
Chloride as Cl, mg/L	27.18	63.82	92.18	Min: 0 - Max: 300.0	103.15
Copper as Cu, mg/L	-	-	-	2.0 max	-
Lead as Pb, mg/L	-	-	-	Min: 0 - Max: 0.1	-
Nickel as Ni, mg/L	0.07	0.03	0.03		-
Nitrates as NO_3, mg/L	0.53	0.50	0.41	Min: 0 - Max: 50.0	1.27
Sulfate as SO_4, mg/L	43.81	113.67	539.10	250.0 max	509.8
Iron as Fe, mg/L	-	-	-	1.0 max	-

4.8 Soil Quality Analysis

Table 4.4 summarizes the chemical analysis results of soil samples from various locations in Hwange. The chemical analysis results of soil samples from various locations around Hwange reveal notable concentrations of heavy metals. Copper concentrations vary significantly, with higher levels observed at the Truck Stop (53.70 mg/L) and Lukosi River (11.11 mg/L), while other sites show moderate to lower levels. Lead concentrations are highest at the Lukosi River (50.50 mg/L) and Mpongola River (52.32 mg/L), suggesting potential contamination. Nickel levels also vary, with elevated concentrations at the Truck Stop (31.79 mg/L) and Mpongola River (36.17 mg/L). Arsenic was not detected in the analyzed samples. The high standard deviation for the elements show that there is a significant difference between the soil quality of the tested sites in relation to the elements under study.

Table 4.4. Chemical Analysis Results of the Soil Samples from Hwange

Parameter	**Coal Fines Dump Site**	**750m**	**1km**	**1.5km**	**Lukosi River**	**Mpongola River**	**SD**
Arsenic as As, mg/L	-	-	-	-	-	-	-
Copper as Cu, mg/L	12.02	-	53.70	-	-	11.11	24.33
Lead as Pb, mg/L	43.38	31.91	49.92	17.89	50.50	52.32	13.57
Nickel as Ni, mg/L	11.46	25.31	31.79	13.96	11.75	36.17	10.84

Table 4.5 summarizes the comparative analysis of soil parameters at various distances from the dumpsite in Hwange. These results indicate variations in soil characteristics at different distances from the dumpsite and in nearby riverbanks. Bulk density increases from the dumpsite to 1km away, suggesting compaction due to human activity. pH levels fluctuate, with the most acidic conditions observed at 1km from the dumpsite and more neutral conditions closer to the Lukosi and Mpongola rivers. Organic carbon content shows variability, possibly influenced by local vegetation and anthropogenic activities. These findings provide insights into soil quality changes influenced by proximity to the dumpsite and adjacent river environments, crucial for assessing environmental impacts and planning remediation measures. The standard deviation for the parameters was generally low which shows that there was no statistically significant differences between the sites.

Table 4.5. Comparative Analysis of Soil Parameters at Various Distances from the Dumpsite

Parameter	Dumpsite	750m from the site	1km from the site	1.5km from the site	Lukosi river	Mpongola river	SD
Bulk density (g/cm^3)	1.58	1.62	1.79	1.46	1.32	1.27	0.2
pH	6.3	6.5	5.7	6.4	6.9	6.8	0.43
Organic carbon (%)	0.9	1.1	0.7	1.1	1.3	1.3	0.23

4.9 An Assessment of the Cleaner Production Options for the Coal Fines

The coal and coal fines production information for the coal fines at Hwange Colliery Company is presented in Table 4.6. The mining company operates using open cast and underground mining. Approximately over 2 million tonnes of coal are mined per year of which about 10% end up as coal fines which are disposed on open dump sites. The average gross calorific value for the coal fines is 17.43MJ/kg.

Table 4.6. Hwange Colliery Company Production Information

Type of mine	Open cast and underground mining
Quantity of Coal mined/ year	2 026 472 tonnes
Percentage of coal fines produced	10%
Method of coal fines disposal	Open dumpsites
Gross Calorific value of coal fines	**17.43MJ/kg**

Table 4.7 shows the results of the feasibility scan for the coal fines utilization options that may be used at Hwange Colliery Company. The technologies that underwent the assessment are coal water slurry, fluidized bed technology, briquetting, pelletization and brickmaking. All the options that

have been put forward have been proven that they are capable to utilize coal fines for value added products and can be implemented in Zimbabwe. The options greatly result in the reduction of the coal fines that are currently disposed of and being disposed which is crucial in providing sustainable solutions to coal fines management. Coal water slurry and fluidized bed technology may not be economically feasible for implementation in Zimbabwe as they require larger investments which companies may not be willing to put through given the economic environment as they may not be financially profitable in the end. Pelletization, briquetting and brickmaking are cheaper to implement therefore are more feasible in Zimbabwe.

Table 4.7. The feasibility scan for the cleaner production options for the coal fines that are produced at Hwange Colliery Company

Cleaner production option	Coal water slurry	Pellets	Briquetting	Fluidised bed technology	Brickmaking
Technical feasibility					
Is it a proven technology?	✓	✓	✓	✓	✓
Can the technology be implemented currently in Zimbabwe?	✓	✓	✓	✓	✓
Environmental feasibility					
Can it result in the reduction of environmental impacts?	✓	✓	✓	✓	✓
Is there a reduction in the quantity of coal fines?	✓	✓	✓	✓	✓
Is it sustainable for the environment?	✓	✓	✓	✓	✓
Economic feasibility					
Is it financially sustainable in Zimbabwe's economic environment?	×	✓	✓	×	✓
Is it profitable?	×	✓	✓	×	✓

Table 4.8 shows the cost and benefits results for brickmaking, pelletization and briquetting. Brickmaking requires a concrete mixer and a press machine which cost $3500 and $11000 respectively. The working capital operations and maintenance costs require approximately $311000 per year. The production of bricks is expected to produce a gross income of approximately $329 702.40 per year. The press machine for pelletization costs approximately $12000 and the expenses that were projected amounted to $312000 per year with a gross income of between 228 000 – 576 000 per year depending on the production rate. The briquette press machine costs approximately $2 850 with the expenses amounting to $512 000 per year. The gross income was projected to be between $576 000 to $1 152 000 depending on production.

Table 4.8. Projected costs and benefits for brickmaking, pelletization and briquetting using coal fines at Hwange Colliery Company

	Brickmaking	**Pelletization**	**Briquetting**
Machinery cost	Vertical shaft concrete mixer 1.5m3/mix – **$3500usd** Manual press machine 3000 – 20000 pieces/8hrs – **$11000usd**	Coal fines pelletizer **$12 000usd** 500 -1000kg/hour	Briquette Press Machine **$2850usd** 1-2 tonnes/hour
Operation cost	$300 000/year	$300 000/year	$500 000/year
Maintenance cost	$1000/year	$2000/year	$2000/year
Fixed capital	$100 000	$100 000	$100 000
Working capital	$10 000	$10 000	$10 000
Quantity of coal fines utilised/year	7 776 tonnes/year	4 320 tonnes/year	8 640 tonnes
Productivity	2 198 016 bricks/year	2 880 – 5 760 tonnes/year	5 760 – 11 520 tonnes/year
Market prices	15cents/block	100`usd/tonne	100usd/tonne

Projected gross income/ year	$329 702.40 USD	$288 000 – $576 000 USD	$576 000 – $1 152 000 USD

Figure 4.6. Briquettes produced using coal fines, Kaolin clay and Molasses

Table 4.9 is the summary of the cost benefit analysis results through the payback period, net present value and internal rate of return. The payback period for brickmaking, briquetting and pelletization were 15, 13 and 17 months respectively. The net present value for briquetting was the highest which amounted to $1 771 493.18 followed by brickmaking with $838 831.50 then pelletization with $679 746.00. briquetting had the highest internal rate of return of 90%, and briquetting and pelletization had an internal rate of return of 75% and 64% respectively.

Table 4.9. Cost-benefit analysis results for brickmaking, pelletization and briquetting using coal fines at Hwange Colliery Company

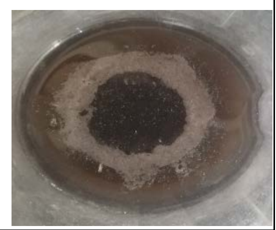
	Brickmaking	Briquetting	Pelletization
Payback period	15 months	13 months	17 months
Net present value	$838 831.50	$1 771 493.18	$679 746.00
Internal rate of return	75%	90%	64%

Table 4.10. presents the results of the water resistance test for the briquettes that were produced. The briquettes that were produced using a 20% molasses weight ratio to the coal fines were stable and did not rapidly dissolve in water as shown in Table 5.9a. This was evidenced by a larger section of the briquette that was still compact after 2 hours of being immersed in water. The 30% molasses briquettes were stable for 5 minutes and started disintegrating at approximately 10 minutes of being immersed in water until they totally disintegrated within 17 minutes. The briquettes that were produced using 20% and 30% kaolin clay disintegrated within 30 seconds and 1 minute respectively. Table 5.9b shows the water resistance results for binderless and composite briquettes. The binderless briquettes immediately disoriented upon being immersed in water. The 30% composite briquettes were slightly stronger as they managed to withhold a larger portion of the briquette until they disintegrated in approximately an hour. The briquettes that were produced using 10% molasses and 10% kaolin clay disintegrated within 5 minutes.

4.9.1 Water Resistance Test

Table 4.10. Results of the Water Resistance Test for the Briquettes

a) Water Resistance Test for 20% Molasses, 30% Molasses, 20% Kaolin Clay and 30% Kaolin Clay

Time	20% molasses	30% molasses	20% kaolin clay	30% kaolin clay
Start				
10 seconds				
30 seconds				
1 minute				
5 minutes				

10 minutes				
15 minutes				
30 minutes				
2 hours				

b) Water Resistance Test Results for the Binderless and Composite Briquettes

Time	**30% composite**	**20% composite**	**Binderless**
Start			
5 seconds			
30 seconds			
1minute			
5 minutes			

			
10 minutes			
30 minutes			
I hour			

4.9.2 Drop Shutter Test

Figure 4.7 shows the results of the drop shutter test for the briquettes that were produced. The composite briquettes did not disintegrate much upon falling from a height of 2m. The binderless briquetting completely disintegrated upon reaching the hard surface. The 30% kaolin clay briquette disintegrated to form several pieces. The 30% molasses briquette partially disintegrated but not as much as the 30% kaolin clay briquette. The 20% kaolin clay showed little to no signs of breakage upon reaching the hard surface.

a) 10% molasses & 10% kaolin clay

b) 15% molasses & 15% kaolin clay

c) binderless briquette

d) 30% kaolin clay

e) 20% kaolin clay

f) 30% molasses

g) 20% molasses

Figure 4.7. results of the drop shutter test for the briquettes

Table 4.11 shows the summary of the results of the physical analysis test that led to the 20% molasses briquette being regarded as the optimum. Only the 20% molasses briquette managed to withstand the water resistance test. The 20% molasses, 30% molasse, 20% kaolin and 30% composite briquette were still intact after the drop shatter test. This led to the 20% molasses briquette being regarded as the optimum as it was the strongest for both the tests that were conducted.

Table 4.11. A Summary of the Physical Strength Analysis Test Results

Briquette composition	Water Resistance Test	Drop Shutter Test
Binderless	×	×
20% molasses	✓	✓
30% molasses	×	✓
20% kaolin clay	×	✓
30% kaolin clay	×	×
20% composite	×	×
30% composite	×	✓

Figure 4.8 is the proximate analysis results for the optimum briquettes. The moisture content was 8.29% and the as content was slightly higher as compared to the coal fines with 19.17%. the volatile matter and carbon content were high at 35.57% and 35.86% respectively.

4.9.3 Proximate Analysis for the Optimum Briquettes

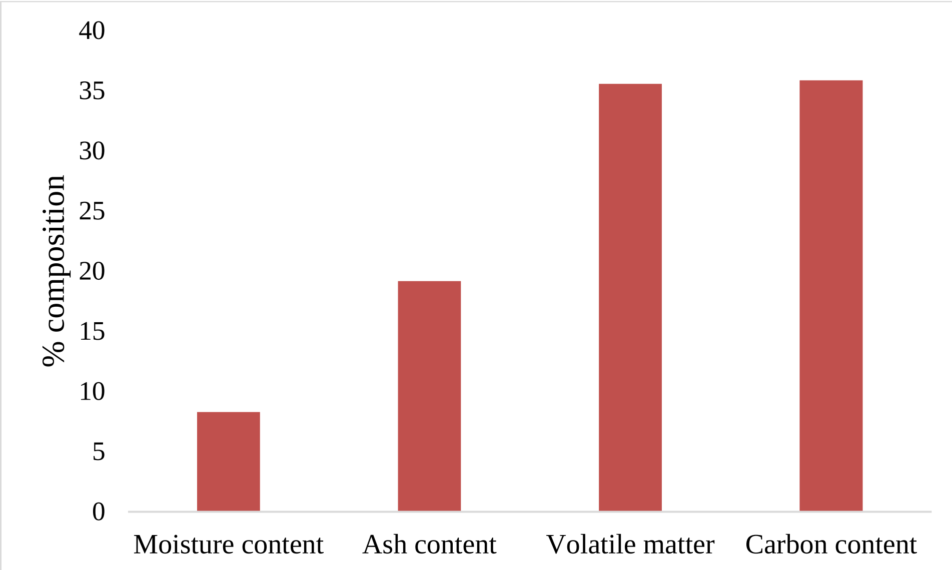


Figure 4.8. Proximate analysis results for the optimum briquettes

4.9.4 Ultimate Analysis and Higher Heating Values for the Optimum Briquettes

Table 4.12 presents the results of the ultimate analysis which show that the optimum briquettes had a carbon content of 39.027%, Hydrogen 4.07%, oxygen 27.832% and sulfur 2.03%. The HHV was calculated using Mendeleev's equation and was found to be 21.59MJ/kg.

Table 4.12. Results of the Ultimate Analysis and HHV for the Optimum Briquette

Element	**Percentage composition**
C	39.027
H	4.07
0	27.832
S	2.03
HHV	**21.59MJ/kg**

4.9.5 Thermogravimetric Analysis

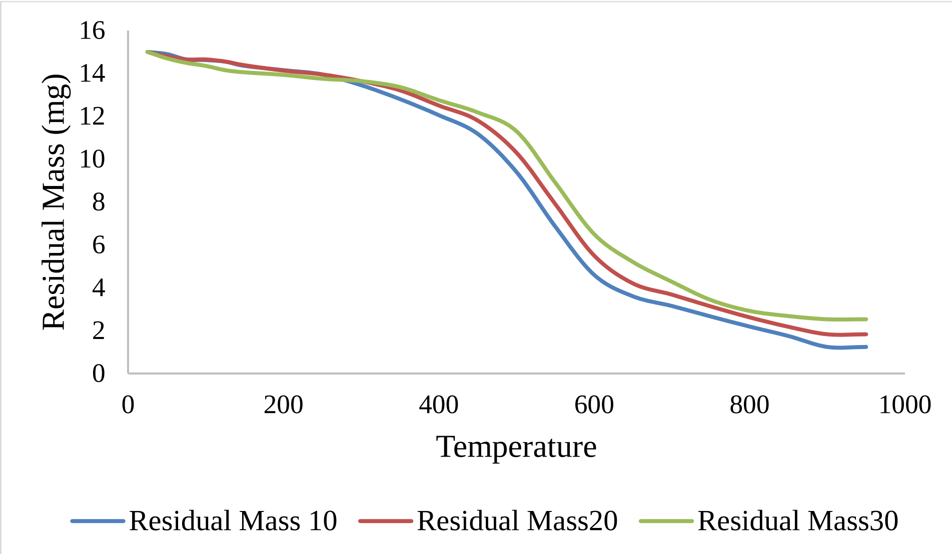
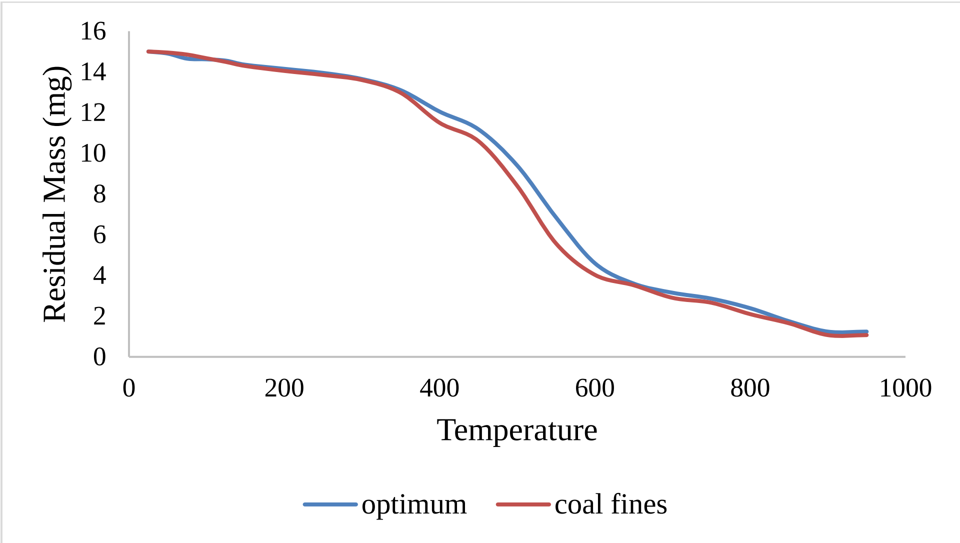


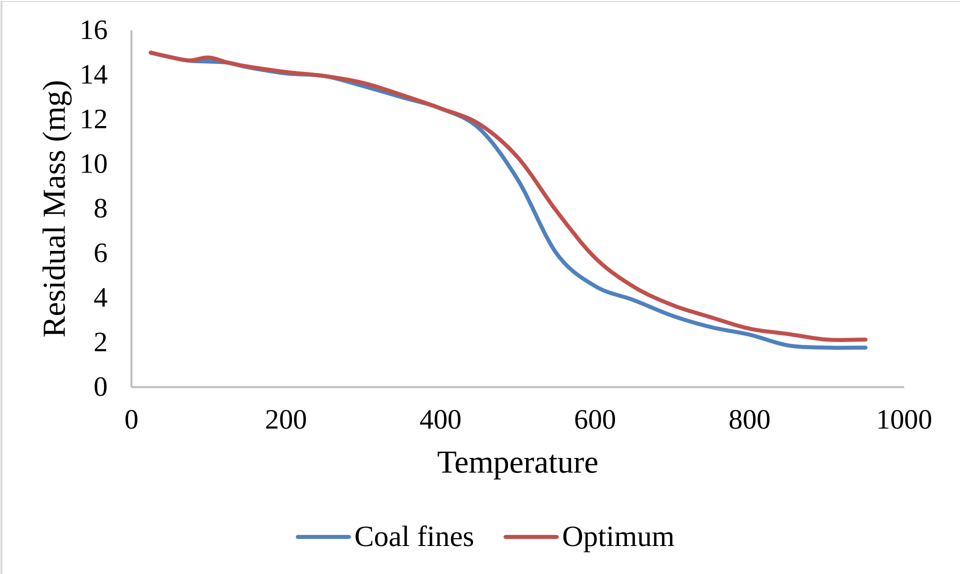
Figure 4.9. TGA for the optimum briquettes

Figures 4.10a, b and c present the comparisons of the combustion patterns of the coal fines and the optimum briquettes. The combustion patterns are relatively the same for all heating rates however it was noted that the optimum briquettes produced slightly higher residual mass with no further mass loss for all the heating rates.

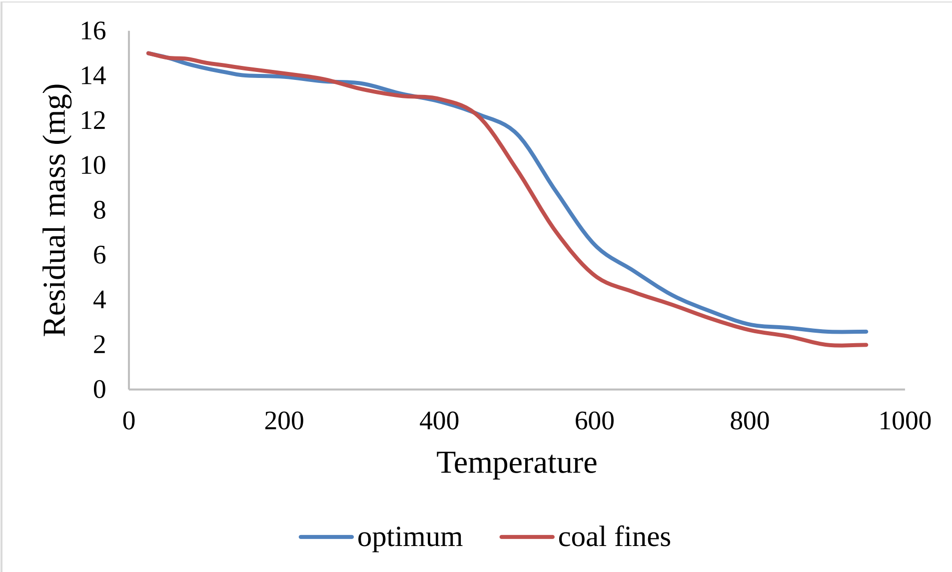
Figure 4.10. Comparisons of the TGA curves for Coal Fines and Optimum Briquettes



a) 10°C/ minute Heating Rate



b) 20°C/minute Heating Rate



c) 30°C/minute heating rate

CHAPTER FIVE: DISCUSSION

5.1 Particle Size Distribution

The sieve analysis results are presented in Table 4.1. The sieve analysis shows that fewer particles of less than 20% of the samples that were analysed passed through the 0.2 mm and 0.4 mm sieve. More particles were found within the size range of 0.6 to 1.5 mm which was up to 80%. This may have been due to the production process of the colliery which led to the specific size of coal fines to be produced. Site C had coal particles that were larger than 3 mm as evidenced by the cumulative percentage of the sieve analysis being 93%. This shows that approximately 7% of the coal fines deposits consisted of coal particles that were larger than 3 mm. This may have been due to machinery malfunction which led to larger coal particles being mixed with the coal fines.

The sieve analysis shows that fewer particles of less than 20% of the samples that were analyzed passed through the 0.2 mm and 0.4 mm sieve. More particles were found within the size range of 0.6 to 1.5 mm which was up to 80%. This may have been due to the production process of the colliery which led to the specific size of coal fines to be produced. Site C had coal particles that were larger than 3 mm as evidenced by the cumulative percentage of the sieve analysis being 93%. This shows that approximately 7% of the coal fines deposits consisted of coal particles that were larger than 3mm. this may have been due to machinery malfunction which led to larger coal particles being mixed with the coal fines.

Site A had more coal particles passing through the 1.0 mm sieve as compared to site B and C. The dumpsite where samples for site A were collected was the oldest dumpsite where the coal fines may have been deposited while coal production in the colliery was being done using different methods and machinery which may have led to the varying sizes. Weather elements may have also contributed to the much-reduced sizes of the coal fines as they were deposited for some time and the changes in weather patterns may have led to the further reduction in size of the coal fines. Site A and B had approximately 80% of their coal particles pass through the 1.5 mm sieve. The production processes that were used when coal fines were deposited at site A and B may have been the same which could lead to the slight variance in the particle sizes of the samples from these sites. (X. Zhang et al., 2021) discussed that the differences in particle sizes may be due to the coal fines being produced in coal mines which produce ultra-fine particles or production from the coal wash plant, which produces coarser coal fines. Site C had more particles of sizes 2.0 mm and above which may have been attributed to machinery malfunction or changes in production processes. The presence of coarser particles in the coal fines has the potential to increase the ash content of the coal fines. (Chen et al., 2021) analyzed coal fines through proximate analysis and concluded that the coarser the coal fines are the higher the ash content.

From an environmental perspective, the presence of finer particles, especially those passing through smaller sieves, can contribute to air pollution. Fine coal particles, when suspended in the air, can lead to respiratory issues and contribute to the formation of particulate matter, affecting air quality. A study by Nemukula & Madyira (2023) emphasized the environmental concerns associated with fine particle emissions from coal-related activities. The deposition of coal fines with varying particle sizes can impact soil quality(Nemukula & Madyira, 2023). Smaller particles may leach contaminants more readily into the soil, affecting soil health and potentially contaminating groundwater. Zhang et al. (2021) discussed the potential for soil contamination due to coal mining activities, including coal fines deposition (H. Zhang et al., 2021). Fine coal particles can also pose risks to water quality if they leach pollutants into water bodies. The presence of larger particles could also lead to sedimentation issues, affecting aquatic ecosystems.

The deposition of coarse coal with coal fines may be reduced by repairing the machinery to ensure that only coal fines are deposited in the process. This may also lead to the reduction of the quantity of coal fines that are produced as the machinery will be more efficient. Therefore, coal mining industries such as Hwange Colliery Company should incorporate cleaner production elements in their working cycle which ensures that machinery is fully serviced and working at its maximum efficiency to reduce waste production.

5.2 Proximate Analysis

The results from proximate analysis of the coal fines from Hwange Colliery show that the coal samples from site A had lower moisture content than sites B and C (figure 4.2). This was attributed to gravity drainage and evaporation through wind movement and solar energy which potentially stripped moisture off the coal fines (Goede et al., 2016). The higher volatile matter and fixed carbon content presented by the results show that the coal fines may be easier to ignite and they also have greater chances of high energy production (J. Zhang et al., 2021). Coal fines are susceptible to spontaneous combustion, especially when stored in large quantities and exposed to oxygen. The presence of volatile matter and organic material in coal fines can lead to self-heating and ignition, posing fire hazards in stockyards (Di et al., 2021). Uncontrolled fires not only release harmful gases and smoke into the atmosphere but also require significant resources for firefighting and mitigation. This is a major hazard to the community if the coal fines piles ignite as they increase the chances of fire accidents to humans and animals. Air pollution is also bound to occur in the process. (Soto-Rivero et al., 2021) analyzed coal fines by proximate analysis and the moisture content, ash content, volatile matter and fixed carbon were 8.54%, 8.04%, 35.58% and 56,38% respectively. The differences in the proximate analysis results may be attributed to the differences in the quality of the coal that produced the coal fines.

Site A had a gross calorific value of 19 MJ/kg which was high as compared to site B and C which had 17.96 and 15.33 respectively. This may have been due to the low moisture content and high carbon content which led to more potential for energy production from the coal fines in the event that they are combusted. The increase in moisture content in site B and C may have led to the reduction in the gross caloric value of the coal fines from these sites as the high moisture inhibits the potential of the coal fines to produce energy. The high GCV is a good indicator for the potential that the coal fines have for utilization. Value addition may be done to produce marketable products through which energy may be harnessed which increases the economic value of the coal fines. According to the Mendeleev's equation, Site A, B and C had a gross calorific value of 22.72MJ/kg, 21.28MJ/kg and 21.05MJ/kg respectively (Figure 4.3). The equation produced higher GCV values than equation 1 which indicates the potential that the coal fines have for energy generation. Therefore, efforts should be made to introduce technologies that harness energy from coal fines at Hwange Colliery Company.

5.3 Elemental Analysis of the Coal Fines at Hwange Colliery Company

The elemental analysis results for the coal fines at Hwange Colliery Company are presented in Figure 5.4 The nickel content across all samples and sites is relatively consistent, ranging from approximately 0.14% to 0.16% (figure 4.4a). While nickel is not typically a major component in coal fines, its presence can be of environmental concern due to its toxicity and potential impact on human health and ecosystems (Rizwan et al., 2024). Monitoring nickel levels is important to assess potential risks during coal processing and utilization. Copper content shows variations among samples and sites, with values ranging from around 0.1% to 0.12%. Copper is another trace element that can have environmental implications, especially in terms of aquatic toxicity and soil contamination (Rehman et al., 2019). Proper management of copper-containing coal fines is necessary to prevent environmental damage and ensure regulatory compliance.

Cobalt content is relatively consistent across samples and sites, with values around 0.03% (Figure 5.4a). Cobalt, like nickel, is a trace element that can pose health and environmental risks if not managed properly (Leyssens et al., 2017). Monitoring cobalt levels is important, particularly in waste management and disposal practices involving coal fines. Iron content varies among samples and sites, ranging from approximately 5% to 6.8% (Figure 5.4b). Iron is a major component in coal fines and plays a role in combustion processes and ash formation. Higher iron content can influence ash characteristics, slagging, and fouling tendencies during combustion, affecting operational efficiency and environmental emissions (Vamvuka et al., 2018). Sulfur content shows variations across samples and sites, with values ranging from around 1.3% to 1.8%. Sulfur is a critical element in coal fines as it contributes to sulfur dioxide (SO_2) emissions during combustion, leading to acid rain formation and air quality issues (Buraerah et al., 2023). Managing sulfur content is essential to minimize environmental impacts and comply with emission regulations. Magnesium oxide and calcium oxide content are minor components in coal fines, with values generally below 1%. These oxides can influence ash properties, such as melting behavior and ash fusion temperatures, which impact combustion efficiency and boiler performance (Deng et al., 2021). Proper ash management strategies are necessary to address these aspects. Aluminum oxide, silicon dioxide, and chromium oxide are also minor components in coal fines. These oxides contribute to ash composition and characteristics, affecting ash disposal, environmental leachability, and potential reuse or recycling options. The presence of trace elements in coal fines was also noted by (Kumari & Bhattacharya, 2023) which indicates that the issue of the presence of heavy metals may be a challenge for various coal mining industries and surrounding communities. It can also be concluded that clay and inorganic materials are present in the coal fines therefore, the prediction of the behaviour of these elements on the environment may be done and management strategies may be put in place to ensure reduced environmental damage from the disposal of the coal fines (X. Zhang et al., 2021).

5.4 Water Quality Analysis

The onsite water analysis results are presented in Table 4.2. The turbidity of the groundwater from the analyzed sites was generally low as it ranged from 0.34 to 0.55 NTU. The results indicated that the water was clear and suitable for drinking in regards to clarity (World Health Organization., 2011). This shows that the coal fines had little to no effect on the turbidity of the groundwater in Hwange. However, regular analysis is crucial to maintain stable conditions amid the disposal of coal fines on open dump sites, emphasizing the need for swift action to utilize these fines effectively. WHO also recommends that drinking water should not exceed 5 NTU at any time and that it should ideally be below 1 NTU for aesthetically pleasing water. Turbidity levels above these thresholds can indicate potential issues with water quality and may require corrective actions.

The EC of the water samples ranged between 741 and 2030 µS/cm. The EC values at the Baobab site range from 2000 to 2030 µS/cm. These values are significantly higher than the WHO guideline of 800 µS/cm (Rahman et al., 2016). High EC levels in water can indicate increased mineral content, such as salts and metals. It is possible that runoff from coal fines disposal sites introduced minerals into the water, leading to elevated EC levels. Excessive EC can affect the water's taste and may indicate the presence of contaminants, which could potentially include substances associated with coal fines, like heavy metals or organic compounds. The EC values at the Barzem site are relatively lower, ranging around 741 to 742 µS/cm. These values are within the WHO recommended limit of 800 µS/cm. The values observed at St. Patrick's Pre-School are within this range and thus do not raise immediate concerns regarding water quality from an EC perspective.

While the EC levels here are within the guidelines, it is essential to monitor trends over time to ensure they remain stable.

The pH values at all sites range from 6.86 to 8.20. These pH levels are generally within the acceptable range for drinking water, which typically falls between 6.5 and 8.5 according to the World Health Organization (Yehia & Said, 2021).

Table 4.3 shows the results from the analysis of water that was collected at St Patrick's Preschool, Baobab and Barzem in Hwange. No traces of arsenic, iron, copper and lead were found in the water. Traces of nickel were also found in the water which is unacceptable in drinking water. The elements that were analyzed in the water were within the range of the specified requirements which indicated little to no pollution of the groundwater in Hwange. However, traces of nickel were found in the water samples, which is unacceptable in drinking water. WHO (2021) states that prolonged oral exposure to nickel may have negative impacts on human and animal health. A 2-year study was done using rats and dogs on the long-term effects of nickel on body systems and it was noted that body weight reduced with increasing nickel dosage. Therefore, strict monitoring should be done on the groundwater to ensure that the health of the Hwange community is safe from nickel pollution (Word Health Organization, 2021). A high concentration of sulfate is also noted in the water from Barzem averaging 113.67 mg/L. Even though the maximum recommended is 250 mg/L, the concentration of sulfate in the water should be constantly monitored to make sure it does not increase which may be harmful to human health. The concentration of sulfate in Baobab samples is above required for drinking water with the highest recorded being 539.10 mg/L. This may have been because the hotel is in closer proximity than the other sites that were tested therefore there is a possibility that the contamination may have been from the coal fines. High sulphate levels in water above 500 mg/L may cause laxative effects and dehydration which is fatal for humans and animals. However, people are said to adjust to the water after a few days but infants should be given water with a sulphate content of less than 300 mg/L (University of Minnesota, 2021). However, it is important to make sure that drinking water parameters are in line with the required standards despite the source of pollution.

5.5 Soil Analysis Results for Hwange

Table 4.4 presents the chemical analysis results of soil samples obtained from different locations. Soil samples were collected at increasing distances from the coal fines dump site to note the differences that may occur due to distance. Copper, lead and nickel were present in the soil that was collected at the dump site. Traces of lead and nickel were found in all the soil samples that were tested. This may have been due to movement of coal particles from coal fines dump sites as dust which ends up leading to soil pollution. Copper was present at the truck stop that is 1 km away from the dump site as well as Lukosi River.

The presence of heavy metals in soil greatly affects the soil enzyme activity which affects the agricultural productivity of soils (Wyszkowska et al., 2006). This can be greatly evidenced by low yields that occur in Hwange which may be attributed to the effects of the soil being polluted by heavy metals. The heavy metals in the soil may have been transported as coal dust from the coal fines that are on open dump sites at Hwange which shows that there is imminent need for them to be utilised in order to save the soil quality and agricultural productivity of Hwange soils. The heavy metals also have the potential for bioaccumulation and biomagnification in plants which may be harmful when consumed by humans and animals as they would have entered the food chain and may cause several health issues.

Table 4.5 shows the results from the analysis of soil parameters in Hwange. The bulk density was generally high in the areas that were tested. This is because the soils are heavily compacted which reduces the suitability of these soils for agricultural purposes as it negatively affects infiltration, microorganism activity and root growth (Birkas & Rousseva, 2003). The pH was more acidic at a 1 km distance from the coal fines dump site which may not only be attributed to coal fines but also leakages from trucks as this is a truck stop area. The organic carbon is generally low in the soils that were analysed. This means that the soils cannot fully support farming for communities to survive therefore soil rehabilitation is required to support agriculture and improve livelihood in the surrounding community.

The presence of coal fines piles at Hwange Colliery Company may be a major threat to the environment and the surrounding communities. Coal is an important energy source, especially for developing countries which are thriving for growth (Ozgur, 2019). Therefore, coal fines production is inevitable and proper waste management systems should be put in place to ensure the reduction of the effects of coal fines globally which has been evidenced by the results of this research. Coal fines also require specific machinery for their use as they are usually not suitable for use in industries (Adeleke et al., 2019). The development and use of equipment for coal fines may be expensive which makes it difficult for industries to be interested (Ramudzwagi et al., 2020). Competing energy production technologies such as hydro power generation and nuclear energy may be a major drawback to the adoption of coal fines utilization technologies especially in areas where they are facing little to no challenge when utilizing these technologies (Wehnert & Andreeva, 2019). There is a need for ways to improve coal fines utilization so that it may be a lucrative business so that industries utilize the coal fines and harness energy while reducing the possible effects on the environment.

However, efforts are being made through various research to ensure that coal fines are utilized sustainably. Technological innovations to improve the efficiency and effectiveness of coal fines utilization technologies are paving the way for increased coal fines utilization (Ramudzwagi et al., 2020). Further studies may also be done to assess the effects of coal fines disposal on air quality and the projected effects on the surrounding communities, flora and fauna.

The results that have been obtained from the comprehensive analysis of the characteristics of the coal fines that are produced at Hwange Colliery Company may be used to determine the best method for utilization of the coal fines. if the coal fines have a high HHV, there is a need for energy extraction methods that may be used for the coal fines. However, if the coal fines have ow HHV and very high ash content, the coal fines may be used for other purposes such as brickmaking.

5.6 An Assessment of cleaner production options for the coal fines

The cleaner production options that were used in this study were focusing on producing useful products from the coal fines. This is mainly because there are vast quantities of coal fines that have been disposed of on the ground and these need to be utilized as they are an environmental threat in their current state. The specific cleaner production options that were opted for analysis after the literature review was done were:

- Coal water slurry
- Pellets
- Briquettes
- Fluidised bed technology
- Brickmaking

5.6.1 The feasibility scan for the cleaner production options for the coal fines that are produced at Hwange Colliery Company

Table 4.7 shows the results of the feasibility scan that was done for the coal fines utilization options that have been suggested for the coal fines that are produced at Hwange Colliery Company. All the cleaner production options proved to be technically and environmentally feasible through a literature review which pointed out that the utilization of the coal fines through these options was a better option than the status quo at Hwange Colliery Company where the coal fines are disposed on open dump sites. However, coal water slurry and fluidized bed technology require more infrastructure to be implemented therefore it may be difficult for them to be put into consideration. Since the implementation of coal water slurry and fluidized bed technology requires a larger investment for implementation, the acceptance of these options may be difficult in Zimbabwe considering the economic environment. It may take longer to get returns from the utilization of coal fines through coal water slurry and fluidized bed technology which is a big risk in business and not worthy taking given that there are other options which have the potential for quicker returns. Therefore, it was opted that these options be left out for further assessment mainly due to financial reasons. The cleaner production options that were left for utilization for the coal fines at Hwange Colliery Company were briquetting, pelletization and brickmaking.

The coal fines production rate is approximately 200 000 tonnes per year at Hwange Colliery Company. Table 4.6 gives a clear presentation of the basic information for coal and coal fines production at Hwange Colliery Company. This information was used to project the costs and benefits that may be realized due to the utilization of coal fines using the options that were previously assessed in Table 4.7.

5.6.2 Cost-benefit analysis for the cleaner production options

Table 4.8 presents the projected costs and benefits that may be realized from briquetting pelletization and brickmaking as a comparison to determine the 2 methods that may be further opted for regarding the utilization of the coal fines at Hwange Colliery Company. Brickmaking requires a concrete mixer and a press machine which cost $3500 and $11000 respectively. The working capital operations and maintenance costs require approximately $311000 per year. The production of bricks is expected to produce a gross income of approximately $329 702.40 per year. This shows that brickmaking may have great potential for income generation with the utilization of coal fines.

The press machine for pelletization costs approximately $12000 and the expenses that were projected amounted to $312000 per year with a gross income of between 228 000 – 576 000 per year depending on the production rate. The projected figures show that pelletization has great potential for income generation however there are chances whereby a loss may result if the production rate is low which may be a risk. Therefore, if pelletization is considered, attention must be given to the production rates to ensure that the production targets are met for profit realization.

The briquette press machine costs approximately $2 850 with the expenses amounting to $512 000 per year. The gross income was projected to be between $576 000 to $1 152 000 depending on production. This shows that briquetting has more potential as compared to pelletization and brickmaking. There is however need for proper management to ensure that the production targets are met so that the maximum realization of profits is guaranteed.

Table 4.9 presents the net present value, payback period and internal rate of return for the coal fines utilization options for the coal fines at Hwange Colliery Company. This is the summary of the cost-benefit analysis for the coal fines at Hwange Colliery Company which was analyzed through the use of projected figures from potential projects that may be undertaken to add value to the coal fines for further utilization. The payback period was higher for pelletization which required 17 months to bring in back all the initial capital invested into the project. Brickmaking required 15 months and briquetting 13 months. Therefore, in terms of payback period, the best project to go for is briquetting followed by brickmaking and pelletization respectively. This is because projects with a lower payback period present a less risky investment than those with a higher payback period as the shorter payback period means that the capital investment will be returned in a shorter period (Kagan, 2023).

Briquetting had a high net present value followed by brickmaking and lastly pelletization as shown in table 4.9. Fernando, (2023) states that net present value determines the future profitability of a projected investment therefore briquetting is indicated to be more profitable in the future compared to brickmaking and pelletization however, brickmaking had a higher net present value than pelletization (Fernado, 2023).

The internal rate of return was 90%, 75% and 64% for briquetting, brickmaking and pelletization respectively. This indicated that briquetting has the potential to be more profitable followed by brickmaking and pelletization as the internal rate of return presents the rate earned for a given amount invested for a given time (Knoke, 2020). Therefore, investing in briquetting turns out to bring in more profit in comparison with brickmaking and pelletization.

The cost-benefit analysis results clearly show that the 2 methods of coal fines utilization that can be recommended for Hwange Colliery Company are briquetting and brickmaking. These have proven to be feasible in technical terms, environmental terms as well as financial projections. In the event that these projects have shown to be feasible to implement on the ground, they can be further scaled up to accommodate the quantities of coal fines that will be produced at the mine to ensure that all coal fines are utilizes and not disposed of on open dumpsites. Since the coal fines at Hwange Colliery Company have shown that they have a potential for energy production which was shown by the high HHV, briquetting was selected as the option that may be recommended for utilization at Hwange.

5.7 Analysis of the Practical Feasibility of the production and utilization of briquettes Using the Coal fines at Hwange Colliery Company

5.7.1 Water resistance test

Table 4.10 Presents the water resistance test results for the briquettes that were produced. The briquettes that were produced using a 20% weight ratio to the coal fines were stable and did not rapidly dissolve in water (table 5.10a). A large part of the briquette was still compact even after being immersed in water for over 2 hours. This may have been due to stronger bonds that may have been formed between the coal fines and molasses. A balance between the ratio of the coal fines and molasses may have also contributed to the coal fines becoming stronger. The briquettes that were produced using 30% molasses as weight percentage of coal managed to stay stable in water for over 5 minutes and they dissolved at approximately 10 minutes. The briquette was separated after being immersed in water for 17 minutes (Table 5.10a). This may have been due to the fact that the bonds that were formed between the coal fines and molasses were not fully stable which led to them dissolving quicker than the 20% molasses briquettes. The biomass may have attracted the moisture which led to the disintegration of the briquette (Adeleke et al., 2019)

The briquettes that were produced using kaolin clay dissolved in water within a shorter period of time as compared to those that were produced using molasses. This may have been due to the fact that kaolin clay formed weaker bonds with the coal fines which were separated by water faster than molasses. This makes kaolin clay not suitable for the coal fines that are being produced at Hwange Colliery Company as they are not strong if they get in contact with water. All the briquettes that were produced using kaolin clay only dissolved in under one minute. This makes it difficult for production and storage of the briquettes therefore making them not fit for production. Therefore, there is a need for further optimization of the briquettes that may be produced using kaolin clay to ensure that they are waterproof. Mangena and Du Cann (2007) found that the water resistance of the briquettes is largely dependent on the mineral matter and inherent properties of the coal, therefore; the water resistance of these briquettes may have been hindered by the high content of silicates and aluminium that may have been present in the coal fines. Kaolin clay proved insufficient for high water resistance briquette formation therefore composite briquettes may be the solution to ensure high water resistance capacity of the briquettes.

Table 4.10b Presents the results of the water resistance test for the composite and binderless briquettes that were produced from the coal fines from Hwange Colliery Company using both molasses and kaolin clay as binders. The 30% composite briquettes were slightly stronger as they managed to withhold a larger portion of the briquette for approximately an hour and they completely disintegrated after an hour. This may be attributed to the high content of molasses which provided for the stronger bonds for the briquettes to last longer whilst being immersed in water. The briquettes that were produced using 10% molasses and 10% kaolin clay disintegrated within 5 minutes. This may be attributed to the lack of balance between the coal fines and the binding agents which led to the production of briquettes that were not highly waterproof (Borowski & Hycnar, 2013). There is a need for further assessment of the coal fines – molasses – kaolin clay ratios to ensure a balance that produces highly resistant briquettes as these composite briquettes show great potential through the 30% composite briquettes that were produced.

5.7.2 Drop shutter test

The briquettes that were produced were dropped from a height of two meters to determine if they would withstand transportation. The composite briquettes that were produced using both molasses and kaolin clay at 10% weight percentage of the coal fines each could not withstand the two-meter drop. This shows that these briquettes are not strong enough for storage or transportation therefore further assessment is required to determine the best composition that can withstand transportation and storage without breaking (Botha, 2019). The 30% composite briquettes (15% molasses and 15% kaolin clay) formed strong briquettes that managed to withstand the drop shutter test as the briquette remained intact after being dropped. This shows that the utilization of both molasses and kaolin clay at optimized ratios has a chance of producing high quality briquettes with high strength for storage and transportation.

The binderless briquettes completely disintegrated upon reaching the ground from the two-meter height as shown in Figure 4.5c. the briquette requires a binder to ensure its stability so that they can be usable for energy extraction. The 30% composite briquettes (15% kaolin clay and 15% molasses as binders) broke to pieces after being dropped. This may have been because there was no balance between the bonds that were formed between the coal fines, molasses and kaolin clay.

The briquettes that were produced using 20% and 30% kaolin clay were strong as they managed to withstand the drop shutter test. Therefore, in terms of transportation, the briquettes that are produced with 30% are manageable as they do not easily break upon falling. However, the same briquettes could not withstand the water resistance test which makes them unsuitable for production.

The briquettes that were produced using molasses as a binder managed to withstand the drop shutter test as they did not shatter upon being dropped. This may have been due to strong bonds and balance between the coal fines and molasses which managed to produce high quality briquettes. Therefore, the 20% molasses briquettes proved to be more physically stable than the other compositions as they managed to withstand the water resistance and drop shutter test. Therefore, they were regarded as the optimum and further analysis was done on them. The results of the drop shutter test are summarized in table 5.11.

5.7.3 Proximate Analysis for the Briquettes

The optimum was subjected to proximate analysis and the results are presented in figure 4.7. The moisture content was 8.29% and was relatively low which shows that the briquettes that were produced are of good quality as the low moisture content allows for higher gross calorific value. The ash content was 19.17% which was slightly higher than that of the coal fines. this may have been due to the addition of the binder which also contributed to its residue leading to the sight increase of the ash content. Volatile matter was 35.57%. The higher volatile matter and fixed carbon content presented by the results show the potential that the coal fines have for easy ignition and high energy production (J. Zhang et al., 2021). (Adeleke et al., 2019) observed that the moisture content varies from 2.16% to 2.53% which is generally attributed to the addition of a binder. Curing the briquettes may also decrease the moisture in the briquette. This solves the challenges of spontaneous combustion and fire accidents that the coal fines pose on the environment as the coal fines self-ignite causing fire hazards in stockyards (Di et al., 2021). Air pollution that occurs due to spontaneous fires is also reduced due to briquette production.

5.7.4 Ultimate Analysis of the Optimum Briquettes

Table 4.12 presents the ultimate analysis results of the optimum briquets for the coal fines that are being produced at Hwange Colliery Company. The briquettes showed a high carbon content which indicates that the briquettes have high potential for energy production. This proves that the briquettes are a viable option for the utilization of the coal fines at Hwange Colliery Company. The high energy production is also evidenced by the HHV that the briquettes have of 21.59MJ/kg according to the Mendeleev's equation. The HHV is slightly lower than that of the coal fines which shows that the binder that was used did not have much effect on the energy composition of the briquette which makes it suitable for production and use. The prediction showed that if the briquettes are utilized, the harnessing of energy from the coal fines may be a success, which in turn leads to the reduction in pollution which occurs due to the disposal of the coal fines at Hwange Colliery Company.

5.7.5 Combustion patterns of the optimum briquettes and coal fines

The TGA curve for the briquettes is presented in Figure 4.8. Moisture loss occurred at approximately 105 - 180°C. Volatilization then occurred with the ignition potentially occurring at around 400 - 600°C for the 30°C ignition rate and Mass loss ended at approximately 750°C. The volatilization for the 20°C heating rate was around 350 - 550°C which was slightly lower than that of 30°C heating rate. The heating rate of 10°C/minute allowed for volatilization to occur between 300 - 550°C which was the lowest for the samples that were assessed. This showed that the lower heating rate had the potential of producing valuable results as it allowed for gradual temperature increase thereby giving time for reactions to occur (Botha, 2019). The heating rate of 30°C/minute produced a high ash residual mass of 1.99 grams as compared to the other heating rates. This difference may be attributed to the rapid temperature increase leading to caking which does not allow for maximum capable combustion to occur.

The graph shows that moisture loss was typically the same for the heating rates. However, the volatilization and ignition temperatures differ for the different heating rates due to the different heating patterns that occurred. A rapid residual mass decrease occurred from 400 - 450°C, 400 - 650°C and 300 - 600°C for the 30°C, 20°C and 10°C/ minute heating rates respectively. This clearly shows the effects of the varying heating rates on the combustion of the briquettes. The results also show that curing of the briquettes may be possible within temperatures below 300°C (Adeleke et al., 2019)

It was concluded that the addition of a binder to the coal fines had no significant effect on the combustion patterns of the briquettes. The briquettes showed that moisture loss occurred between 100 - 180°C. Volatilization then occurred and a rapid decrease of the residual mass followed at between 400 – 550°C. The ignition points are expected to lie within this range. From figure 4.9 it is also evident that, under these conditions that the briquettes could not manage to reach the expected carbon burn-out, which was to start between 650 – 900 °C. This may have been due to ash particles blocking the large voids in the briquettes (Hu et al., 2018).

The comparison of the combustion patterns for the coal fines and the optimum briquettes for the heating rates that were used in this study showed that the briquettes have a great potential for use as a heating fuel (figure 4.11). The combustion patterns for the coal fines and the briquettes that were produced presented very slight differences which shows that the briquettes that were produced are a viable option for the coal fines that are produced at Hwange Colliery Company. Therefore, the production of briquettes using the coal fines that are produced at Hwange Colliery Company may be implemented at Hwange Colliery Company to utilize the coal fines that have already been disposed of and the ones that are being produced so that air, water and soil pollution that has emanated from coal fines disposal may be reduced.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- This study comprehensively analyzed the characteristics and environmental implications of coal fines at Hwange Colliery Company, Zimbabwe. The particle size distribution analysis revealed variations among sites, ranging between 0 – 3mm with finer particles predominant in some areas.
- Proximate analysis results indicated differences in moisture content, volatile matter, and gross calorific value average of approximately 17.43MJ among sites, highlighting the potential for energy extraction from coal fines.
- The elemental analysis identified trace elements such as nickel, copper, cobalt, iron, sulfur, and oxides, which can have environmental implications if not properly managed. Copper, lead and nickel were found to be present in the soil in Hwange at levels above 11mg/l which shows the impact that the coal fines may be having on the soil quality.
- Critical feasibility and cost benefit analysis showed that the coal fines that are produced at Hwange Colliery Company may be utilized through briquetting as it has a low payback period of 13 months an internal rate of return of 90% and a net present value of $1 771 493.18.
- The briquettes that were produced using molasses as a binding agent at 20% weight percentage of the coal fines proved to be the most viable ratio amongst the ones that underwent physical strength tests.
- Reactivity analysis showed that the briquettes had similar combustion patterns to the coal fines which means that they are a good source of energy. The briquettes however produced slightly higher ash content due to the addition of molasses.

6.2 Recommendations

- Hwange Colliery Company may implement the production of briquettes in an effort to utilize the coal fines that have already been disposed as well as the ones being currently produced as part of the solution to the coal mining challenges that the coal mining communities face.

- Future research should focus on long-term monitoring and comprehensive socio-economic assessments are recommended to ensure effective implementation and continuous improvement of these strategies.
- The use of composite briquettes may also be analyzed to determine the optimum ratios that may be utilized as they present a great potential to produce high quality briquettes.

6.3 Further Work

- The research comprehensively assessed the environmental impacts of the coal fines in Hwange however, the temporal aspect of sample collection may be put into consideration as variations in weather conditions, seasonal changes, and differing disposal durations could influence the moisture content, particle size distribution, and chemical composition of the coal fines. Therefore, the results might not reflect long-term trends or seasonal variations.
- The research assessed the environmental effects that coal fines disposal has on flora and fauna, however, long-term environmental and health impacts, such as bioaccumulation of heavy metals in local flora and fauna, may be investigated.
- Techno-economic analysis was done for the coal fines at Hwange Colliery Company, nevertheless, future research should also focus on long-term monitoring and comprehensive socio-economic assessments are recommended to ensure effective implementation and continuous improvement of these strategies.
- The use of composite briquettes may also be further analyzed to determine the optimum ratios that may be utilized as they present a great potential to produce high quality briquettes.

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Appendix A

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REVIEW ARTICLE

The ecological effects and valorization of coal fines—a review

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Abstract
The beneficiation and valorization of coal fines is an important element that has to be considered in coal waste management. This review aims to assess the potential ecological impacts that arise due to coal fines dumping and the various methods that can be used for value addition and beneficiation of the coal fines for domestic and industrial use. The PRISMA method was used for the identification and inclusion of studies in the review and studies which focused on coal fines production, utilization, and their effects on the environment which were included in the review. The review showed that several technologies such as briquetting, pelletization, coal–water slurry, brickmaking, and fluidized bed technology have been developed in an effort to reduce the quantities of coal fines in the environment as they are an ecological threat through air, water, and soil pollution. These methods have the potential to be scaled up to the industrial level as there are vast quantities of coal fines to support the industry.

Keywords Coal fines, · Coal fines utilization, · Ecological effects, · Coal, · Energy, · Waste

Introduction

Coal fines are an unavoidable mechanical by-product of the coal mining process (Muzenda 2014). Coal fines have a high moisture content of approximately 25 wt.%, an ash content of approximately 45%, and a net calorific value that ranges between 2 and 14.6 MJ/kg (Muzenda 2014; Le Roux et al. 2015). These properties make the utilization of coal fines difficult which results in their disposal in the environment mostly on open dump sites (Adeleke et al. 2019). Coal fines make up about 15–20% of the coal that is produced by a specific plant and at times may comprise up to 50% depending on the friability of the coal. Coal fines generation in South Africa comprises up to 6% of the total coal that is being produced (Önal et al. 2007; Le Roux et al. 2015).

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The generation of coal fines occurs due to mechanical stress during any step within the production, beneficiation, and utilization of coal. Coal production comprises the mining and cleaning processes. The cleaning process includes pre-crushing to produce coal sizes as required by the market and coal fines are also produced in the process (Önal et al. 2007; Le Roux et al. 2015). Modern mechanized techniques tend to increase the quantity of coal fines that are produced within the coal mining processes (Guan et al. 2018).

Coal fines may be produced during the process of extraction of coal bed methane due to mechanical abrasion, pressure fluctuations, and liquid erosion (Adeleke et al. 2019). The properties of coal and its geological conditions may also contribute to the production of coal fines. The mining technique that is used for coal extraction and the type of crushing system used to produce the desired coal particle sizes for the market also influence the quantity of coal fines (Honaker et al. 2013).

In the current world energy sector, coal generates approximately 27% of the total energy that is produced (United Nations. Statistical Division 2022). In 2021, 7.5 billion tonnes of coal were produced for consumption. This means that a substantial amount of coal fines were produced which require attention to minimize their effects on the environment (Belonogov et al. 2023).

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