SUGARCANE BAGASSE: AN ALTERNATIVE ADSORBENT FOR THE REMOVAL OF HEAVY METALS FROM TOXIC WASTEWATER FROM THE MINING INDUSTRY

by

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ABBREVIATIONS AND ACRONYMS

µg/L:	Microgram per litre
µm:	Micrometre/ Microns
m^2/g:	Square metre per gram
m^3/s:	Cubic metre per second
mg/kg:	Milligram per kilogram
mg/L:	Milligram per litre
nm:	Nanometres
pH:	The acidity or alkalinity of a substance
AMDW:	Acid mine drainage water
AOP:	Advanced oxidation process
BET:	Brunauer- Emmett -Teller
CDWG:	Canadian Drinking Water Guidelines
DEAT:	Department of Environmental Affairs and Tourism
DFFE:	Department of Forestry, Fisheries, and the Environment
EHS:	Environment, Health & Safety
DMRE:	Department of Mineral Resources and Energy
DWAF:	Department of Water Affairs and Forestry
EC:	European Commission
FTIR:	Fourier Transform Infrared Spectroscopy
HCS:	Hazardous Chemical Substances
ICP AES:	Inductively Coupled Plasma Atomic Emission Spectroscopy
IFC:	International Finance Corporation
ISO:	International Organisation for Standardisation
MC-X:	Mining Company (MC-X)
MC-Y:	Mining Company (MC-Y)
NEMA:	National Environmental Management Act
OECD:	Organisation for Economic Co-operation and Development
SANAS:	South African National Accreditation System
SANS:	South African National Standard
SAWQG:	South African Water Quality Guidelines

SCB:	Sugarcane Bagasse
SCBA:	Sugarcane Bagasse Ash
SCPC-A:	Sugarcane Processing Company A
SCPC-B:	Sugarcane Processing Company B
UESA:	Uniform Effluent Standards Approach
UN SDG:	United Nations Sustainable Development Goals
USEPA:	United States Environmental Protection Agency
UV/VIS:	Ultraviolet-Visible Spectroscopy
WBG:	World Bank Group
WFD:	Water Framework Directive
WHO:	World Health Organisation
WRC:	Water Research Commission
WTP:	Water Treatment Plant
XRF:	X-Ray Fluorescence

ABSTRACT

South African mining companies are currently exploring various water purification technologies to treat the wastewater to potable levels. One of the most employed methods in wastewater treatment within the mining industry involves ion exchange techniques that utilize polymer resins and activated carbons. However, the disposal of non-biodegradable resins, for example, presents environmental challenges, in addition to the excessive costs associated with it. This study sought to assess the effectiveness of sugarcane bagasse (SCB) as an alternative adsorbent in the purification of wastewater from the mining industry, thus providing a natural, biodegradable ion exchange method that is environmentally friendly. SCB, which is a major by-product of the sugarcane processing industry, offers a promising alternative for wastewater treatment and management. The SCB samples were sourced from two sugar cane processing plants, and wastewater was collected from two mining companies based in Gauteng Province. The experimental setup involved the application of pristine, pulverized and gas-pre-treated SCB as well as SCB Ash with mining wastewater as a control. Other parameters studied included varying the pH, temperature, surface area, adsorption coefficients, pressure, and gas effects, supported by graphical representations. Results indicated that SCB is effective in removing 48% of copper for pristine SCB at ambient temperature and unadjusted pH. Oxygen pre-treated SCB at 120 °C and removed 95% of iron at pH 4.5, and pulverized SCB of 75 microns pre-treated at a constant temperature of 25°C removed 81% of nickel at pH 4. Nitrogen pre-treated SCB at 180 °C removed 85% of manganese at pH 4.5. Changing the pH of wastewater to nine only enhanced the removal of zinc to 96%. An unadjusted pH of 4.5, which is the original pH of the mine wastewater, achieved the highest adsorption of up to 85% for manganese. The selectivity of SCB for heavy metal removal from wastewater was observed with pulverized SCB, confirming that changes in SCB surface area affect the rate and efficiency of heavy metal adsorption. This phenomenon was observed when pulverized SCB removed the highest of metal to over 80% manganese, iron, and zinc. An increase in contact time to four hours did not yield better removal efficiency since the heavy metals were removed within the first two hours of the experiment. The initial concentration of heavy metals in the wastewater was less than 1 g/L for all heavy metals, and the rate of adsorption of these heavy metals was not in any way linked to their concentration. Therefore, SCB

presents good prospects as an adsorbent for the removal of heavy metals from the mining industry, and it works similarly to resins and activated carbon. Mining companies may implement the use of SCB as an adsorbent for dissolved metals in wastewater, whereas farmers may consider modification of SCB to use it as an organic fertilizer at the end of its lifecycle as an adsorbent because it is bio-degradable, readily available, and environmentally friendly.

Keywords*:* Natural adsorbent, Sugarcane bagasse, Sugarcane bagasse ash, Water purification, Water quality, Heavy metal removal, Mine effluent treatment, Water contamination, Hazardous chemical substances, Ion exchange resins.

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1. CHAPTER 1: INTRODUCTION

1.1 Background

Water is the source of life, and the United Nations Sustainable Development Goals (UN SDG) 2030 Agenda 6, Clean Water and Sanitation, and 14, Life Below Water, put the onus on countries to prevent water pollution, eliminate the dumping of hazardous chemical substances, and the release of untreated wastewater into water bodies (United Nations, 2015). Therefore, countries must protect and restore water ecosystems, promote water recycling and reuse, employ sustainable freshwater supply to address scarcity, and implement integrated water resource management.

The mining industry globally, as one of the freshwater contaminators, continues to struggle with managing hazardous chemical substances, thereby creating a strain on the quality of the water system (Illoms *et al*., 2020). The major concern is the adverse effects of industrial effluents containing toxic heavy metals and pollutants, which negatively affect the aquatic ecosystem (Rahman *et al*., 2019). Some of the biggest challenges the mining industry faces include inappropriate waste management, which can lead to accidental spillage of materials containing hazardous chemicals or the unintended release of untreated wastewater. When mine dumps are vulnerable to erosion and silting, runoff from rainfall carries pollutants into the aquatic system, while dumps situated by the riverbank raise the suspended particulate concentration in surface water (Sankhla *et al*., 2016). When it rains, the leachate flows into the water systems, resulting in contaminated water that requires treatment before it is acceptable for the ecosystem.

When dumps that contain sulphur materials such as pyrite (FeS_2) get oxidised, acid mine drainage (AMD) becomes the most difficult wastewater to treat. The occurrence of sulphur deteriorates the quality of water by lowering its pH level. Since mining and metallurgy use copious quantities of water, it has become critical to minimise water consumption in moving towards a more sustainable mining industry and the circular economy. Heavy metals are non-biodegradable, and they are a persistent source of water contamination globally (Karri *et al.,* 2020). Water pollution due to hazardous chemical substances, such as contamination by heavy metals, is a continuous threat to human health and the environment (Anastopoulos *et al.,* 2017; Zaynab *et al.,* 2022). Many challenges are associated with water pollution from the mining industry, for

example, by impacting farming land, where decanted mine water stored in the soil alters its chemical balance, leading to the relocation of farmers and surrounding communities to alternative farming areas (Naidoo *et al.,* 2022).

Poorly managed sludge dams result in runoff stormwater carrying dissolved heavy metals into the soil, seeping away, and affecting the quality of groundwater. When runoff stormwater reaches surface water bodies, the water becomes more acidic, while the heavy metals settling on the riverbed dissolve again under heavy rain (Lu *et al.,* 2021). Pollution of water by heavy metals and other pollutants in the freshwater supply remains a challenge, whose effects are a global concern that has increased during the past few decades (Javed *et al.,* 2018). According to Kumar *et al. (*2019), pollution of aquatic ecosystems with trace elements is a global problem. For countries classified as underdeveloped by the UN, the lack of equipment and technical expertise to detect heavy metal pollution remains the biggest obstacle relating to water contamination. This necessitates the development of primary guidelines and standards for drinking water (USEPA, 2010), which indicate chemicals that pose a health risk to humans with maximum allowable limits, with secondary guidelines regulating the public in the management of drinking water by focusing on taste and odour aspects (USEPA, 2012).

Most mining companies employ wastewater treatment methods for the removal of hazardous chemical substances (Awaleh *et al.,* 2014). These methods include, but are not limited to, solvent extraction, chemical precipitation and neutralisation, membrane filtration, adsorption, and ion exchange (Rashid *et al.,* 2021). Alternative methods for treating wastewater from the mining sector, including selective resins and activated carbon, among others, have proven effective in managing water pollution and wastewater treatment for numerous years. However, the challenge with the use of these methods is the waste management since they are costly and non-biodegradable.

In ancient times, distillation, crystallisation, nano-filtration, sublimation, extraction, and chromatography were among other methods used to purify, separate, and enhance the properties of chemical compounds (Ahmad *et al.,* 2019).

Water treatment techniques, for example, among various other techniques, neutralisation, precipitation and membrane filtration are successful, but there are

concerns relating to low economic feasibility, difficulty in design and operation, high operational and maintenance costs, and environmental aspects such as waste management. There is not enough documented evidence on the purification of mining wastewater using natural absorbents and membranes, except for cellulose (Almadani, 2023). Water companies such as Rand Water produce potable water using methods such as coagulation, flocculation, sedimentation, stabilisation, and chlorination, while the home environment centre uses granular activated carbon, reverse osmosis, and ultra-violet (UV) disinfection.

Ion exchange using physical and chemical methods for wastewater purification is common and preferred. The use of synthetic resins remains an effective conventional method of wastewater treatment, but the synthesis and cost of this method remain high; hence, the need to employ natural ion-exchange methods such as SCB is relevant (Kithinji *et al.,* 2022).

South Africa is a freshwater-scarce country, and the distribution of available water resources is unequal. At the same time, freshwater demand exceeds supply, leading people, particularly in rural areas, to grapple with severe water shortages (CSIR, 2010; Water Research Commission, 2014). Challenges such as climate change, population growth, high water consumption, mining operations, inadequate wastewater treatment, and water resource management increase the demand for clean water (Hoang *et al*., 2019; Zhou *et al*., 2019). Surface water threatened by point-source pollution from partially treated wastewater becomes a problem for the population's recreational, nutritional purposes, and potential use (Vu *et al*., 2017; Hoang *et al*.,2020; Edokpayi *et al*., 2021). Since mining effluents compose the main source of chemical pollution in South African water systems, and they aggravate challenges of freshwater supply and scarcity in the country and globally (Illoms *et al*., 2020), there is a need to undertake such a study and explore alternative methods and technologies for wastewater treatment from mining industries.

Thus, this study aimed to develop a sustainable wastewater treatment technique using natural, readily available, cost-effective, and biodegradable materials, and assist in meeting the objectives described by the UN Sustainable Development Goals six, twelve, fourteen, and seventeen for the 2030 Agenda. If potable water is achieved using SCB, it will contribute to water recycling and reuse for different purposes, whilst

assisting in addressing water scarcity challenges in South Africa. It will also assist in preventing excessive use of chemical fertilisers, thereby preserving soil texture and its mineral balance essential for sustainable crop production. The mining industry will eliminate the use of polymer resins in treating mine wastewater and contribute to the environmental management of waste generated in the sugar processing industry, while ensuring the circular economy principle is implemented.

1.2 Problem statement

Water contamination with heavy metals has become a serious environmental issue due to rapid urbanisation and industrialisation (Sarker *et al*., 2021). Most mining companies apply wastewater treatment methods for the removal of hazardous chemical substances (Awaleh et al., 2014). These methods are not limited to solvent extraction, chemical precipitation and neutralisation, membrane filtration, adsorption, and ion exchange (Rashid *et al*., 2021). Chemical treatment methods are preferred because of their simplicity, flexibility, and economic feasibility (Azam *et al*., 2020), although they produce sludge that is not easy to filter, leading to waste and environmental management issues (Macedo *et al*., 2022).

Wastewater treatment in the mining industry using ion exchange methods such as resins and activated carbons has scientific evidence for successful treatment of wastewater. However, there is an environmental challenge that comes with the handling of loaded synthesised resins and activated carbon, as well as the high cost that is associated with the disposal thereof (Chaudhary *et al*., 2020). Additionally, ion exchange techniques involving selective resins, for example, are eluted using dilute acid when loaded with impurities, which leads to the generation of more effluent that requires treatment before releasing the water into the municipal water system. Therefore, this research focuses on the adsorption and ion exchange methods of treating toxic wastewater from the mining industry using SCB to address a gap that exists in the use of environmentally friendly technologies.

1.2 Aim and Objectives

1.2.1 Study Aim

This study aimed to evaluate the effectiveness of SCB as an alternative adsorbent for the removal of heavy metals from toxic wastewater from the mining industry.

1.2.2 Study Objectives

- To compare the effectiveness of pristine and gas pre-treated SCB using oxygen, nitrogen, hydrogen, or air in removing heavy metals such as iron, manganese, nickel, and zinc from the mining wastewater.
- To establish the performance characteristics of SCB by comparing the unmodified and the pre-treated SCB in a fluidised reactor.
- To establish the effectiveness of sugarcane bagasse ash (SCBA) as an alternative material to SCB in purifying mining wastewater.
- To compare treated water to the standards set for drinking water by South African National Standards (SANS 241), and water quality guidelines for industrial effluents as determined by the Department of Agriculture and Forestry, and the City of Johannesburg Municipal bylaws.

1.3 Research Questions

Environmental challenges facing ion exchange methods for the removal of heavy metals from mining wastewater have raised the following questions:

- Can pristine SCB or modified through pulverisation and catalysis, be used as a cheaper and more effective adsorbent material for the removal of heavy metal ions from wastewater generated from the mining, mineral processing, and metallurgical industries?
- Can SCBA work efficiently enough to produce the desired outcome, like SCB, in the purification of mining wastewater?
- Can pristine SCB perform the same as the gas pre-treated bagasse that has been pressurised under different natural gases in a fluidised reactor?
- Can SCB-treated water be of the same quality as per the guiding water quality standards? The guiding water quality standards are indicated in Appendices one to ten and are as follows:

  Appendix 1: SANS 241 Chemical, physical, and aesthetic determinants of requirements for drinking water.

  Appendix 2: Chemical constituent requirements for drinking water and human health criteria.

  Appendix 3: Chemical determinant requirements for the City of Johannesburg municipal bylaws.

Appendix 4: Chemical constituents' requirements for aquatic organisms' freshwater quality criteria.

Appendix 5: Chemical constituents' requirements for aquatic organisms' saltwater quality criteria.

Appendix 6: Chemical determinants requirements for agriculture- irrigation water quality criteria.

Appendix 7: Chemical determinants requirements for agriculture- livestock water quality criteria.

Appendix 8: Chemical determinants and requirements for aquaculture water quality criteria.

Appendix 9: Chemical determinants requirements for recreational water quality criteria.

Appendix 10: Chemical constituents' requirements for industrial water quality criteria.

1.4 Rationale/Justification of Study

Mining companies use chemicals, such as lime, and non-biodegradable materials, such as polymer resins, for the purification of mining wastewater. Although these methods are effective in water purification, the safe disposal remains a challenge since the cost of regeneration and reuse is high. Farmers, on the other hand, use excessive artificial fertilisers to produce sugarcane. This research investigates a value chain opportunity between the farmers, the mining industry, and the sugarcane industry to meet circular economy principles, to complement the United Nations (UN) Sustainable Development Goals (SDGs) for the 2030 Agenda, as they enhance, advance and progress their businesses.

The outcome of this research presents a potential use of SCB as an alternative adsorbent material for treating mine-impacted wastewater. SCB is an environmentally friendly, biodegradable, readily available, and cost-effective adsorbent that can work efficiently just like commercial resins and activated carbon. SCB is also selective in removing specific heavy metals under adjustable conditions. Unlike polymer resins, heavy metal-loaded SCB can be exposed to the following:

- ***Pyrolysis***: Heavy-loaded SCB can be exposed to a furnace at elevated temperature to turn into ashes. The SCB ash may be modified with phosphates to be used as a fertiliser for legume production.
- ***Hydrometallurgy***: SCB loaded with heavy metals can be exposed to hydrometallurgical processes such as leaching. Heavy metals can be recovered from the heavy metal-loaded SCB before it can be reused or presented to the farmers.

1.5 The Scope of Study

This research focuses on the ion exchange method using SCB as a sustainable alternative material for the treatment of toxic wastewater from a mine. Many researchers have engaged in the adsorption of base metals from wastewater of variable origins using chemically modified SCB, fibres, polymer resins and activated carbon. However, the study focuses on the use of pristine, pulverised and gas pre-treated SCB to remove heavy metals from the mining wastewater. The study only focuses on the effect of temperature, pH, surface area, and gas pretreatment of SCB on the removal of heavy metals such as chromium, cobalt, copper, iron, lead, manganese, nickel, and zinc. The reason for the selection of these heavy metals is that many mining companies extract, recover, refine, and purify such heavy metals, and most of their environmental challenges mostly involve with these heavy metals. Moreover, this study does not involve anions such as nitrates, chlorate, and sulphates, nor other hazardous chemicals such as cyanide, arsenic, or radioactive material such as uranium and thorium.

1.6 Limitations of the Study

This study is only limited to the scope of mining wastewater since other researchers have assessed the effectiveness of SCB in heavy metal removal from other aqueous solutions and industrial wastewater from different sectors. The study is limited to the use of natural SCB and does not include SCB preparations using hard chemicals like acids or bases. These limitations are due to a lack of subject knowledge of thermodynamics and physical chemistry, a shortage of human resources, expertise, and a constrained budget, and most importantly, the study is focused on the application of natural methods in environmental science fields. Chemical assay and evaluation of environmental risks of pollutants based on the bioassay to provide

reasonable, intuitive, and dynamic evidence of the health risks of wastewater will not form part of this study due to a lack of ecotoxicological and other related expertise.

1.6 The Hypothesis

This research work investigates the effect of SCB and sugarcane bagasse ash (SCBA) as a sustainable alternative method to ion exchange techniques for removing heavy metal ions from toxic wastewater generated from the mining industry.

To establish that SCB can work to purify the mining industry wastewater by removing heavy metals such as copper, cobalt, chromium, iron, lead, manganese, nickel and zinc, as well as determine the effect of the pore size on the surface area of SCB, the pH of the solution, the pretreatment temperature and the pretreatment of SCB on the absorptivity of heavy metals from wastewater.

1.7 Significance and Importance of the Study

The significance of this research applies to the sugar processing companies, the mining companies, and the agricultural industry (farmers). Although some sugar processing companies burn SCB for energy generation, they continue to face challenges with handling and storage of copious quantities of SCB and SCBA, leading to environmental issues such as air and soil pollution that may extend to groundwater pollution. This research establishes the value chain, where mining companies utilise the SCB and SCBA to treat the wastewater, easing the burden of waste handling and storage to the sugar processing companies. On the other hand, the farmers would use the SCBA and prevent the use of chemical fertiliser. This contribution enhances sustainable waste management and the preservation of soil for future generations.

The mining companies could use environmentally friendly material, which enables them to save waste disposal costs associated with the use of resins and activated carbon. There is a potential to save water using SCB for the purification of mining wastewater. Once the treated wastewater achieves one of the water quality standards, the water can be reused for a specific purpose.

1.8 Structure of Dissertation

Chapter 1 (Introduction): The chapter discusses the impact of heavy metals on water quality during processing and recovery in the mining industry, making the mining

sector one of the main water contaminants. It further describes the aims and objectives of the study, which is to decontaminate mining wastewater using sugarcane bagasse (SCB) that is chemically unmodified to establish its capability to produce similar results as activated carbon, polymer resins and other natural materials such as biochar and agricultural waste. This chapter aims to replace the use of polymer resins and activated carbon by introducing the environmentally friendly SCB. The novelty of this study is that although similar research using SCB has been done to purify different industrial wastewater, the purification of mining wastewater has not been explored. The outcome of this research will establish the use of SCB in the mining industry for wastewater purification, eliminating the use of polymer resins and industrial activated carbon. The research highlights the need for companies to implement the concept of circular economy, focus on the UN Sustainable Development Goals for Agenda 2030, and create a working relationship between farmers, sugarcane processing industries and mining companies.

Chapter 2 (Literature Review): The chapter provides a summary of reviewed work that has been conducted by researchers globally using different natural materials, including SCB, in the purification of different industrial wastewater and aqueous solutions. Several wastewater treatment methods, such as chemical precipitation, adsorption, and ion exchange, have been tested by the mining industry. Although the outcome of these methods is satisfactory, economic and environmental concerns, such as storage, handling, treatment, and disposal of impregnated material, remain a challenge. Hence, this research aims to introduce methods involving SCB, which is a cost-effective, readily available, and environmentally friendly material for the purification of mining wastewater.

Recent findings on the use of SCB for treating wastewater from these industries produce conflicting interpretations and findings, indicating that SCB is only effective when chemically modified. The effectiveness of SCB, for example, in the removal of heavy metals such as chromium in the paint industry requires activation of SCB using acid or base, thus introducing the carboxylic and hydroxyl functional groups. This study, therefore, aims to introduce the use of unmodified SCB for the removal of heavy metals from mining wastewater. The efficacy of using pristine SCB in the adsorption of heavy metals in toxic wastewater is comparable to findings in studies involving the

use of chemically modified SCB, even though studies related to the application of mine wastewater are limited.

Chapter 3 (Experimental Methods): The chapter highlights the methods used to test SCB in the treatment of mining wastewater. Mine wastewater was sourced from mining companies that process, handle and recover heavy metals around Gauteng Province. The SCB has been obtained from the sugar processing companies based in different regions of the KZN province. The SCB was pulverised at 75 microns, and the gas pretreatment was done in a fluidised reactor at a constant gas flow rate, pressure and variable temperatures of up to 180 °C. The wet bench work involved the transfer of a 20 g sample of pristine, pulverised and gas pre-treated SCB in a scotch bottle with the wastewater from the mining companies. The scotch bottle was transferred to a shaking table for up to 5 hours, under different conditions, such as variable pH. The slurry was filtered, and the flow-through was taken to an accredited testing laboratory for chemical analysis. The results were analysed and interpreted based on analytical chemistry principles.

Chapter 4 (Results and Discussion): The analytical results obtained from the ISO 17025:2017 accredited lab was grouped in categories for pristine, pulverised, and thermally pre-treated SCB. Analytical results indicated that pristine SCB pre-treated at ambient temperature was effective in removing 48% copper from the mine wastewater at pH 2.

Oxygen pre-treated SCB at 120 °C removed 95% iron from the mine wastewater at pH of 4.5. The influence of the surface area of SCB was noted in the removal of nickel, achieving an 81% reduction of nickel using pulverized SCB at 75 microns, at pH 4.5. Additionally, an 85% removal of manganese from the mine wastewater at pH 4.5 was observed for nitrogen pre-treated SCB at 180 °C. A change in pH to nine enhanced the absorptivity of zinc, reaching up to 96% zinc removal. An unadjusted pH of 4.5 achieved the highest adsorption of manganese up to 85%, and the selectivity of SCB in heavy metal removal from wastewater was enhanced with changes of surface area of the SCB.

From the literature review, these results are comparable to the results obtained by different researchers for the removal of heavy metals from various industries. Based on the outcome of this research, it can be deduced that SCB does not necessarily

require chemical modification for the removal of heavy metals from mining wastewater. The pre-treatment of SCB using various gases at different temperatures in the fluidized reactor enhances the efficiency and the selectivity of SCB in removing heavy metals. Also, pulverization as a pre-treatment method confirms the significance of the surface area of the adsorbent material. **Chapter 5 (Conclusion and Recommendations):** The chapter concluded that SCB, both pristine, pulverised and gas pre-treated, and SCBA were successful in the removal of copper, iron, manganese, nickel, and zinc from the mine wastewater. Future research work may be explored to investigate the effectiveness of SCB as an adsorbent for the removal of anions such as chloride, sulphates, nitrates, and cyanate. Furthermore, this study did not investigate the capability of SCB to remove radioactive material such as uranium and thorium, as well as other hazardous chemical substances such as arsenic. Recent studies did not indicate how heavy metal impregnated SCB has been addressed, but this research indicates that SCB impregnated with heavy metals may further be processed through hydrometallurgy or pyrolysis before being used by farmers as a potential fertiliser. Finally, the research has established that using SCB under different conditions targets a specific heavy metal removal and outlines extraction methods of heavy metals and future work that will involve process engineers and other experts extracting the heavy metals selectively through column sequencing.

2. CHAPTER 2: LITERATURE REVIEW

2.1 Background

The treatment of wastewater from the mining industry using different methods, such as chemical precipitation, physical membrane filtration, selective resins, activated carbon, and many other methods, has yielded efficiency in dealing with water pollution and wastewater treatment for many years. However, the challenge with the use of these methods is waste management since they are costly and non-biodegradable. This study focuses on SCB because it is biodegradable, economically viable, and readily available. The importance of this study lies in the fact that SCB is a waste from sugarcane processing, and there are challenges associated with the environment, storage, and handling of SCB. The study was to detect and establish whether SCB is effective in the treatment of wastewater from the mining industry and, in so doing, encourage further research on whether SCB can be modified based on the analytical results and guidelines for water quality standards as described in chapter four and the appendices 1 to 10. This may create a value chain between the sugar manufacturers, the farmers, the water sector, and government departments such as the Department of Fisheries, Forestry, and the Environment (DFFE) and Water and Sanitation (DWS).

Most mining companies apply wastewater treatment methods for the removal of hazardous chemical substances (Awaleh *et al.,* 2014), which include, but are not limited to, solvent extraction, chemical precipitation and neutralisation, membrane filtration, adsorption, and ion exchange (Rashid *et al.,* 2021). Wastewater treatment using chemical methods is easy, fast, and efficient, except that they are based on a lab scale, which is not economically feasible for small industries, while physical methods, such as filtration, are not complicated to use even in high pollutant concentrations, because physical methods only work effectively for suspended particles and dyes. The chemical treatment method is a preferred treatment method because of its simplicity, flexibility, and economically feasible nature (Azam *et al.,* 2020). Chemical treatment methods produce sludge that is difficult to filter, leading to another environmental management issue (Ponnu Sámi *et al.,* 2023).

Heavy metals are natural components of the Earth's crust; they are metallic elements with high atomic weight and density greater than that of water. Heavy metals are non-degradable and cannot be destroyed by normal chemical or biological processes, so

they are permanent toxic materials even at low concentrations (Gohermi *et al*., 2015), and they are a source of water contamination globally (Karimi *et al.,* 2020). Heavy metals are also bio-accumulative, have neurological impacts, and some are carcinogenic (Ali *et al*., 2019). They can interfere with chemical processes by inactivating chemical catalysts and biochemical processes by enzyme inhibition (Abd Elnabi *et al.,* 2023). Heavy metals such as copper (Cu), iron (Fe), chromium (Cr), zinc (Zn), and nickel (Ni) are essential metals for the aquatic environment in trace amounts (Karalliedde *et al.,* 2012). These elements play a significant role in biochemical systems and are required as micronutrients (acting as cofactors) for life processes in aquatic plants, animals, and microorganisms, while elements such as cadmium, mercury, and lead are non-essential toxic metals, even in trace amounts, with no known biological function, but pose serious environmental and economic impacts (Talbot *et al*., 2017). Copper is a heavy, typical transition metal that occurs widely in nature and is the third most-used metal in the world (Mallik *et al*., 2022). While it is one of the most toxic heavy metals, it is an essential element required by humans for enzyme synthesis and for bone and tissue development (Cheng *et al*., 2022). Copper comes in different forms, including the metal Cu, the cuprous ion Cu(I), and the cupric ion Cu (II). According to Varma and Misra (2018), in an aqueous environment, copper can contaminate groundwater systems, affecting drinking water, which can threaten human health (Ortega *et al*., 2022).

2.2 General Perspective on Water Pollution

There are many sources of water pollution; however, the primary focus of this study is mining and metallurgical activities, and the use of environmentally friendly ion exchange methods for wastewater purification. Pollutants are substances that cause undesirable effects when introduced into the environment. Most environmental pollutants arise from anthropogenic activities such as mining, agriculture, and industrialisation (Ukaogo *et al.,* 2020), whereas natural pollutants such as forest fires, volcanic eruptions, biological pollution, and pollen can also have significant environmental pollution effects. Water quality is affected by various water pollutants with distinctive characteristics, such as agricultural and atmospheric pollutants, which include pesticides, herbicides, pathogens, and sediments, among others (Chaudhry *et al.,* 2017). Agricultural pollutants, such as nitrogen-rich fertilisers, have high water

solubility and reach water bodies through rainwater runoffs or floods, causing eutrophication (Vera-Herrera *et al.,* 2015). Atmospheric pollutants are small particles in the air that reach the water bodies through rain. An example of such pollutants is carbon dioxide produced after the burning of fossil fuels (Copeland, 2016). Pathogens and bacteria are microorganisms that pollute drinking water and cause diseases. Herbicides and pesticides are chemicals used to control weeds and pests, and both contribute to water pollution (Roy *et al*., 2014). Sedimentation runoff affects water quality and decreases the capacity of streams and rivers. Chemical pollution arises from chemical factories as by-products during manufacturing processes and plays a huge role in water pollution (Chaudhry *et al.,* 2017).

2.3 Heavy Metal Contamination as a Source of Water Pollution

Heavy metals are non-biodegradable, and they are a source of water contamination globally (Karri *et al.,* 2020). Water pollution due to hazardous chemical substances, such as contamination by heavy metals, is a continuous threat to human health and the environment (Anastopoulos *et al.,* 2017; Zaynab *et al.,* 2022). Many challenges are associated with water pollution from the mining industry, for example, by impacting farming land, where decanted mine water stored in the soil alters its chemical balance, leading to the relocation of farmers and surrounding communities to alternative farming areas (Naidoo *et al.,* 2022). Sludge dams that are poorly managed result in stormwater runoff carrying dissolved heavy metals into the land, and runoff seeps away, affecting groundwater quality. When stormwater runoff reaches surface water bodies, the surface water becomes more acidic, and heavy metals settled on the riverbed dissolve again under heavy rain conditions (Lu *et al.,* 2021). Pollution of water by heavy metals and other pollutants in the freshwater supply remains a challenge in many parts of the world, and the pollution effects are a global concern that has increased during the past few decades (Javed *et al.,* 2018). According to Kumar *et al.* (2019), pollution of aquatic ecosystems with trace elements is a global problem. For countries classified by the UN as underdeveloped, a lack of equipment and technical expertise to detect heavy metal pollution in water remains the biggest challenge relating to water contamination that led to the development of the USEPA (2022) primary guidelines and standards for drinking water, indicating chemicals that pose a health risk to humans with maximum allowable limits and a secondary guideline the

USEPA (2012) for guiding the public in managing drinking water, focusing on taste and odour.

In Johannesburg, Gauteng province, gold mining activities in the Witwatersrand area have caused consistent and pressing problems with the quality of water bodies, particularly in the aquifer overlying and adjacent to the Witwatersrand area (Durand 2012; Turker *et al.,* 2016; Frimmel *et al.,* 2019). The problems resulted from the dewatering of the aquifer and contamination caused by acid mine drainage (AMD), which remains the most difficult mining wastewater to purify. Three of the mine dumps are the most hazardous because of their high uranium, cyanide and sulphate content, heavy metal pollution, and AMD. Rivers that are connected hydraulically to this watercourse draw uranium-polluted plumes through the karst aquifer, and the ecological impacts of discharged effluent on wetlands and groundwater have significantly affected the quality of water sources in Gauteng and North-West Provinces. Environmental reports are not accessible to the public, but to the government, which is lenient towards mining companies for the sake of maintaining cordial relationships (Durand, 2012).

In the past decade, the water quality of rivers, wetlands, and groundwater has deteriorated due to the discharge of effluents from mines in Gauteng and the North-West Province (Minnaar, 2020; Atangana *et al.,* 2021). Gold mining activities in the Witwatersrand area have caused consistent and pressing problems with the quality of water bodies, particularly in the aquifer overlying and adjacent to the Witwatersrand area (Durand, 2012). The problems result from the dewatering of the aquifer and pollution caused by acid mine drainage (AMD), which remains the most difficult mining wastewater to purify (Naidu *et al.,* 2019). According to the Department of Mineral Resources and Energy (DMRE), there are over 8,000 derelict and ownerless mines in South Africa, which would take a long time to rehabilitate due to the excessive cost associated with it and the shortage of human and other resources required to address the issue (Mhlongo & Amponsah-Dacosta, 2016).

The Witwatersrand goldfield stretches across four hydraulically distinct mining basins: the eastern basin in Ekurhuleni, the central one in Johannesburg, the western one in Krugersdorp, and the far west one in Carletonville. Three of the mine dumps known to be the most hazardous because of their high uranium content are connected

hydraulically to this watercourse, and Zuurbekom, a source of Johannesburg's potable water, draws from this uranium-polluted plume through this aquifer (Durand *et al.,* 2012). The Olifants River catchment, located in the Mpumalanga and Limpopo provinces of South Africa, has been described as the most polluted river in South Africa (Ramudzuli, 2019). Heavy metal pollution index, as indicated by a recent study, shows that more than seventy-five per cent (75%) of the area does not have good water quality (Atangana *et al.*, 2021). The authors highlighted that infants, children, and adults consuming water from the contaminated boreholes were exposed to significant amounts of metals such as uranium.

2.4 Global Perspective on Water Quality

According to Kumar *et al.* (2019), pollution of aquatic ecosystems with trace elements is a global problem. Underdeveloped countries, as indicated in Figure 2-1, lack the equipment and technical expertise to detect heavy metal pollution in water, and remain the biggest challenge relating to water contamination. The World Health Organisation drinking water quality guidelines indicate that the chemical requirements for drinking water focus on the public health of people (WHO, 2022). According to Sunday *et al.* (2022), poor water quality occurs when pollutants such as organic, inorganic, biological, radioactive, and many other pollutants are introduced directly or indirectly into water sources, altering the physical, chemical, and biological properties of water and interfering with its regular intended use. Improper treatment of these pollutants makes the water bodies unsafe for people, affecting the quality of food, thus leading to poor health and general well-being of people, animals, and other living organisms.



Figure 2-1: Underdeveloped countries (in blue) according to the United Nations

Many rivers and streams are unfit for swimming, fishing, and providing drinking water (USEPA, 2008). Several technologies are used to deal with hazardous chemical substances and their negative impacts. However, negligence, lack of accountability from mining companies, and illegal dumping are prominent, leading to challenges of pollution of water systems, particularly during rainy seasons.

USEPA (2022) gives primary guidelines for drinking water standards, indicating chemicals that pose a health risk to humans with maximum allowable limits. A secondary guideline is available; however, it is not enforceable but guides the public in managing drinking water regarding taste and odour. The establishment of the Canadian Drinking Water Guideline is based on scientific research on health, aesthetic, and operational effects (CDWG, 2022).

Brazil has suffered environmental disasters involving failures in tailing dams in gold and tin mining in 2015 and 2019, respectively (Do Carmo *et al.,* 2017), while in New Zealand, residents are exposed to elevated levels of nitrates in their drinking water (WHO, 2022). International epidemiological studies show an association between cancer and nitrate ingestion from drinking water, and this exposure may cause deaths. After the iron ore tailings dam of Samarco Mineração S.A. company collapsed in Brazil, it caused environmental damage and pollution of the watercourse from the

Doce River to the Atlantic Ocean (Do Carmo *et al.,* 2017). The incident led to the disruption of the potable water supply to residents, the destruction of towns, and the death of 260 people. The team of experts deployed to assess the extent of the environmental damage did not assess the environmental impact caused by iron ore tailings in the water system.

In parts of New Zealand, a study conducted by Richards *et al.* (2022) revealed that residents are exposed to high nitrate exposure levels in their drinking water, with around nine percent (9%) increase above the normal nitrate allowable concentration (Schulz Lehner *et al.,* 2018), and there is a relationship between nitrate exposure and cancer prevalence (WHO, 2017). According to the WHO (2017) guidelines, the acceptable nitrate concentration in drinking water is 11.3 mg/L, while in European countries, legislative and regulatory efforts such as the Water Framework Directive (WFD) have been laid out to protect or reduce pollution in aquatic sources (European Commission, 2000). The purpose of the directive was to ensure the protection of all water bodies, prevent further deterioration, promote sustainable water use and long-term protection, improve the aquatic environment, and progressively reduce water system pollution. This directive has aligned with the current research as it aims to decontaminate water from the mining industry. International epidemiological studies have shown some association between cancer and nitrate-contaminated drinking water, and this exposure may cause death (Essien *et al.,* 2022).

Rivers in the vicinity of mines or abandoned mines, such as the eastern harbour of South Korea, situated next to the Songcheon gold-silver mine in Samsan-ri, Yeongok-Myeon, Gangneung-Si, are prone to pollution (Lim *et al.,* 2008). Little research has been conducted to establish the extent of the environmental impact of such locations, highlighting the need for environmental impact assessment and rehabilitation. Singh *et al.* (2021) revealed that the Yamuna River, which plays a significant role in drinking water supply, agriculture, aquaculture, and is a holy water resource in Delhi, India, has water that is contaminated with hazardous pollutants. Sample analyses of the river indicated the presence of heavy metals in the water, for example, lead at 40 µg/L, and chromium up to 52 µg/L, which are well beyond the permissible limits published by the WHO for chromium of 50 µg/L and lead, 10 µg/L, respectively. The river water is too contaminated to be used for drinking, cooking, or washing purposes, and this heavy

metal contamination may lead to major diseases, such as kidney failure, slow growth, cancer, and neurotoxicity (Sharma *et al.,* 2020). The individuals residing near the river should be fully informed of the adverse effects of drinking the water and consuming edibles irrigated with the river water (Mishra *et al.,* 2019).

Water quality, human health risk, and heavy metal accumulation in Nile tilapia and African catfish from the Kitchener Drain of Egypt were assessed by Matwally *et al.* (2023). The authors revealed the presence of heavy metals from mining activities and highlighted the need for water quality monitoring, which is currently lacking (Al-Afify *et al.,* 2022). A quarter (250) of the nation's Water Treatment Plants (WTPs) are in deteriorating condition and cannot provide safe drinking water, while river basins suffer from pollution (Addo-Bediako, 2023). Analytical results indicate that the concentration of trace metals in the surface sediments of the rivers is highest at 107.6 mg/kg for arsenic, 274.3 mg/kg for copper, and 281.7 mg/kg for nickel. This outcome is an indication of the adverse impact caused by mining activities in the area and the need for the implementation of a continuous water monitoring program.

2.5 Water Quality: Standards, Policies, and Risk Management

Water quality is a measure of the suitability of water to support human use, habitat for aquatic life, and recreation. Boyd (2019) described water quality in terms of the chemical, physical, and biological influence of pollutants on water and its suitability for an intended use, depending on the amount of dissolved or suspended contaminants in water bodies. According to Momba *et al.* (2010), some water treatment systems still fail to produce drinking water quality that complies with or conforms to SANS 241 requirements. This finding indicated a decrease in removal efficiency for selected pollutants, e.g., oestrogen, from wastewater treatment plants using different processes such as solid-phase extraction and liquid chromatography.

In South Africa, there are different water quality standards for different water purposes. These quality standards are listed at the end of chapter four as appendices one to ten. In this study, treated wastewater using pristine and pulverised gas-treated SCB were benchmarked against the water quality standards to establish the level of water produced by SCB.

The World Health Organisation has a set of water quality guidelines for drinking water that supersedes the SANS. Water quality guidelines from SANS are less stringent than

the SAWQG target values. The International Finance Corporation (IFC) of the World Bank Group has published Environmental, Health, and Safety (EHS) Guidelines for Environmental and Ambient Water Quality, specifically for wastewater and ambient water quality.

Section 13(a) of the *Local Government: Municipal Systems Act* of 2000 (Act No. 32 of 2000) requires municipal managers to establish, through chemical testing and monitoring, the exact amount of hazardous chemical substances present in water before they are released into the water system to ensure legal and environmental compliance. All effluent generators must provide and maintain effective measures to prevent the entry of any substance that may adversely affect water quality.

Chapter three of the South African Constitution outlines the responsibilities that the various levels of government and other state entities must adhere to in terms of corporate governance. The *National Environmental Management Act* (NEMA) 17 of 1998, instructs every institution involved in activities that may potentially harm the environment to work together towards an integrated system for environmental management and take into consideration the "duty of care and remediation of environmental damage" in South Africa.

The then Department of Environmental Affairs and Tourism (DEAT), now called the Department of Forestry, Fisheries and the Environment (DFFE), published a white paper on integrated pollution and waste management for South Africa and a policy on pollution prevention, waste minimisation, impact management, and remediation (PP, WM, IM & R) (DEAT 200). Oldeland *et al*. (2021) emphasise the importance of safeguarding water resources to ensure their sustainable utilisation, highlighting that research on water quality is essential for informing policy decisions related to water resource management. The Department of Water Affairs and Forestry indicated compulsory wastewater treatment in their policy document, required by the *Water Act* of 1956 (DWAF, 2021). Options to prevent and minimise waste are considered, and discharged wastewater must meet the minimum effluent standard or receiving water quality objectives (RWQO), according to South African Water Quality Guidelines. The Department of Water and Sanitation (DWS) has developed several standards and guidelines to describe water quality (DWAF, 1996). The guidelines are intended to

support the development and execution of risk management plans that ensure the safety of drinking water (WHO, 2011).

The Initiative for Responsible Mining Assurance (IRMA) is the global standard for water quality from mines for social and environmentally responsible mining. It allows mining companies to use the IRMA standard as an accredited tool for the assessment of mine sites.

Testing of water is a strategy and a tool to manage the risk associated with the use or exposure to contaminated water, which may lead to disease and other issues, to meet its intended purposes. The primary focus of this study is the concentration of heavy metals as pollutants originating from the mining sector. The pH and chemical analysis for heavy metals using ICP-AES, in an accredited testing laboratory by SANAS 17025:2017, are the methods used in this study.

2.6 General Overview of Wastewater Treatment Methods

In ancient times, distillation, crystallisation, nano-filtration, sublimation, extraction, and chromatography were among other methods used to purify, separate, and enhance the properties of chemical compounds (Ahmad *et al.,* 2019). As indicated in Table 2-1, water treatment techniques are successful. Still, there are concerns about low economic feasibility, difficulty in design and operation, high operational and maintenance costs, and environmental aspects such as waste management. There is not enough documented evidence on the purification of mining wastewater using natural absorbents and membranes, except for cellulose (Almadani, 2023). Water companies such as Rand Water produce potable water using methods such as coagulation, flocculation, sedimentation, stabilisation, and chlorination, while the home environment centre uses granular activated carbon, reverse osmosis, and UV disinfection.

Many mining companies implement wastewater treatment processes to eliminate harmful chemical substances (Awaleh *et al.,* 2014). These methods include, but are not limited to, solvent extraction, chemical precipitation and neutralisation, membrane filtration, adsorption, and ion exchange (Rashid *et al.,* 2021). Chemical methods are easy, fast, and efficient, but the problem is that they are based on a lab scale and economically not feasible for small industries, while physical methods, such as filtration, are not complicated to use even in high concentrations, since it only works

effectively for suspended particles and dyes. The chemical treatment methods are preferred because of their simplicity, flexibility, and economically feasible nature (Azam *et al.,* 2020). Chemical treatment methods produce sludge that is difficult to filter, leading to waste and environmental management issues (Ponnusamy *et al.,* 2023). Wastewater treatment in the mining industry using ion exchange methods such as resins and activated carbon has scientific evidence for successful treatment of wastewater; however, there is an environmental challenge that comes with the handling of loaded synthesised resins and activated carbon, as well as the high cost that is associated with the disposal thereof (Chaudhary *et al.,* 2020). Ion exchange techniques make use of specialised resins. When these resins are saturated with impurities, they can be eluted with a dilute acid solution. This process results in the production of additional effluent that needs to be treated before being discharged into the municipal water system.

2.7 Wastewater Treatment Methods and Their Applications

South Africa has 1,085 water treatment plants (WTPs) for potable water and only four significant river basins: the Komati, Limpopo, Maputo-Usutu-Pongola, and Orange-Sengu (WRC, 2016). WTPs are designed to precipitate and clean river water, typically carrying a heavy load of suspended solids such as fine clay (The Water Research Commission, 2016). Unfortunately, the Olifants River basin, like many of our South African basins, has become a victim of pollution (Hansen, 2015). This requires increasing the water supply and quality, desalination, and removing uranium toxicity from acid mine water (Xiao *et al.,* 2021).

As indicated in Table 2-1, there are various kinds of wastewater treatment methods for effluents from different industries. The following discussion focuses on the strengths and shortcomings of methods applied in wastewater treatment.

2.7.1 Adsorption

Adsorption is a mechanism in which a molecule or ion in a gaseous or liquid phase sticks to and remains on a solid phase (Han *et al.,* 2021). Adsorption can be physical, where the adsorbate binds to the adsorbent surface due to a chemical or electrostatic attraction. In the chemical interaction, the adsorbate is bound to the adsorbent surface by the formation of a covalent bond (Saha & Chowdhury, 2011). According to Grassi

et al. (2012), the adsorption process for the removal of contaminants from water has become a global approach because of its low installation costs, high performance, and easy operational design.

The adsorption process using modified SCB has emerged as the principal method for removing heavy metals from wastewater due to its efficiency, ease of implementation, and adaptability, considering operational, design, and environmental considerations (Dilpreet *et al.,* 2023).

Adsorption performance is influenced by the surface area of the adsorbent, the initial concentration of the adsorbate, the adsorbate's nature, the pH of the solution and temperature, dosage of the adsorbent, pressure, and contact time (Yaashika *et al.,* 2019). Various adsorbents such as activated-carbon biochar, nano adsorbents, bran, and such are emerging in the purification of wastewater from different industries. Activated carbon is widely used in the adsorption process for water purification because it is highly porous, with a large surface area that effectively removes pollutants, though it has the limitation of incurring higher costs (Prasannam *et al.,* 2021). Low-cost natural adsorbents such as farm and household waste, plant waste, and biosorbents are becoming successful green technologies (Sardar *et al.,* 2021), while biomass and cellulose, such as rice husk, walnut shell, coconut shell, and bagasse, are equally efficient adsorbents (Rehman *et al.,* 2012). Other natural and inorganic adsorbents include silica gel, activated alumina, and zeolites (Li *et al.,* 2011). SCB has not been evaluated enough to purify wastewater from the mining industry, but for the removal of heavy metals such as chrome for dye removal in the textile industry.

2.7.2 Membrane Technology

Membrane technology is a scientific and engineering technique that uses selective, semi-permeable materials (polymers, ceramics) to separate, purify, or concentrate substances in liquid or gaseous streams, commonly driven by pressure or concentration gradients (Zhang *et al.,* 2012). It is used in a wide range of applications such as pervaporation, ultrafiltration, microfiltration, electrodialysis, and reverse osmosis. Membrane technology has gained preference from different industries for wastewater purification because it has low energy utilisation, is easy to use, and is a

low-cost process (Rathi & Kumar, 2021). In addition, membrane technology has the potential to solve water shortage and energy consumption problems. Although membrane technology is used in conjunction with other processes for a more effective separation method, it has challenges that relate to concentration polarisation, low membrane lifetime, membrane fouling, and low selectivity (Kumar, 2012).

2.7.3 Chemical Precipitation

Chemical precipitation using lime ($Ca(OH)_2$), caustic soda (NaOH), sodium bicarbonate ($NaHCO_3$), sodium sulphide (Na_2S), sodium hydrogen sulphide (NaHS), or soda ash (Na_2CO_3) for removing heavy metals from industrial wastewater has been widely applied due to its simplicity and low-cost operation, within a wide range of temperatures (Türkmen, *et al.,* 2022). This technique uses pH adjustment to convert heavy metal ions into less soluble compounds such as hydroxides, carbonates, and sulphides, which can be removed physically using sedimentation, filtration, or flotation (Azimi *et al.,* 2017). The problem associated with this application is the production of low-density sludge and gypsum, which presents disposal and dewatering challenges (Fu *et al.,* 2011). The presence of complexing agents in the wastewater and the concentration of ionic metals may prevent hydroxide precipitation (Pohl*,* 2020).

2.7.4 Advanced Oxidation Processes

The advanced oxidation process (AOP) is a highly competitive technology in wastewater treatment for the removal of organic pollutants and for the inactivation of pathogenic microorganisms (Deng & Zhao, 2015). AOP is related to the generation of reactive oxygen species (ROS) such as hydroxyl (OH) in enough quantity to produce reclaimed effluent. The OH radicals, with other simultaneous reactions, can remove wastewater toxic products and transform them into non-dangerous pollutants (Mierzwa *et al.,* 2018). The radicals further react to form superoxide and hydrogen peroxide, leading to their chemical destruction (Saravanan *et al.,* 2022). AOPs such as photocatalysis have been proposed as a tertiary treatment for urban effluents due to their ability to detoxify wastewater streams with persistent contaminants (Al-Dawery, 2013). AOP is an alternative technology that can destroy a wide variety of contaminants and kill microorganisms in industrial wastewater. However, there are challenges associated with the use of AOP, such as high operational costs and minimal feasibility. Most wastewater treatment plants use chlorination, ultraviolet (UV)

radiation, and ozone to traditionally treat wastewater containing microorganisms and bacteria.

2.7.5 Ion Exchange Methods

Ion exchange, using both physical and chemical methods, is a common and preferred method for wastewater purification. The use of synthetic resins and activated carbon remains an effective conventional method of wastewater treatment; however, the synthesis and cost of these methods remain high, highlighting the need to employ natural ion-exchange methods, such as SCB, which is proving relevant (Kithinji *et al*., 2022). A study conducted in India, involving chelating resins and zeolite in removing metal ions from wastewater, reported high dependency on the pH of a solution, selectivity, origin of material, and the activation process, which was not based on green chemistry synthesis (Wong *et al*., 2018).

Table 2-1: Classical and contemporary technologies used to remove heavy metals from wastewater.

Method	Method description	Strength	Limitations	Source
Adsorption	Adherence of the material to the surface of the adsorbate.	Applicable in a wide range of pH, with high removal efficiency; Easy to use, flexible, and cost-effective. Simplicity in design.	Regeneration of the adsorbent is necessary.	(Chakraborty *et al*., 2020)
Advanced oxidation processes (AOP)	Employs use of ozone, hydrogen peroxide, electrical discharge, persulfates, and oxygen in conjunction with UV-VIS to generate radical reactive species.	Formation of *in situ* reactive radicals. Minimal or no chemical usage. No sludge generation.	Not applicable on a large scale.	(Ji *et al.,* 2022)
Biochar (Sugarcane bagasse, wood biochar, straw biochar, bamboo biochar)	Created through utilisation of various raw materials; includes a wide range of solids, sewage waste/sludge, agricultural residues e.g., crop straw, orange peel, animal manure, etc.	Environmentally friendly Economically feasible Easily designed adsorbent. Versatile.	Not applicable for large-scale.	(Chen *et al.,* 2022)

Biological Process (Biosorption, Bioaccumulation Bioremediation, Phytoremediation Mycoremediation	Uses microorganisms to treat wastewater, e.g., bacteria and viruses.	More competitive than physical and chemical methods.	Requires large land area. High sensitivity to diurnal variation and chemical toxicity. More restrictive design options and operational procedures.	(Sharma *et al.,* 2021)
Chemical Precipitation	The use of microorganisms, such as bacteria and viruses, to treat wastewater.	A low-cost and simple method that is effective in removing most heavy metals.	It generates sludge and makes it difficult to manage. It uses chemicals.	(Crini, *et al.,* 2019)
Coagulation/ Flocculation	Changes the form of dissolved metal ions into solid particles to facilitate sedimentation. The coagulation reagent precipitates metal ions by changing pH, electro-oxidising potential, or co-precipitation.	Easy separation of the resulting products and pollutant absorption.	It generates secondary pollution.	(Sakhi *et al*., 2018)
Electrochemical treatment method	An oxidation-reduction reaction in a circuit containing an electrolyte,	Metal recovery is effective. Have simple operational management.	Limited shelf life. Cross-sensitive to other gases.	(Bard *et al.,* 2022)

	anode, and cathode at a given voltage to precipitate heavy metals	Easy to operate.		
Flotation	Involves injection of air that forms bubbles to remove solids	Low-cost dewatering.	High operating and maintenance costs.	(Peleka *et al.,* 2018)
Ion exchange Resins	Injection of air to form bubbles to remove solids.	Low energy consumption. Regeneration of resins. Cost-effective.	Resin fouling. Adsorption of organic substances.	(Kansara *et al.,* 2016)
Membrane filtration Nanofiltration	Membrane filtration uses membranes to separate solids from liquids; Nanofiltration is a membrane water purification method that removes dissolved impurities and colour from wastewater. Nanofiltration is a membrane water purification method that removes dissolved impurities and colour from wastewater.	Efficient separation and selectivity at low pressure.	Expensive operation, Scaling, and fouling.	(Imdad *et al*., 2022)
Photocatalysis	UV radiation and hydrogen peroxide are	It possesses high oxidising potential.	Extremely costly.	(Tang *et al.,*2018)

	used to generate highly reactive radicals (OH•) that oxidise a wide range of pollutants.	Degrades heavy metals and organic complexes with complexing agents. It does not produce sludge.		
Phytoremediation	Uses plants to reduce, degrade, assimilate, and metabolise heavy metals.	Environmentally benign.	Slow process that requires large land surface area.	(Bhat *et al.,* 2022)
Reverse osmosis	Separation techniques that involve the application of pressure to a solution, forcing the solvent to move from low concentration to high concentration using a semi-permeable membrane, leaving the solutes behind	Easy to operate. Chemical-free. Compatible with other methods.	Energy intensive. Costly equipment. Poor permeability to water.	(Abdullah *et al.,* 2019)

Over the last 30 years, wastewater treatment has evolved from designing treatment technologies for safe effluent discharge into natural water bodies to employing techniques, such as physical, biological, chemical, and sludge treatment, to address a variety of issues, including wastewater recycling, waste treatment solutions, and pollution prevention. Methods of adsorption technology have gained increasing interest due to their simplicity and minimal by-products (Almadani, 2023).

A wide range of materials falls under investigation for adsorption, encompassing natural minerals, clays, activated carbons, biochar, organic and inorganic nanoparticles, polymer membranes, and composites (Iwuozor *et al.,* 2021) to support the circular economy principle. Passive treatment of contaminated wastewater involves the development of a self-operating system that works without any human intervention (IIED, 2000), where an artificial wetland in which algae and bacteria work together to filter, adsorb, absorb, and precipitate heavy metal ions to reduce the acidity of the effluent. Scientific evidence to support the production of water through efficient, economical, and eco-friendly methods is indicated in Figure 2-2. However, there is a concern relating to waste management and the existing gap in using SCB and other natural ion exchange methods.

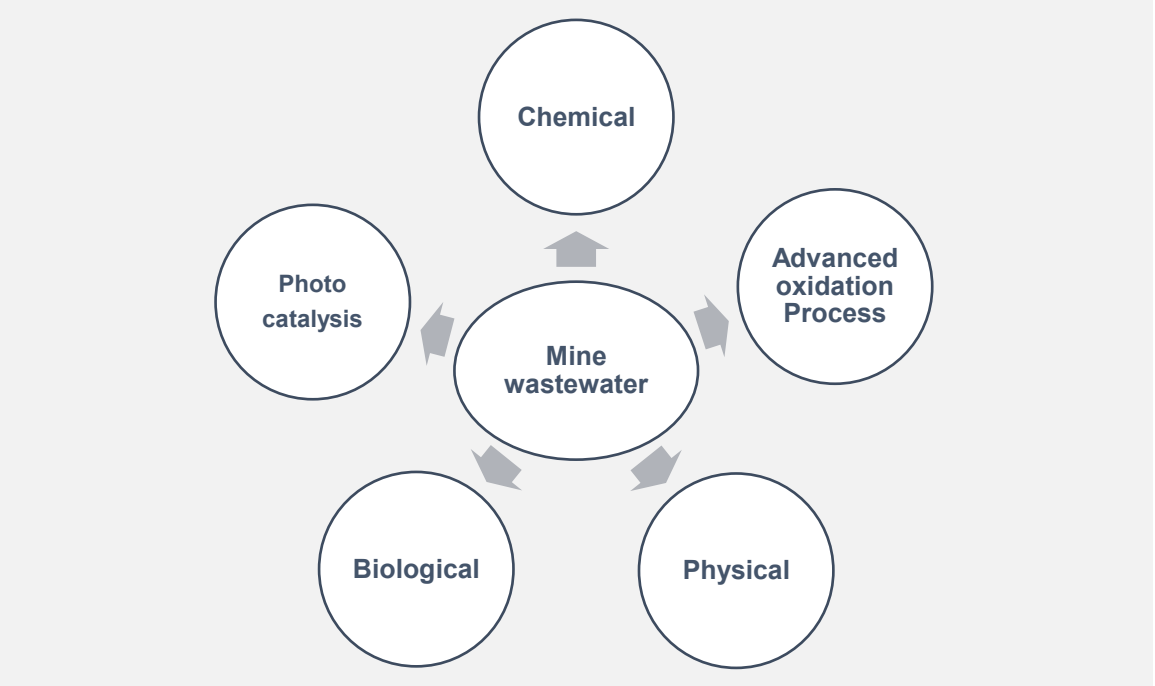


Figure 2-2: Adsorption methods for wastewater treatment for various industries (Haresh Bhuta, 2014)

A noteworthy record highlights the impressive adsorption efficiency of activated carbon derived from sawdust and peanut shells, utilised for metal removal in aqueous organic solutions (Noor *et al.,* 2024). Different forms of modification of agricultural waste involve the use of cellulosic fibres derived from peanut shells, treated with varying concentrations of alkaline solutions and different temperature settings. These fibres were modified using chemicals that transform them into cellulose acetate (Nasser *et al.,* 2023), and it was concluded after evaluation that the fabricated fibres by carboxylation, copolymerization, and hydrogenation are effective as water filters and demonstrate high efficiency.

Noor *et al.* (2024) have introduced sulphur-containing groups to cellulose for wastewater purification due to the high affinity of sulphur-containing groups to cellulose in wastewater, and due to the high affinity of sulphur functional groups towards heavy metals. The application of industrial waste to soil in agricultural production systems is an easy and cost-effective technique to dispose of these substances. The study by Noor et al. (2024) also reported that the conversion of waste into organic manure not only lowers pollution but also enriches the soil and reduces fertiliser costs. Table 2-2 indicates the benefits of using agricultural waste to enhance the continuous application of organic substances and maintenance of soil production capacity, fertility, and nutrient status (Xue *et al*., 2016).

Table 2-2: Benefits of using agricultural waste.

Agriculture	Environment	Economic	Social
Animal feed	Carbon sequestration.	Cheap source of fuel, fibre, and electricity production.	Binding material.
Fertiliser	Runoff mitigation.	Raw materials for pulp and paper.	Improved relationships between industrial and farming communities.
Fermentation	Removal of phenol from water in the environment.	Cheap precursor for biogas production.	
Yeast production	Removal of reactive dye from aqueous solution.	Cheap fertilisation cost.	Wide community involvement.

Manure	Reduce the disposal problem.	Skilful use of locally available products.	Better knowledge sharing.
Soil reclamation	Reduce cost of fertilizer application.		Interlinking policymakers.

2.8 Wastewater Treatment: Sugarcane and its by-products

Sugarcane (*Saccharum officinarum*) is a major crop belonging to the Gramineae family, mostly cultivated in tropical and sub-tropical countries with the primary purpose of obtaining raw sugar (Bordonal *et al.,* 2018). Brazil is the largest producer of sugar cane, contributing 25% of the annual world production of 648 million tonnes, followed by India, China, and Pakistan at 348, 124, and 64 million tons respectively (Bordonal *et al.,* 2018).

Sugar industries are discarding copious amounts of SCB daily, which causes different environmental problems, and hence the need to identify an appropriate method for its disposal (Solomon, 2016). SCB is a cellulosic agro-industrial by-product released after crushing and extracting juice from the canes. The resulting residue is a dry, pulpy, fibrous residue with 50% cellulose, 25% hemicellulose, lignin, pentosans, and just over 2.4% ash. Its application as a raw material for pulp, paper, electricity production, and fermentation is widely known (Yadav & Bhatnagar, 2015). The processing of one ton of sugarcane crushing results in the production of approximately 300 kg of SCB (Iwuozor *et al.,* 2022). The most economical application of SCB in the sugar industry is as a fuel in energy generation for boilers, while a small proportion is used in manufacturing enzyme products and drugs. SCB is rich in nutritional value, and it participates in enzyme production, protein enrichment, and is a substrate for microorganism culture.

The sugarcane industry releases enough by-products that have a significant environmental impact while producing sugar and beverages. A survey conducted by Ibrahim and Workneh (2023) indicated challenges such as contamination of water, off-odour particulates contaminating the air, and smoke clouds that emanate from the sugar industry. Dlamini *et al*. (2018) conducted a study in Durban, South Africa, highlighting the economic benefits of the sugar cane processing industry, including

increased gross domestic product (GDP) and national trade, energy co-generation, environmental stability, and community empowerment through electricity generation.

Sugar industries produce different organic by-products that have an immense potential to improve the soil's physical, chemical, and biological properties towards crop productivity. Organic wastes are rich in different macro- and micro-nutrients that are essential for plant growth. The increasing cost of mineral fertilisers and the degradation of soil health are key issues that these organics, along with mineral fertilisers, can efficiently solve by enhancing plant nutrient availability (Krishnaveni *et al.*, 2020).

Combustion of SCB results in the production of sugarcane bagasse ash (SCBA). Each tonne of SCB produces about 25 kg of SCBA, although the ash does not contain a considerable amount of minerals. However, it is used as fertiliser and animal feed when mixed with molasses. SCBA is an effective product for phenolic compound removal from wastewater and remediates expansive soils, and this study established whether SCBA can work effectively, as compared to SCB, in the removal of heavy metals from the mining wastewater.

2.9 Properties of SCB as an Ion Exchange Method

SCB has a high polysaccharide content, making it the main active coagulating agent. A study conducted by Nasser *et al.* (2023) showed that SCBs with high polysaccharide content require a lower coagulant dosage. It further highlights future perspectives on the application of extracted SCB as a natural coagulant in the removal of various other pollutants, such as colour, biochemical oxygen demand, and heavy metals from sources of wastewater such as palm oil mill effluent. In India, a study conducted by Thanki *et al.* (2021) on bio-adsorbents to reduce toxic metals concluded that the adsorption of heavy metals such as cadmium and lead using SCB depends on the ionic strength of the metals, which is inversely proportional to the adsorption capacity while being directly proportional to temperature. Due to the lack of uniformity in the concentration of contaminants in wastewater, pollutant species compete for active sites during the adsorption process, depending on the ionic strength. Pramadika *et al.* (2023) reveal that SCB, and bamboo charcoal are effective in the reduction of total dissolved solids (TDS), as well as the lowering of the pH and salinity. A study conducted by Beyan *et al.* (2021) indicated the effectiveness of modified SCB

adsorbent in reducing turbidity from wastewater, while Wang *et al.* (2018) investigated the competitive adsorption of Zn (II), Cu (II), Pb (II), and Fe (II) in a quaternary solution-using hybrid and biomass biochar developed from SCB and concluded that the two adsorbents had a removal efficiency of 99% over the dosage range studied, displaying their capability of removing heavy metals from the aqueous solution. It is thus evident that SCB is effective in adsorbing heavy metals from aqueous solutions, but there are still limited documented studies for the application of SCB in extracting heavy metals from mining effluent.

Adsorbent materials such as natural fibres, ash, clay, activated alumina, bentonite, and activated carbon have been used to extract heavy metal ions from aqueous solutions; the adsorption efficiency depends on the chemical and physical properties of the adsorbent (Koppula *et al.,* 2022). Table 2-3 describes the adsorbent materials that have been evaluated for the removal of heavy metals from industrial wastewater.

Table 2-3: Adsorbent materials that have been evaluated for the removal of heavy metals from industrial wastewater

Adsorbent Type	Example	Advantage/Disadvantage	Reference
Carbon-based adsorbent	Activated carbon. Biological carbon. Carbon nanotubes.	Raw biochar has surface hydrophobicity, a small number of functional groups, and weak binding ability, leading to ineffective removal of heavy metals from wastewater.	(Zhou *et al*., 2010) (Sahu *et al.*, 2010) (Fu *et al.,* 2022)
Mineral adsorbent	Zeolite. Clay. Fly ash. Clay. Minerals.	Clays and clay minerals have small particle sizes and a complex porous structure with a high specific surface area, which allows strong physical and chemical interactions with dissolved substances.	(Uddin, 2017) (Pu *et al.,* 2020)
Polymer adsorbent	Natural biomass/ Chitosan.	Polymer adsorbent has a variety of functional groups on its surface, and these groups can combine with	(Mallik *et al.,* 2022)

		heavy metal ions in water to remove them from the water.	

Lumadede *et al*. (2022) used activated carbon extracted from SCB for the decolourisation of sugar cane syrup. The experimental test work was conducted at pH 7, with syrup samples placed in a water bath at a temperature of 800 °C with 0.1 M hydrochloric acid and thymol blue as a buffer. This comparative study revealed that activated carbon derived from sugarcane bagasse was able to remove the dye from the sugar syrup effectively, like commercial activated carbon, and therefore, SCB can be used as a cheaper alternative for activated carbon. From the same argument, insight was sought from the sugarcane bagasse as a wastewater purification method as an alternative to other technologies for potable water production.

On the other hand, Kasbaji *et al. (*2023) have indicated the high adsorption of cadmium from aqueous solution using SCB impregnated with carboxyl functional group material. These comparative studies revealed that activated carbon derived from SCB was able to remove the dye from the sugar syrup as effectively as the commercial activated carbon. The removal of cadmium from the aqueous solution was achieved. However, it involved the introduction of carboxylic functional groups, which were not clearly defined, but presented acidic characteristics. From these experiments, insight was sought that the SCB can work as a purifying agent. However, the test work included chemical modification of the SCB. Hence, this study introduced the use of SCB as a potential bio-degradable material, modified for heavy metal extraction material. Table 2-4 highlights the use of SCB as a purification material in different applications, indicating the corresponding efficiency in removing various heavy metals from industrial wastewater to produce potable water.

Table 2-4: Different technologies have different efficiencies when evaluated for the removal of copper from industrial wastewater.

Technique	Extraction material applied	Efficiency (%)	References
Membrane separation	**Cellulose Acetate, a TiO_2-based membrane.** Membrane separation is the most widely used technology for Cu (II) treatment in the industry, concentrating and purifying heavy metals while removing contaminants for later recovery. However, membrane fouling is always an obstacle limiting its process efficiency, so there is a need to develop cost-effective, efficient, and environmentally friendly flushing technologies.	84 – 88	(Li *et al*., 2017)
Ion exchange	**Resins & Zeolite ion exchanger.** Has high capacity and fast rates for contaminant removal, efficient elution, and lifetime durability. The efficient elution is beneficial for Cu (II) recovery, but the long-term reusability of the resin and the possibility of recovering the target compounds from the regenerated solution limit the application.	64 – 99	(Yu *et al*., 2019)
Electrochemical reaction	Electrochemical cell & bio-electrochemical system.	91 – 99	(Sulonen *et al*., 2018)
Chemical precipitation	Synthetic Nesquonite.	99.9	(Shan *et al*., 2013)
Adsorption	Agro-industrial waste.	89	(Pfeifer *et al*., 2012)
	Zeolite, bentonite, and steel slag.	98 – 99	
Biotechnology	Microalgae.	95	(Tam *et al*., 1998)

2.10 The Reusability of SCB

Reusability of SCB has not been studied in this research however researchers such as Amer (2015) established that desorption of heavy metal ions from the metal loaded SCB, normally known as elution, performed using nitric acid, achieved 85% removal efficiency and concluded that SCB has a high potential for removal of heavy metals from wastewater and can be re-used at any time after desorption without losing its efficiency. Although Amer's (2015) study was not based on mine wastewater, it further established that the same reusability can be achieved for mine-impacted wastewater. While the study involved the use of strong acids, further studies may establish if weaker organic acids, which are environmentally friendly, such as acetic acid, can be assessed. Molaudzi *et al*. (2022) observed that SCB is a low-cost biosorbent that can be used for the removal of lead ions from contaminated water samples. The reusability performance of SCB presented removal efficiencies for lead ions of above 70% for three adsorption–desorption cycles.

Prachakittikul (2025) demonstrated the potential application of SCB as a promising, reusable, and scalable alternative to conventional powdered activated carbon for secondary decolourisation of clear liquor in sugar refining, applicable in both batch and column modes.

2.11 Highlights of the Literature Review

Recent research studies reveal the use of SCB as an effective ion exchange material for wastewater from industries such as oil refineries, electroplating, textile, paint, palm oil, ceramic, and steel plants. There is no information on the use of SCB for wastewater from the mining industry, and further research and documentation are needed. The research involved the use of natural SCB for the treatment of wastewater from the mining industry, without introducing chemicals such as calcium carbonate for the precipitation of heavy metals from the mine wastewater.

It is necessary to introduce natural sugarcane bagasse as a sustainable, easily accessible, biodegradable material for the adsorption of heavy metal ions from the mining wastewater because the use of SCB in the mining industry only shows the efficacy of natural ion exchange methods for wastewater purification of chemically modified SCB, and the effectiveness depends on the functional groups involved. The

effectiveness of SCB in dye removal from the laboratory-prepared synthetic solution was not uniform, and this was insufficiently reported in mining wastewater treatment (Akpor *et al.,* 2014).

In research studies, modification of SBC involves the use of solutions of chemicals containing carboxylic acid groups, such as vinegar and acetic acids, hydroxyl groups such as sodium hydroxide, as well as oxidants such as ozone and hydrogen peroxide. The effectiveness of SCB in removing pollutants depends on the type of chemicals used during the preparation process and high-temperature conditions. Studies further reveal the effectiveness of SCB in fluoride and nitrate ion removal, but only with high adsorption capacity at high pH in mining wastewater. Evidence on the use of SCB in the treatment of wastewater from the mining industry is lacking, and few of these studies reveal the effectiveness of modified SCB as an absorbent for copper and Cr^{6+} ions at a higher temperature, with little information on the use of natural SCB (Karri *et al.,* 2020).

The existing literature review is based on the use of other agricultural waste as an adsorbent in wastewater treatment and is useful for comparing these adsorbents, as indicated in Table 2-3. It also points to further research on other agricultural waste rather than SCB. Agricultural waste such as SCB, biochar, bamboo culm, banana leaf, and corncob contain a high content of various cellulose types and fibres and are among the most common materials used in natural ion-exchange methods for wastewater purification (Muralidharan *et al*., 2022a). Primary sources of cellulose include wood, cotton, hemp, flax, kenaf, and jute, which are plant-based fibres with high cellulose content and good thermal stability. Agricultural waste from stalks, leaves, and roots can be modified using chemical treatments and incineration for wastewater treatment, depending on their source, treatment, and testing conditions, as they have varying tensile strengths (Sabri *et al*., 2022).

This research focuses on the use of natural SCB in both the pulverised and pristine forms, bagasse ash SCBA, and catalytic processes, where SCB is pre-treated using different gases in a fluidised reactor. The efficacy of pristine SCB in the adsorption of heavy metals in toxic wastewater is comparable to studies involving the use of chemically modified SCB, even though the mine wastewater-related studies are limited. The investigation of the performance of pulverised SCB observed at various

temperatures, pressures, and pH will be considered. The preparation of SCB in this study will only involve milling and sieving, highlighting its low operating and maintenance cost, besides its ability to support the management of agricultural waste and enhance environmental protection.

Finally, it can be deduced from the existing literature that there is little research conducted regarding the environmental impact on the rivers that are located close to the mines, particularly Gauteng and Northwest and that the environmental impact assessment reports are not readily available to the mining companies and those available are not for the public interest but only available to the government which creates a bias due to business and financial interests. River basins are the most affected by high concentrations of trace metals, and there is a shortage of or no monitoring programs for water quality, which leaves the problem unattended. Activated carbon and selective resins are effective for wastewater treatment from a variety of industries; however, the challenge for environmental management remains, since these materials are not biodegradable. In addition to the use of SCB as an adsorbent, a wide range of materials falls under investigation for adsorption, encompassing natural minerals, clays, activated carbons, biochar, organic and inorganic nanoparticles, polymer membranes, and composites (Iwuozor *et al.,* 2021) to support the circular economy principle.

2.12 Circular Economy and Sustainable Development

In this work, a potential application of the principles of circular economy has been noted. The model of production and consumption seeks to keep resources in use for as long as possible, while extracting maximum value from them, and then recovering or regenerating products and materials at the end of their life cycle. This minimises waste, pollution and promotes resource efficiency. This research has established that organisations can subscribe to the concept of the circular economy to achieve the best out of their resources, for example, sugar manufacturing.

Sustainable development, on the other hand, highlights human development that aims to meet current needs without jeopardising the needs of future generations. While sustainability focuses on people existing on Earth for a long time, it is based on the prevention of excessive use of natural resources, and it promotes the preservation of these resources. It aims to balance economic development, environmental protection,

and societal well-being. The outcome of the research has established that industries can use natural materials responsibly, thus protecting the environment while focusing on future generations. In addition to this, the outcome of this research has established that the partnership between the three industries is long-standing, which will promote considerations for the next generations. Based on the concept of environmental sustainability, this research may be a basis for future research for organisations to investigate ways and strategies to attain continuous improvement on the concept of environmental sustainability.

2.13 UN SDGs, Integrated Environmental Management and Compliance

The United Nations' sustainable development goals for Agenda 2030 require countries to strive toward achieving clean water (SDG 6) and for responsible consumption and production (SDG 12), Life below water (SDG 14), and partnership for the goals (SDG 17). Integrated management systems, on the other hand, require organisations to acknowledge environmental considerations into daily business, decision-making and to provide environmental solutions that promote competitiveness. The partnership will be enhanced through the SCB-based relationship, where the mining industry will ease the burden of waste handling and storage from the sugar-processing companies while promoting partnership through open and transparent communication. Mining companies may demonstrate that it is possible to avoid non-biodegradable material in wastewater purification, to achieve clean water, UN SDG 6, and to preserve life below water, SDG 14. Farmers can note the possibility of environmentally friendly fertilisers that will be supplied by the mining industry once they have reused the SBC. Since most companies have integrated an environmental management system, including ISO 14001:2015, the need for continuous improvement is a requirement. Once organisations adopt these principles, environmental sustainability and compliance are imminent.

3. CHAPTER 3: RESEARCH METHODOLOGY

3.1 Research Design

The methodology used for this study was quantitative. Quantitative research methodology is the study of the nature of phenomena, especially suitable for answering questions of why something is (or is not) observed, assessing complex multi-component interventions, and focusing on intervention improvement (Black, 1999). Quantitative research focuses on logic, numeric, and unchanging experimental data, making it an objective, descriptive, correlational, and comparative approach. It attempts to establish cause-and-effect relationships among the variables (Hassan *et al*., 2021).

The study used quantitative analytical methods, which involve gathering data in accredited analytical chemistry laboratories through equipment such as X-ray fluorescence (XRF), inductively coupled plasma atomic emission spectroscopy (ICP – AES), and atomic absorption spectroscopy (AAS) for chemical analysis, among other analytical techniques.

The study methodology was exploratory, an approach that focused on research questions that have not been studied before, in the sense that the natural, unmodified SCB has not been studied thoroughly.

3.2 Materials and Reagents

SCB samples (pristine, pulverised, gas pre-treated and ash) were collected from sugar processing companies. Sodium hydroxide (98% pure from Sigma-Aldrich, Merck) was made into a 1.0 M solution, and ammonium acetate (98%) and glacial acetic acid (99%) were from Sigma-Aldrich, Merck. Columns (from Listco Glass Blowers (Pty) Ltd., glass sample bottles, Scotch bottles (200 mL and/or 1 L), and a shaker table from Labo Tech. Beakers, Buchner funnel (from Glass World), filter papers from Microsep (Pty) Ltd, spatula, and weighing crucibles. Analytical balance (Radar) and calibrated mass pieces, thermometer, pH metre (Metrohm SA), a handheld XRF (Hitachi X-met Expert and Olympus model, Delta Professional), and an ICP-AES (Perkin Elmer).

3.3 Sample Collection

3.3.1 Bagasse Collection

Sugarcane bagasse (SCB) samples (pristine and pulverised) were sourced from two sugar processing companies in KwaZulu-Natal (KZN) province, South Africa, as indicated in Figure 3-1. SCB was dried in a thick transparent plastic on the laboratory floor surface, and no other methods of drying were introduced. A representative pristine SCB sample was used without physical or chemical modification, while another sample was pulverised and sifted to 75 microns. SCBA, waste from the electricity generation process at one of the sugarcane-processing plants, was used in this study as an ion exchange method for the purification of wastewater from mining companies, comparing its performance with the natural and pulverised SCB.



Figure 3-1: A pile of SCB waste at the SCPC-A sugar processing plant and a representative sample of unprocessed SCB in Sezela, KZN (Picture by Alice M, Courtesy of SCPC-A company)

3.3.2 Mine Effluents/Wastewater Collection

Water Samples were collected from MINTEK, a research organisation that deals with a variety of hazardous chemical substances, and a platinum group metals producer based in Gauteng Province, South Africa. The wastewater samples were collected in a 25 L jerry can, with no preservative added, with the assistance of personnel working at the wastewater treatment plant. The wastewater was received with an average pH of 4.5.

3.4 Experimental Procedure

The experimental work was conducted at the facilities and laboratories of MC-Y (Council for Mineral Technology), situated in Randburg, Johannesburg Metropolitan Municipality, Gauteng Province, in South Africa. MC-Y, a global leader in mineral, mining, and metallurgical technologies, is a state-owned research company and innovation centre that reports to the Department of Minerals and Energy (DMRE) with a mandate to serve the industry in minerals and their derivatives through research and development as well as mineral technology transfer. Laboratory experiments were conducted using SCB and SCBA under different pH conditions for wastewater from MC-Y and MC-X, as indicated in Table 3-1. Unwashed SCB was characterized by a handheld XRF from the hydrometallurgy laboratory to determine the chemical composition of all SCB samples before milling to a 75-micron sieve passing.

A pristine SCB sample tested for mine wastewater at pH 2, 4.5 or 9, respectively

Pulverised SCB sample tested for mine wastewater at pH 4.5 or 9.

Thermal/Gas-pre-treated SCB sample at ambient pressure and at different temperatures of 25, 60, 120 and 180 °C, and tested for mine wastewater at pH 4.5 or 9.

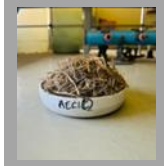
SCBA sample tested for mine wastewater at pH 4.5.

Benchmarking: The quality of water produced using SCB vs water quality guidelines (Appendices 1 – 10).

BET and FTIR analysis will be conducted as part of the research

Approximately 20 g pristine SCB was weighed in a weighing crucible on an analytical balance and transferred into 4 x 1000 ml Schott bottles, with 100 ml of wastewater at pH 2, 4.5, 7, or 9, wastewaters respectively from MC-X and MC-Y effluent plants at 25 ^{o}C. as summarised in Table 3-1 below:

Table 3-1: Summary of detailed test work for all the SCB, SCBA, and gas + thermally pre-treated SCB used under different conditions

Evaluate No	Detailed Description
1 	Approximately 20 g pristine SCB was weighed in a weighing crucible on an analytical balance and transferred into 4 x 1000 ml Schott bottles, with 100 ml of wastewater at pH 2, 4.5, 7, or 9 from the MC-Y effluent plant at 25 °C. The closed bottles were then transferred to a roller table.(Appendix 11) for four hours. A sample was taken out of each bottle hourly and filtered through the SCB slurry by gravity to generate a profile filtrate sample. The profile samples were analysed using the ICP-AES technique at WATERLAB (Pty) Ltd, based in Pretoria, South Africa.
2 	Test one was repeated using approximately 20 g of pulverised SCB, which was weighed using a weighing crucible in an analytical balance and transferred into 4 x 1000 ml Schott bottles with 100 ml of wastewater. The closed bottles were transferred to a roller table, shaken, and the slurry filtered by gravity to generate profile samples.
3 	Approximately 20 g of pulverised and pristine SCB was measured using a weighing crucible in an analytical balance and transferred into 4 x 1000 ml Schott bottles with 100 ml of wastewater at pH 4.5 or 9 from all mining effluent plants mentioned in test one, at 60 °C. Due to desorption observed at this temperature, no further temperature increase was conducted for this experiment. The closed bottles were placed on a hot plate with a magnetic stirrer. The bottles were shaken for four hours, taking each bottle hourly, and the sugarcane bagasse (SCB) slurry was filtered by gravity to generate profile filtrate samples.

4 	Approximately 20 g of the pulverised SCB was weighed and transferred to a column (Appendix 12) in a fluidized reactor (Appendix 13) for the catalysis process. The sample was pre-treated using air, oxygen, hydrogen, and nitrogen at 25, 60, 120, and 180 ^{o}C, at ambient pressure. The pre-treated samples were used as mentioned in Tests 2 and 4.

Figure 3-2: A graphic summary of the experimental test work described in Table 3-1

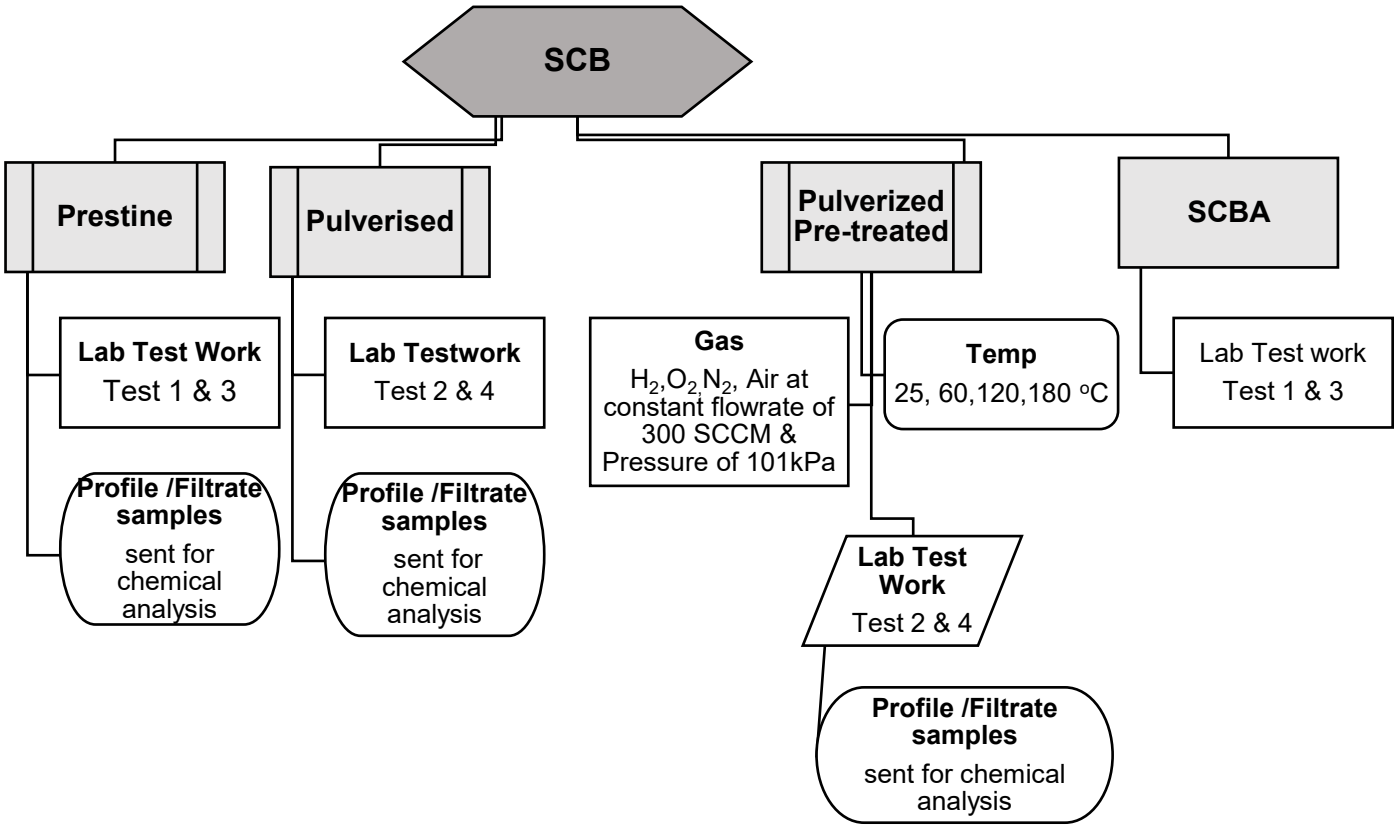


Figure 3-2: A flow chart representing the experimental procedure as described in Table 3-1

3.5 Data Collection

WATERLAB (Pty) Ltd. used ICP-AAS to analyse water samples generated from wastewater treatment using modified and unmodified SCB. The laboratory test results were assessed based on analytical chemistry principles to establish whether sugarcane bagasse is a suitable and effective adsorbent for base metal ions in treating contaminated wastewater from the mining industry. The techniques stated above were used to collect, evaluate, and predict trends in the presence of heavy metals in treated water samples using SCB. The research solely depended on the chemical analysis of treated water from an accredited testing laboratory, WATERLAB (Pty) Ltd, to establish the presence and concentration of heavy metal ions as scientific evidence to indicate whether sugarcane bagasse (SCB) is an effective ion exchange method to adsorb the heavy metal ions in wastewater generated from mining and metallurgical processes. Chemical testing involved the use of a pH meter, atomic emission spectrometry (AES), inductively coupled plasma atomic emission spectrometry (ICP-AES), and a handheld XRF spectrometer to determine the composition of SCB and the concentration of

copper, cobalt, chromium, iron, lead, manganese, and zinc by an ISO 17025: 2017 accredited laboratory.

Characterisation and elemental analysis of SCB were conducted at MC-Y, Advanced Materials Division, using Brunauer-Emmett-Teller (BET) analysis for surface area determination (Appendix 14), Fourier Transform Infrared Spectroscopy (FTIR) for functional group properties of SCB (Appendix 15), and X-ray fluorescence (XRF) for chemical analysis (Appendix 16).

3.6 Data Analysis

The findings from the chemical testing laboratory were evaluated with chemical techniques and an Excel spreadsheet to produce a graphical depiction of heavy metal removal in relation to concentration over time, considering various pH levels, temperatures, and surface areas for unprocessed, ash-treated, and gas-treated SCB. The following equation (1) was used to calculate the percentage efficiency of the adsorption of heavy metals from the mining wastewater.

$$\%\, Efficiency = \frac{C_{initial} - C_{fnal}}{C_{initial}} \times 100\,\% \qquad \text{Equation (1)}$$

where $C_{initial}$ = original concentration of metal in the wastewater,

while C_{final} = concentration of metal in wastewater at the end of the experiment.

3.7 Statistical Analysis

In this study, profile samples were taken hourly for each experiment, and the average values of the concentrations were compared against the standard limit requirements for water quality standards. The water quality standards used are SANS 241: 2015, *Drinking water specifications for contaminants,* municipal requirements for mining effluents, and the 2018 Initiatives for the Responsible Mining Assurance (IRMA) standards for ethical mining. The IRMA standards are:

Drinking Water and Human Health criteria, Agriculture-Irrigation Water Quality criteria, Agriculture-Livestock Water Quality criteria, Aquaculture Water Quality criteria,

Recreational Water Quality criteria, and Industrial Water Quality criteria. This study used analytical results from the testing laboratory based on analytical and inorganic chemistry. Averages of the concentrations were determined using analytical chemistry statistical methods. The results were analysed and compared using the initial and final concentrations in the treated wastewater and the values for determinants against the standard limit requirements using the water quality standards.

3.8 Pre-treatment of SCB

Materials pre-treatment is an important step in the adsorption process to functionalise, activate and/or modify the surface properties; hence, it was conducted for pulverised SCB in this research by introducing SCB into a fluidised reactor, connected to different gas sources, variable temperatures, and a constant gas flow rate and pressure. Adsorption experiments were conducted using SCB and sugarcane bagasse ash (SCBA) at different pH conditions to treat mine-impacted wastewater.

Untreated, pure, and ground SCB was utilised for the lab experiments aimed at eliminating heavy metals from wastewater. The SCB was ground to a particle size of 75 microns through sieving. The selection of this particle size is based on experience when dealing with particle size in hydrometallurgical processes. A bigger particle size of material results in less efficient adsorption, while a smaller particle size inhibits the flow of water through the SCB particles and prevents contact with the adsorbate. Unwashed SCB was characterised using the handheld HITACHI XRF to determine the chemical composition of all SCB samples.

3.9 Data Validation

In this research, the analytical testing laboratory, WATERLAB (Pty) Ltd, was selected for chemical analysis of water samples. The reason for this selection is that WATERLAB (Pty) Ltd is an independent and ISO 17025:2017 SANAS accredited (Accreditation number T0391) laboratory, which specialises in water analysis only, T0391, meaning that there is a functional quality management system in place within the laboratory and assurance for the analytical results produced with evidence of the following aspects:

Quality assurance was established by the involvement of highly competent personnel with an excellent background in chemistry and an advanced understanding of good laboratory practices. The following considerations were made for quality assurance purposes.

- Equipment such as balances, standard mass pieces, and thermometers used was calibrated by an ISO 17025:2017 accredited calibration laboratory and verified using standard reference materials. Only suitably qualified personnel with appropriate experience, knowledge, and skill, with the authority to use the testing equipment, participated in this work.
- Water sample analysis was done in duplicate.
- Standard solutions from the suppliers come with a certificate of analysis for traceability purposes.
- The reference materials that were used were within the ±2% range of the certified value, with a standard deviation of 5-10%.
- Signatories: Technically qualified staff signed off on reports of analysis, which ensures consistency in the reproducibility and accuracy of the test results.
- Quality of reagents: Solvents and chemicals used were of analytical grade AR.

3.10 Ethical Considerations

A permission letter to conduct the study within the MC-Y effluent plant was requested through the research, development, and innovation (RDI) division at MC-Y (Appendix 22). Access to the wastewater treatment plant from mining companies MC-X and MC-Y was obtained through the assistance of MC-Y's Hydrometallurgy Divisional Manager and the mine effluent plant manager. Companies SCPC-A and SCPC-B issued authorisation letters, which were submitted to UNISA as part of the Ethics Clearance. The final ethical clearance obtained from UNISA is in Appendix 24. The approval letter from the mining company is attached in Appendix 20 and the sugarcane processing company in Appendix 21, respectively.

4. CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 RESULTS

4.1.1 Background on the Results

The analytical results for the removal of heavy metals from mining wastewater using SCB and SCBA tested at different pH values and temperature conditions are presented in seven categories as follows:

- A pristine SCB sample tested for mine wastewater at pH 2, 4.5 or 9.
- Pulverised SCB sample tested for mine wastewater at pH 4.5 or 9.
- Thermal/Gas-pre-treated SCB sample at ambient pressure and at different temperatures of 25, 60, 120 and 180 °C, and tested for mine wastewater at pH 4.5 or 9.
- SCBA sample tested for mine wastewater at pH 4.5.
- Benchmarking: The quality of water produced using SCB vs water quality guidelines (Appendices 1 – 10).
- BET analysis.
- FTIR analysis.

Wastewater was received with a pH of 4.5 and adjusted to a pH of 2 using acetic acid and to a pH of 9 using 0.1 M sodium hydroxide. Acetic acid is a household, less hazardous and readily available organic acid, while sodium hydroxide is a strong base, which is also readily available, hence their selection. Analytical results revealed that the highest removal of heavy metals from mine wastewater occurred at a pH of 4.5. The wastewater at pH 4.5, as collected from the mine companies, was used as is, and adjusting the pH to 2 and 9 did not necessarily enhance the efficiency of SCB in removing heavy metals from mining wastewater.

SCB and SCBA were collected from the sugar companies and analysed using a handheld XRF machine at the AA lab in hydrometallurgy. Some of the samples were analysed before pulverisation without washing or modification. Table 4-1 is a summary of the analytical results from the handheld XRF indicated in Appendix 18.

Table 4-1: Characterisation of SCB by XRF, indicating elemental concentrations (µg/L).

Sample*	Fe	Cr	Mn	Zn	Pb	Ca	K	Cl
SCPC-A	5.61	0.05	0.29	0.04	0.03	4.43	2.39	0.46
SCPC-A	5.60	0.06	0.28	0.04	0.03	4.15	2.44	0.39
SCBA	1.64	0.05	0.09	0.04	0.04	0.60	1.13	0.13
SCBA	1.69	0.05	0.09	0.30	0.04	0.48	1.17	0.26
SCPC-B	2.30	0.05	0.13	0.01	0.02	1.34	1.26	0.46
SCPC-B	2.28	0.05	0.13	0.01	0.08	1.33	1.29	0.39

*SCPC-A: Sugarcane Processing Company A
SCPC-B: Sugarcane Processing Company B
SCBA: Sugarcane Bagasse Ash

SCB collected from both sugar processing companies was dried and analysed before use. From Table 4-1, XRF analysis revealed that SCB contained a significant amount of iron in both samples. The results indicate that iron and manganese levels in SCB are minimal, even though a considerable amount of manganese was detected in the samples from SCPC-A. Chlorine, calcium and potassium were substances outside the scope of this research, despite showing notable concentrations, and their presence was also ignored (Refer to Appendix 18).

4.1.2 Pristine SCB sample

Table 4-2 presents the results for the use of pristine SCB in a variety of pH conditions for the removal of heavy metals from mining wastewater. At a pH of 2, only copper was removed (16%), indicating less efficiency of pristine SCB in removing copper from mine-impacted wastewater. At a pH of 4.5, the outcome of the experiment shows the adsorption efficiency of SCB as copper (48%), nickel (44%), and zinc (39%). Removal of these heavy metals from the wastewater occurred within the first two hours of the experiment. After the third and fourth hours, there was no further change observed except in some instances, where desorption occurred.

Table 4-2: Heavy metal concentration(mg/L) in wastewater filtrate over time after treatment with pristine SCB at pH 4.5 at 25 ^{o}C

Wastewater Filtrate (hr) 25 ^{o}C	Zn	Cu	Co	Cr	Fe	Pb	Mn	Ni
0	0.93	5.87	0.09	0.03	0.83	0.06	1.33	1.87
1	0.43	2.89	5.37	0.03	0.80	0.05	2.30	0.97
2	0.51	3.06	5.51	0.03	0.76	0.07	2.28	0.99
3	0.53	2.96	5.52	0.03	0.89	0.07	2.29	1.00
4	0.60	2.98	5.61	0.03	2.17	0.05	2.25	0.99
5	0.57	3.05	5.73	0.03	1.45	0.05	2.38	1.05
SANS 241	-	2.00	-	-	0.30	-	0.10	-
Drinking water/human health	3.00	1.00	-	-	0.30	-	0.50	0.20
Irrigation	2.00	0.20	-	-	5.00	-	0.20	0.20
Livestock	24.00	0.5	-	-	10.00	-	0.20	1.00
% Heavy metal removed	39	48	0	0	0	16	0	44

At pH 7, there was no observable improvement in the adsorption efficiency of the pristine SCB with the effectiveness of adsorbing copper, nickel, and zinc was minimal, remaining under 5%. Nevertheless, when the pH was raised to nine, the results indicated some adsorption for zinc (15%), nickel (21%), and manganese (19%). A change in pH enhanced the selectivity of SCB, which adsorbed copper only at pH 2. Residual copper, iron, lead, nickel, and zinc after treatment with the SCB shows that the water meets the requirements for SANS 241 standards, Drinking water and human health standards, as well as for irrigation and livestock.

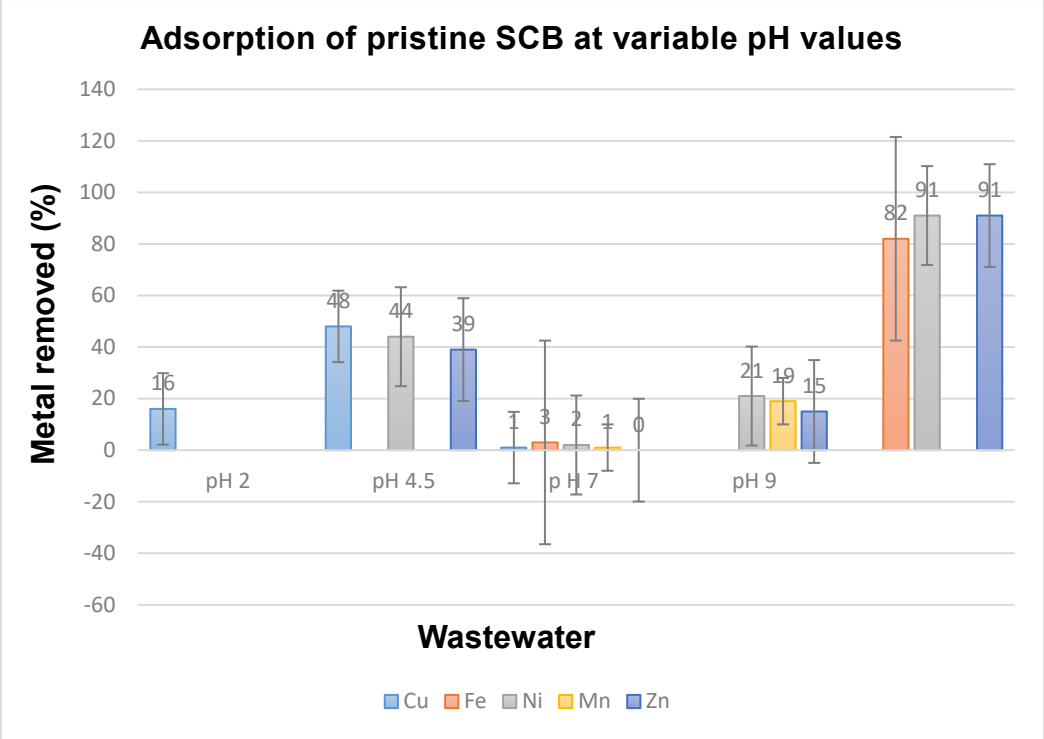


Figure 4-1: Heavy metals removed (%) by pristine SCB at different pH values.

Recent studies conducted using different wastewater treatment methods indicated in the literature review in Table 2-4, do not indicate the source of the wastewater discussed. However, resins produced 64% copper removal efficiency, agro-industrial waste removed 89% of copper, and chemical precipitation achieved the highest removal efficiency of 99% (Kithinji *et al*., 2022). The study focused on the removal of Zn (II), Cu (II), Pb (II), and Fe (II) from a quaternary solution using hybrid biochar and biomass biochar derived from spent coffee grounds (SCB). The findings revealed that both types of adsorbents achieved a remarkable removal efficiency of 99% (Chen *et al*., 2022).

The present study has *established that SCBA can remove* up to *60% of copper from min*ing *wastewater*. Pristine SCB was not effective in the removal of certain heavy metals, such as iron, at all pH conditions. Therefore, pristine SCB is selective in removing specific heavy metals (e.g., copper at variable pH conditions, which is important in selective extraction methods such as hydrometallurgy based on the targeted heavy metal.

4.1.3 Pulverised SCB sample tested at pH 4.5

Pulverized SCB with a particle size of seventy-five microns was used to treat the mine-impacted wastewater. Based on experience, pulverization to a particle size above 75 microns causes surface area challenges. Over-pulverising of SCB may lead to slime formation and inhibit water flow when SCB is used to treat the mining wastewater. The data presented in Table 4-3 illustrates the efficiency of the pulverised SCB in removing heavy metals at a pH of 4.5, showing that it achieved removal rates of 86% for iron, 80% for manganese, and 71% for zinc. In this experiment, no extraction of heavy metals was achieved at pH 2 and pH 7.

Table 4-3: Heavy metal concentration(mg/L) in wastewater filtrate over time after treatment with pulverized SCB using wastewater at pH 4.5.

Wastewater filtrate (hr)	Zn	Cu	Co	Cr	Fe	Mn	Ni
0	1.78	0.315	0.07	0.19	6.68	2.47	1.63
1	1.46	0.30	0.04	0.05	2.99	0.61	0.18
2	1.06	0.27	0.04	0.06	1.94	0.66	0.15
3	0.50	0.28	0.07	0.10	1.82	0.56	0.16
4	0.51	0.30	0.08	0.14	1.01	0.41	1.24
SANS 241	-	2	-	-	0.3	0,1	0,1
Irrigation	2	0.2	-	-	5	0.2	0.2
Livestock	24	0.5	-	-	10	0.2	1.0
Drinking water/Human health	3	1	-	-	0.3	0.5	0.5
% Heavy Metal Removed	71	6.34	0	25	86	80	23.9

The experiment achieved the highest efficiency in removing heavy metals when the pH was set at 4.5, utilising the pulverised SCB. This underscores how the surface area and pore size of the adsorbent play crucial roles in the adsorption processes.

While iron is the most commonly found heavy metal in our water testing, it still falls short of the standards set by SANS 241 for drinking water and the guidelines for drinking and human health quality. Further purification techniques, like utilising a permeable membrane, can be applied to enhance the quality of wastewater, ensuring it aligns with the specified standards.

4.1.4 Pulverised SCB with wastewater at pH 9

Table 4-4 presents the efficiency of SCB in adsorbing heavy metals from wastewater adjusted to pH 9, which removed Zn (93%), Ni (81%), and Fe (26%).

Table 4-4: Heavy metal concentration (mg/L) in wastewater filtrate over time, pH 9 wastewater used with pulverized SCB

Wastewater filtrate (hr)	Zn	Cu	Co	Cr	Fe	Mn	Ni
0	2.10	0.23	0.06	0.39	19	3.35	0.78
1	1.75	0.21	0.06	0.54	19	2.87	0.18
2	1.26	0.19	0.05	0.45	17	2.86	0.15
3	0.15	0.20	0.11	0.47	16	2.85	0.16
4	0.13	0.20	0.12	0.48	14	2.85	0.15
SANS 241	-	2	-	-	0.3	0,1	0,1
Irrigation	2	0.2	-	-	5	0.2	0.2
Livestock	24	0.5	-	-	10	0.2	1.0
Drinking water/Human health	3	1	-	-	0.3	0.5	0.5
% Heavy metal removed	93	13	-	-	26		81

According to Table 4-4, zinc consistently showed the highest adsorption rates among the heavy metals, with nickel following closely behind. It is worth noting that all heavy metal concentrations complied with water quality standards, except for iron and

manganese. Additional purification techniques, like reverse osmosis, can be utilized based on the intended use of the water.

At 7 pH, there was no extraction of any heavy metal using both pristine and pulverized SCB. The highest efficiency of heavy metal extraction was achieved at the unadjusted pH of 4.5 in mining wastewater for oxygen-pre-treated SCB.

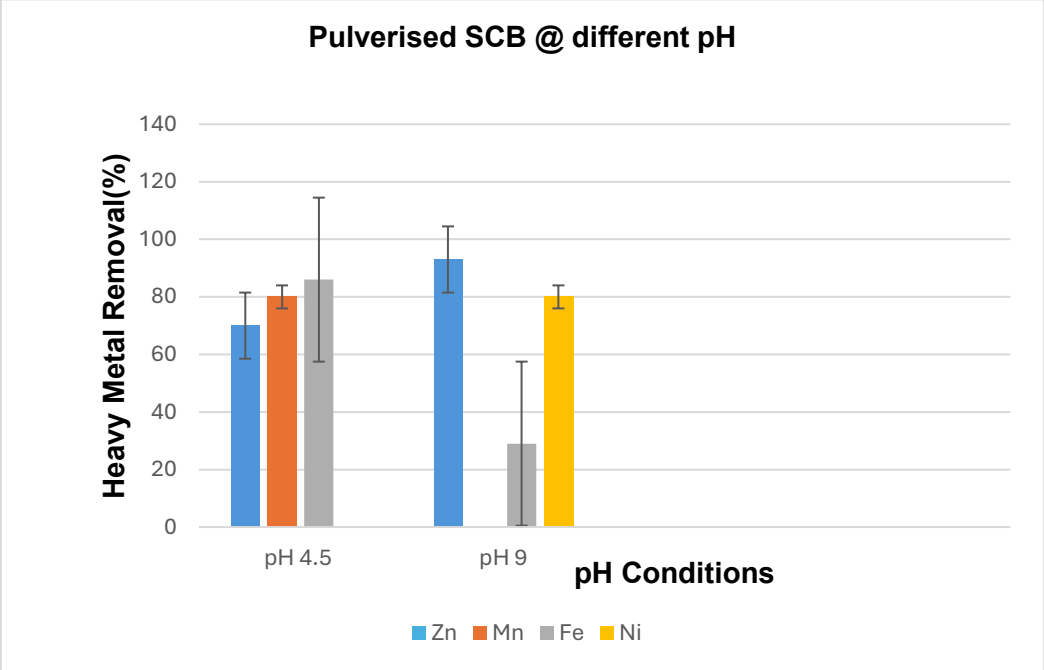


Figure 4-2: Comparison of pH results and their effect.

Based on the observation in Figure 4-2, unadjusted pH 4.5 yielded the highest heavy metal removal efficiency for iron, manganese, and zinc. However, increasing the pH to nine only enhanced the removal of zinc from 71 to 93%. Lower pH has more acidic H+ concentrations. Because heavy metals are positively charged, adsorption of heavy metals at lower concentrations will be lower than at higher concentrations since there is competition between the H^+ of the acid and the + charge of the heavy metal on the adsorbent sites.

Because zinc has a lower oxidation state and was competing for sites with nickel, manganese and iron as indicated below:

$Zn^{2+,}$ $N^{2+,}$ $Mn^{2+,}$ $Fe^{2+/}Fe^{3+.}$

When the pH was increased to 9, its ability to stick to the adsorbent sites was enhanced from 71 to 93 %, meaning zinc was precipitated from wastewater and bonded with the SCB. At pH 9, the selectivity of SCB in removing heavy metals was observed for nickel, which could not be removed at pH 4.5 and manganese (80%), which could not be removed at pH 9 for the same reason.

4.1.5 Thermal Treatment of SCB in a Fluidised Reactor

Before the SCB was used in wastewater treatment, the samples were pre-treated in oxygen, nitrogen, and air at 25, 60, 120, and 180 °C at a constant gas flow rate of 300 standard cubic centimetres per minute (SCCM) and ambient pressure. The pre-treated SCB was used for treating the wastewater as is at a pH of 4.5 without adjustment. The test work for the SCB that was pre-treated in air did not yield any results.

4.1.6 Pretreatment of SCB using Oxygen and Nitrogen at 25 °C

According to Table 4-5, the concentrations of heavy metals in the SCB-treated water comply with the established water quality standards, except for iron and nickel. Pulverised SCB samples that were pre-treated in oxygen at 25 °C showed a significant removal of zinc (87%), manganese (63%), and nickel (68%). At a pH of 4.5 for the nitrogen pre-treated SCB, only nickel (61%) adsorption was observed when pre-treated at 25 °C

Table 4-5: Heavy metal concentration(mg/L) in wastewater filtrate over time using Oxygen pre-treated pulverized SCB at 25 °C

Wastewater Filtrate (hr)	Cr	Co	Cu	Fe	Pb	Mn	Ni	Zn
0	0.03	0.18	<0,010	0.20	0.05	6.26	1.13	3.46
1	0.06	0.35	0.09	2.40	0.05	2.41	0.61	0.59
2	0.03	0.14	-	0.81	0.00	2.55	0.60	0.50
3	0.03	0.19	-	0.35	0.00	2.37	0.64	0.40

4	0.03	0.18	-	1.05	0.00	2.29	0.36	0.46
SANS 241	-	-	2	0.3	-	0.1	-	-
Irrigation	-	-	0.2	5	-	0.2	0.2	3
Livestock	-	-	0.5	10	-	0.2	1.0	24
Drinking water/Human health	-	-	1	0.3	-	0.5	0.2	3
Heavy metal removed (%)	-	-	-	-	-	63	68	87

4.1.7 Pretreatment of SCB using Oxygen and Nitrogen at 120 °C.

Oxygen-pre-treated sugarcane bagasse (SCB) heated at 120 °C, which ultimately turned to ash (refer to Appendix 17), proved to be highly effective in eliminating heavy metals. The removal rates were impressive, with iron achieved at 95% and manganese at 85%, all at a pH of 4.5. After the incineration of SCB at 120 °C, no other experiment was performed above this temperature for the oxygen-pre-treated SCB.

Table 4-6 is a summary of the results for heavy metal removal using oxygen-pre-treated SCB at 120 °C. An increase in temperature in the fluidised reactor from _60_to 120 °C slightly improved the adsorption capacity of SCB for manganese and iron. With SCB pre-treated in nitrogen at 120 °C and pH 4.5, a slightly significant extraction of 20% manganese, 29% nickel, 29% zinc and 58% iron was observed.

Pulverised SCB in powder form was exposed to temperatures higher than 100 ^{o}C, in a fluidised reactor. Since combustion is influenced by fuel, oxygen and heat source, SCB burned into ashes. When combustion occurs at temperatures higher than 100 but below 400 °C, chemisorption of oxygen occurs, and the formation of C-O surface compounds is activated, resulting in a high degree of porosity and an underarticulate surface area.

Based on previous studies, it can be deduced that burned SCB represents the nature of activated carbon, with a composition of 88% Carbon, 0.5% hydrogen, 1% nitrogen and 6 % sulphur. At high temperatures, nitrogen, hydrogen and sulphur are eliminated as volatile gaseous products, and only carbon remains. This leaves carbon with pores that make it an excellent adsorbent, and the adsorption capacity is determined by

physical, porous and mainly chemical structure (Yaashika *et al.,* 2019). Carbon adsorption of molecular species such as cations, in this case, heavy metals are cationic is bonded to the edges of the carbon atoms and gives rise to C-O, C-H, CN, and C-S surface groups (Ziegler *et al*., 1981)

Pulverised SCB in powder form was exposed to temperatures higher than 100 ^{o}C, in a fluidised reactor. Since combustion is influenced by fuel, oxygen and heat source, SCB burned into ashes. When combustion occurs at temperatures higher than 100 but below 400 °C, chemisorption of oxygen occurs, and the formation of C-O surface compounds is activated, resulting in a high degree of porosity and an underarticulate surface area (Tinega *et al.,* 2018). Based on previous studies, it can be deduced that burned SCB represents the nature of activated carbon, with a composition of 88% Carbon, 0.5% hydrogen, 1% nitrogen and 6 % sulphur (Zubrik *et al.,* 2017).

At high temperatures, nitrogen, hydrogen and sulphur are eliminated as volatile gaseous products, and only carbon remains. This leaves carbon with pores that make it an excellent adsorbent, and the adsorption capacity is determined by physical, porous and mainly chemical structure. (Perrich, 2018). Carbon adsorption of molecular species such as cations, in this case, heavy metals are cationic is bonded to the edges of the carbon atoms and gives rise to C-O, C-H, CN, and C-S surface groups.

SCB burned into ash means its physical properties have already changed, representing those of activated carbon with characteristics as described above. The phenomenon explains why 120 °C was highly effective in removing heavy metals. SCB burned into ash means its physical properties have already changed, representing those of activated carbon with characteristics as described above. The phenomenon explains why 120 °C was highly effective in removing heavy metals. The adsorption efficiency depends on the chemical and physical properties of the adsorbent (Koppula *et al*., 2022).

Table 4-6: Heavy metal concentration (mg/L) in wastewater filtrate over time using pulverised SCB, pre-treated in oxygen at 120 °C

Wastewater filtrate (hr)	Cr	Co	Cu	Fe	Pb	Mn	Ni	Zn
0	0.03	0.25	0.01	20.00	0.00	12.00	0.38	0.15

1	0.05	0.19	0.01	3.84	0.01	4.04	0.67	1.47
2	0.06	0.09	0.07	1.03	0.01	2.48	0.50	0.77
3	0.01	0.27	0.01	2.31	-	4.97	0.26	1.82
4	0.03	0.05	0.001	1.05	0.03	1.82	0.87	0.23
SANS 241	-	-	2	0.3	-	0.1	-	-
Irrigation	-	-	0.2	5	-	0.2	0.2	3
Livestock	-	-	0.5	10	-	0.2	1.0	24
Drinking water/Human health	-	-	1	0.3	-	0.5	0.2	3
Heavy metal removed (%)	-	-	-	95	-	85	-	-

From Table 4-6, copper concentration meets all the requirements for all four water quality standards. The level of nickel concentration is suitable for agricultural livestock but falls short of the standards for drinking water and human health, as well as for irrigation in agriculture. Manganese concentration was found to be outside the established water quality standards. Iron, although it was the highest heavy metal extracted, did not meet both SANS 241 and human health drinking water quality standards. Based on the results, SCB-treated water for this experiment requires further treatment to meet the requirements of the water quality standards.

Table 4-7: The residual concentration of heavy metals (mg/l) in wastewater filtrate over time using pulverised SCB pre-treated in nitrogen at 120 °C

Wastewater filtrate (hr)	Cr	Co	Cu	Fe	Pb	Mn	Ni	Zn
0	0.13	0.20	0.10	7.10	0.02	2.30	0.41	0.17
1	0.09	0.20	0.10	5.98	0.02	2.20	0.38	0.16
2	0.03	0.20	0.10	4.96	0.02	2.24	0.37	0.13
3	0.03	0.16	0.10	3.75	0.02	1.93	0.30	0.13
4	0.03	0.16	0.10	2.95	0.02	1.83	0.29	0.12
SANS 241	-	-	2	0.3	-	0.1	-	-

Irrigation	-	-	0.2	5	-	0.2	0.2	3
Livestock	-	-	0.5	10	-	0.2	1.0	24
Drinking water/Human health	-	-	1	0.3	-	0.5	0.2	3
Heavy metal removed (%)	-	-	0	58	0	20	29	29

From Table 4-7, it was observed that the concentrations of nickel and manganese were higher than the water quality requirements for irrigation, drinking water and health standards. Iron, as the most extracted heavy metal, still deviated from the requirements for both SANS 241 and the Drinking Water and Human Health Standards. Copper and zinc concentrations met all the requirements of the water quality standards.

4.1.8 Pretreatment of SCB using Nitrogen at 180 °C

Pulverised SCB pre-treated in nitrogen at 180 °C and ambient pressure at a constant gas flow rate of 300 SCCM was used to remove 85% nickel and 66 % zinc from the mining wastewater at a pH of 4.5, as indicated in Table 4-8. No significant removal of heavy metals was achieved at pH levels of 2, 7 and 9. Although SCB was able to undergo pre-treatment at 180 ^{O}C, the efficiency of heavy metal removal was only significant for nickel and zinc removal. As previously discussed, adsorption depends on the following:

1. Initial concentration of the metal. At lower concentration, the adsorbent has more sites to remove heavy metals, leading to high efficiency of removal observed. Nickel and Zn had 1.9 and 6.45 g/l at the start of the experiment; hence, the percentage of removal is higher. At high concentrations, adsorption sites become occupied and compete for sites, leading to lower heavy metal removal. This explains why iron could not be removed effectively because the initial concentration was 24g/l. In this research, the focus was on the total percentage of heavy metal removed from wastewater rather than adsorption efficiency.

2. The ionic strength and the oxidation state of the metal. Heavy metal ions compete for sites on the adsorbent based on the oxidation state as follows: Zn^{2+}, $N^{2+,}$ $Mn^{2+,}$ Fe^{2+}/Fe^{3+}. Based on this principle, manganese and iron had the power to compete for

sites more than nickel and zinc. Therefore, the increased removal of nickel and zinc in this case, irrespective of their oxidation state, is because manganese and iron occur as 3+.

Table 4-8: Heavy metal concentration (mg/L) in wastewater filtrate over time using pulverised SCB, pre-treated in nitrogen at 180 °C.

Wastewater filtrate (hr)	Cr	Co	Cu	Fe	Pb	Mn	Ni	Zn
0	0.67	0.56	0.01	24.00	0.28	1.37	1.90	6.45
1	0.65	0.49	0.01	20.84	0.21	4.04	0.67	4.47
2	0.63	0.40	0.01	21.10	0.20	3.57	0.71	4.10
3	0.65	0.41	0.01	23.31	0.20	4.97	0.96	4.82
4	0.65	0.46	0.01	23.62	0.21	3.82	0.29	2.22
SANS 241	-	-	2	0,3	-	0.1	-	-
Irrigation	-	-	0.2	5	-	0.2	0.2	3
Livestock	-	-	0.5	10	-	0.2	1.0	24
Drinking water/Human health	-	-	1	0,3	-	0.5	0.2	3
Heavy metal removed (%)	3	18	0	2	25	-	85	66

The concentrations of copper and zinc meet all the requirement standards. Nickel, while being the most significant heavy metal in mine wastewater, shows a deviation of 31% deviation in relation to standards for drinking water, human health and agricultural Irrigation, but is acceptable for agricultural livestock water quality standards. The levels of manganese and iron exceed the acceptable limits set by all water quality standards for this experiment. Additional treatment methods may be employed to effectively eliminate nickel, manganese, and iron, ensuring compliance with water quality standards.

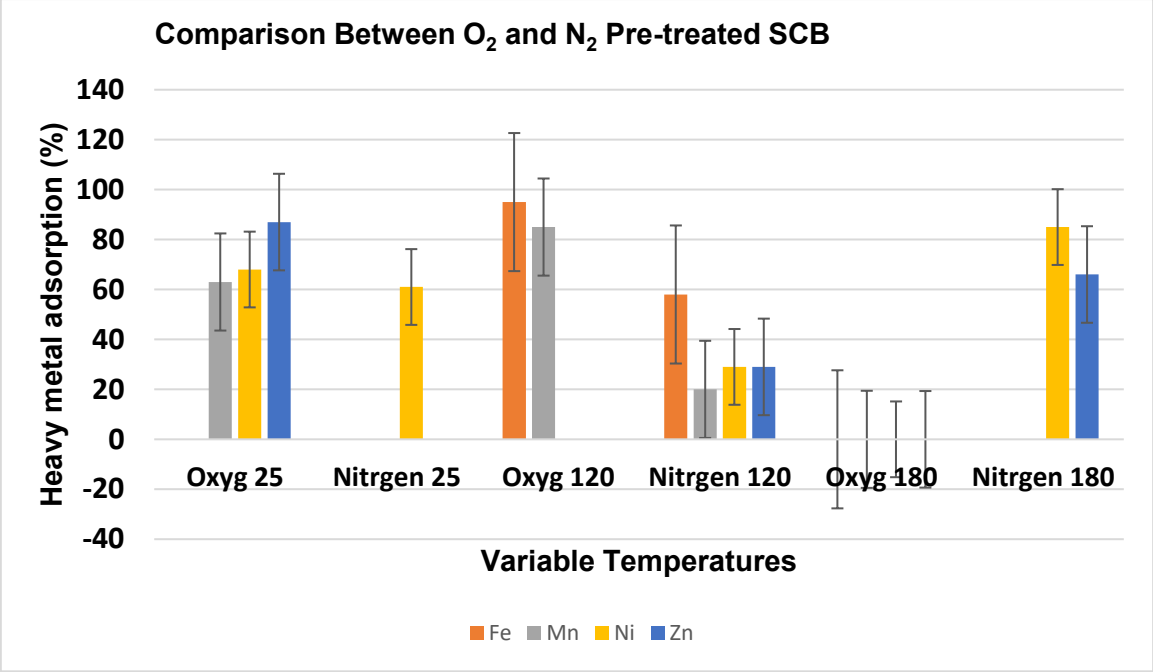


Figure 4-3: Plots of heavy metal adsorption (%) using pre-treated SCB in various gases at different temperatures.

From Figure 4-3, it was observed that at 25 °C, oxygen-pre-treated SCB removed manganese and nickel, with the highest removal of 85% for zinc, whereas nitrogen-pre-treated SCB removed only nickel. There were no significant extractions at 60 °C for both oxygen- and nitrogen-pre-treated SCB, and since oxygen burned to ash at 120 °C, no further test work was conducted for the SCB that was pre-treated in oxygen beyond 180 °C.

The SCB that was pre-treated in oxygen at 120 °C removed iron and manganese at the highest level of 95 and 85%, respectively. However, for nitrogen-pre-treated SCB, a significantly lower percentage of iron (less than 60%) and less than 50% of manganese, nickel and zinc were removed.

The SCB that was pre-treated in nitrogen at 180 °C removed 85% nickel and 66% zinc, and this is the temperature at which nitrogen-pre-treated SCB obtained the highest removal efficiency of nickel and zinc.

From the results presented in Figure 4-3, oxygen-pre-treated SCB remains the most efficient in removing iron and manganese. For nitrogen-pre-treated SCB, increasing the temperature of the fluidised reactor from 120 to 180 °C enhanced the efficiency of

removal of nickel, which increased from less than 30% to just over 80%, while zinc increased from 30 to just over 60% removal.

4.1.9 SCBA Sample

SCBA was utilised solely in wastewater with a pH of 4.5. This pH level was chosen to eliminate the need for adding acid or base to adjust the pH, considering the sensitive nature of the SCBA. After pulverization, SCB becomes an exceptionally fine powder that can easily dissolve in an acidic medium, even in a less strong acid such as hydrochloric acid. The observations made during this experiment, along with the analysis, suggest that if a hazardous chemical—such as nitric acid or sodium hydroxide—is introduced, there is a potential for the material to dissolve completely. Analytical results indicate that only copper (60%) and nickel (12%) were removed from the mining wastewater using SCBA at pH 4.5.

4.1.10 Summary: Adsorption Efficiency of SCB For Heavy Metals

Table 4-9 provides an indication and summary of the results of the test work conducted under different conditions for the removal of heavy metals from mine wastewater using SCB, and the efficiency of heavy metal removal in percentage.

Table 4-9: Summary results of adsorption efficiency (%) of heavy metals from mining wastewater using SCB, at various pH values

SCB conditions	Cu	Fe	Ni	Mn	Zn
Pristine SCB pH 2	16				
Pristine SCB pH 4.5	48	-	44	-	39
Pristine SCB pH 9			21	19	15
Pulverised SCB pH 4.5		86		80	71
Pulverized SCB pH 9	-	26	81	-	93
O_2 Pre-treated SCB 25 ^oC, & pH 4.5	-	-	68	63	87
O_2 Pre-treated SCB 120 ^oC, & pH 4.5	-	95		85	
Nitrogen pre-treated SCB at 25 ^oC, & pH 4.5			61		
Nitrogen pre-treated SCB at 180 ^oC, & pH 4.5	-	85	66		
SCB Ash pH 4.5	60				

From Figure 4-9, it can be deduced that SCB was effective in removing heavy metals when pre-treated in oxygen at 25 °C or 120 °C, while nitrogen-pre-treated SCB was effective in removing heavy metals when pre-treated at 25 and 180 °C. At 60 °C, neither pretreatment by these gases produced results.

4.1.11 Summary of the experimental work /study

Figure 4-4 is a summary of the laboratory test work conducted under different conditions for the removal of heavy metals from mine wastewater. The results, as represented by each column, do not represent the order of the experiment but rather the outcome thereof.

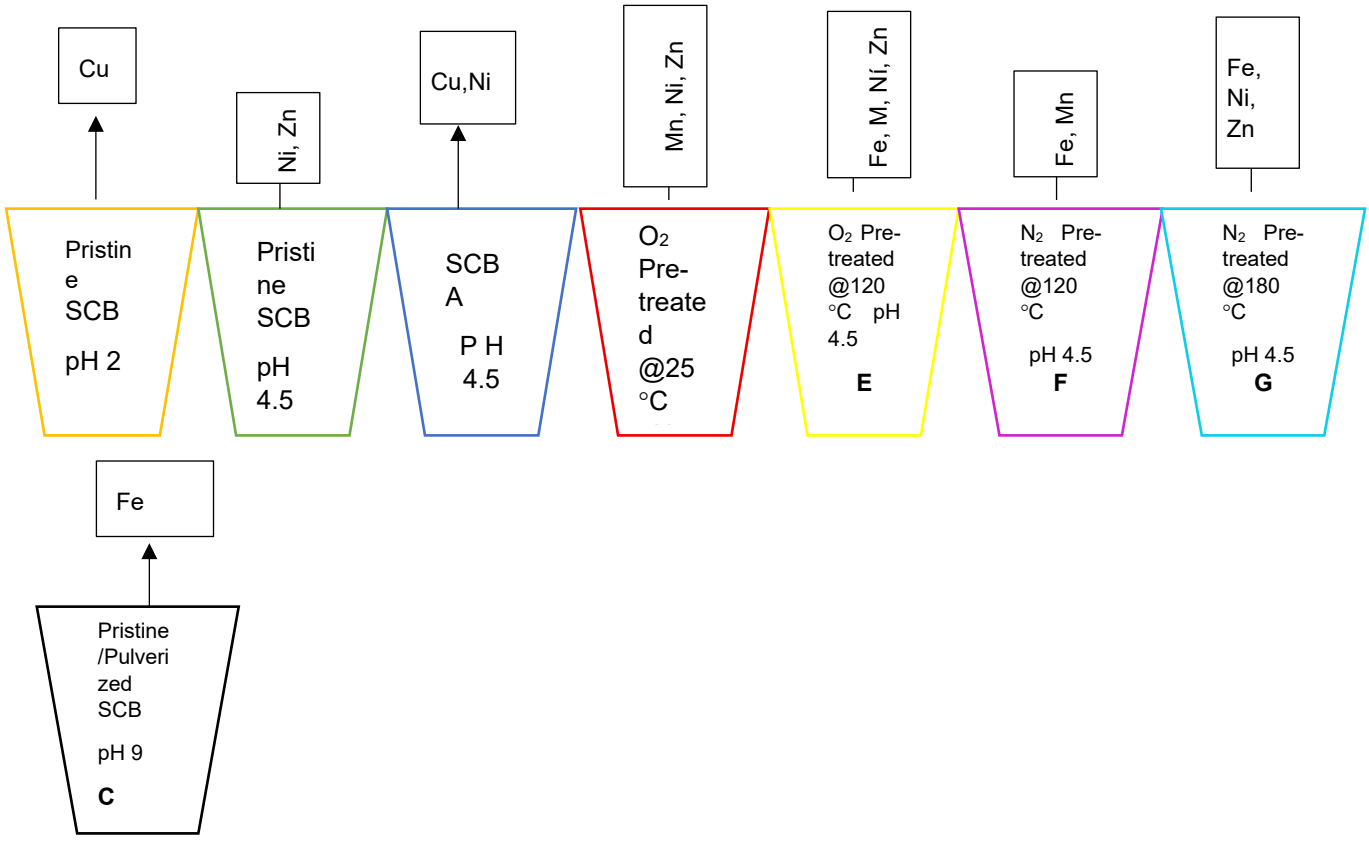


Figure 4-4: A summary of the laboratory experiments conducted for this research.

It would be ideal to remove all heavy metals such as iron, manganese, nickel, and zinc from the mining wastewater in a single treatment process. From Figure 5-1, there are three scenarios in the removal of heavy metals. The first scenario involves the use of pristine SCB under different pH conditions, as indicated in A, B and C. The scenario where pristine SCB is preferred is ideal for low concentrations of heavy metals from

mining waste since the heavy metal removal efficiency using pristine SCB is lower than that of the gas-pre-treated SCB. Another concern when using the pristine SCB is that it does not remove manganese, which can be a challenge for mining companies where manganese is prominent. The outcome of this experiment could not establish the individual removal of manganese, but adsorption of manganese was achieved only in combination with iron or nickel.

The second scenario, column E, involves the use of SCB pre-treated in oxygen at 120 °C, which has proven to have the capacity to remove all heavy metals at once. However, there may be circumstances that require an individual separation of different heavy metals, as indicated in column D, where high-temperature pretreatment is not possible. This scenario is ideal if iron is not a heavy metal of interest, particularly because pre-treating pulverised SCB in oxygen burns at 120 °C.

The third scenario involves the use of nitrogen-pre-treated SCB as indicated in columns F and G, which is easy. However, it involves the use of elevated temperatures that may require extra safety measures to eliminate a fire hazard and high energy consumption.

The last scenario involves the use of SCBA for the removal of copper at pH 4.5. Only 20% of the nickel could be removed in this experiment, which indicates less efficiency.

4.1.12 Benchmarking: Water Quality Standards

For this research, only four water quality standards were used for benchmarking against the water quality produced using SCB: the SANS 241 Drinking Water Standard, Drinking Water Standard for Human Health, Agriculture-Irrigation, and Agriculture-Livestock Water Quality Standards. The reason for this selection is that the analytical results revealed that the residual concentration of heavy metals in SCB-treated water remained high for recreation, industrial, salt water, aqua-organisms, and aquaculture water quality standards, while remaining very low for the City of Johannesburg Municipal by-laws.

In this study, the quality of water produced using SCB was benchmarked using the water quality guidelines indicated in Appendices 1 to 10. It was observed that removal of the heavy metals using SCB met the requirements for the City of Johannesburg municipal by-laws for effluent, which are as follows: Cu, which is a good indication that

mining companies can still maintain their environmental and legal obligations using SCB instead of non-biodegradable resins, which are expensive to dispose of. After the use of SCB, it was observed that the zinc and copper concentrations meet the SANS 241 standard for drinking water, human health, livestock, irrigation, and recreation purposes. The residual nickel and manganese concentrations in the mine wastewater effluents in this research did not meet any of the water quality guidelines.

Table 4-10: Benchmarking: Analytical results (mg/L) per experiment conducted using SCB for heavy metal removal from mine wastewater

	Cu	Fe	Mn	Ni	Zn
SANS 241: Drinking Water	2.00	0.30	0.10	-	-
Drinking Water & Human Health	1.00	0.30	0.50	0.20	3.00
Agriculture- Irrigation	0.20	5.00	0.20	0.20	2.00
Agriculture- Livestock	0.50	10.00	0.20	1.00	24.00
Pristine-SCB @pH 4.5	3.05	1.45	2.38	1.05	0.57
Pulverised-SCB @ pH 4.5	0.30	1.01	0.41	1.24	0.51
Pulverised-SCB @ pH 9	0.20	14.00	2.85	0.15	0.13
Oxygen-SCB @ 25 pH 4.5	0.00	1.05	2.29	0.36	0.46
Oxygen-SCB @ 120 pH 4.5	0.00	1.05	1.82	0.87	0.23
Nitrogen-SCB @ 120 pH 4.5	0.10	2.95	1.83	0.29	0.12
Nitrogen-SCB @ 180 pH 4.5	0.10	23.62	3.82	0.29	2.22

The water quality generated through SCB is suitable for a variety of applications. Other water quality guidelines indicate a need for further treatment methods for the removal of iron, nickel, and manganese, which were out of the maximum allowable limits. The treatment methods can be explored based on the intended water use.

In this research, the quality of water produced using SCB was assessed against the water quality guidelines for Drinking Water, Drinking and Human Health, Agricultural-Irrigation, and Livestock. All heavy metal concentrations meet the requirements of the Johannesburg municipal by-law for effluent, with 50 µg/L chromium, 1,000 µg/L manganese, 300 µg/L iron, 10 µg/L lead, 50 µg/L manganese, and 20 µg/L nickel. Mining companies can effectively meet their environmental and legal responsibilities by using SCB instead of resins and activated carbon. The latter options are costly to

dispose of and can harm the environment. Additionally, SCB allows them to avoid using calcium carbonate for neutralising heavy metals in mining effluent, which typically creates slime that leads to ongoing environmental challenges. Zinc and copper concentrations meet the SANS 241 standard for drinking water, human health, livestock, irrigation, and recreation purposes. Iron did not meet the requirements of many water quality guidelines except for irrigation and livestock. Nickel and manganese concentrations do not meet the water quality guidelines in this research.

4.1.13 The Brunauer -Emmett- Teller (BET) Characterisation of SCB

Surface area is the total area covering three dimensions of an object, and it represents the amount of space occupied by the surface of a material, whereas the porosity of a material is the ability of such material to store fluid. Brunauer-Emmett -Teller (BET) was used for the surface area and porosity of SCB as indicated in Appendix 14. Based on the BET results, SCB has a surface area of 2.003 m^2/g and pore diameter of 0.014 m^2/g, indicating a low capacity of pulverised SCB to allow material to pass through. Materials with a porosity of above 50 nm are microporous, between 2 – 5 nm are mesoporous, and with less than 2 nm are considered microporous. Therefore, SCB is a microporous material and has high capacity to adsorb materials, but the limited surface area lowers that capacity (Skoog *et al*., 2001).

Scientific evidence indicates that a large surface area is directly proportional to the high absorptivity of the target material (Sing, 2013). The more surface area available, the more sites there are for adsorbate molecules to stick to. A material with a large surface area will adsorb significantly more of a substance than a material with a small surface area. The use of the residue showed minimal effectiveness in removing heavy metals from the mining wastewater, yielding results only for copper.

4.1.14 FTIR Characterisation of SCB

Fourier Transform Infrared Spectroscopy (FTIR) was used to obtain a complete spectrum for qualitative identification and functional group properties of SCB, as indicated in Figure 4-5. The highest spectrum of the pulverised SCB, at a range of 2359 to 234 cm^{-1}, means the functional group is a nitrile, C≡N, and is not easily attracted by heavy metal ions. At 2126.81 cm^{-1}, it means alkyne, triple-bonded carbon atoms C≡C, which is also difficult to adsorb heavy metal ions. While at 2900.14 cm^{-1}

means aliphatic, C—H functional group, the hydrogen atom is easily replaceable by heavy metal ions. At 1259.68 cm^{-1}, SCB indicated the aromatic properties, Ọ—O—R, which makes the carbon of this functional group difficult to attract heavy metal ions. The range of 1683 to 1635.56 cm-1 indicates the presence of alkenes due to the characteristic double-bonded carbon atoms (C=C). Additionally, this wavelength range poses challenges for the adsorption of heavy metal ions (Holler et al., 2007). In summary, pulverised SCB showed properties and functional groups such as aliphatic, aromatic, and different wavelength ranges and insignificant peaks between the wavelength range of 1791-1867.31 cm^{-1}. Therefore, pulverised SCB was effective in removing heavy metal ions at 2900.14 cm^{-1}.

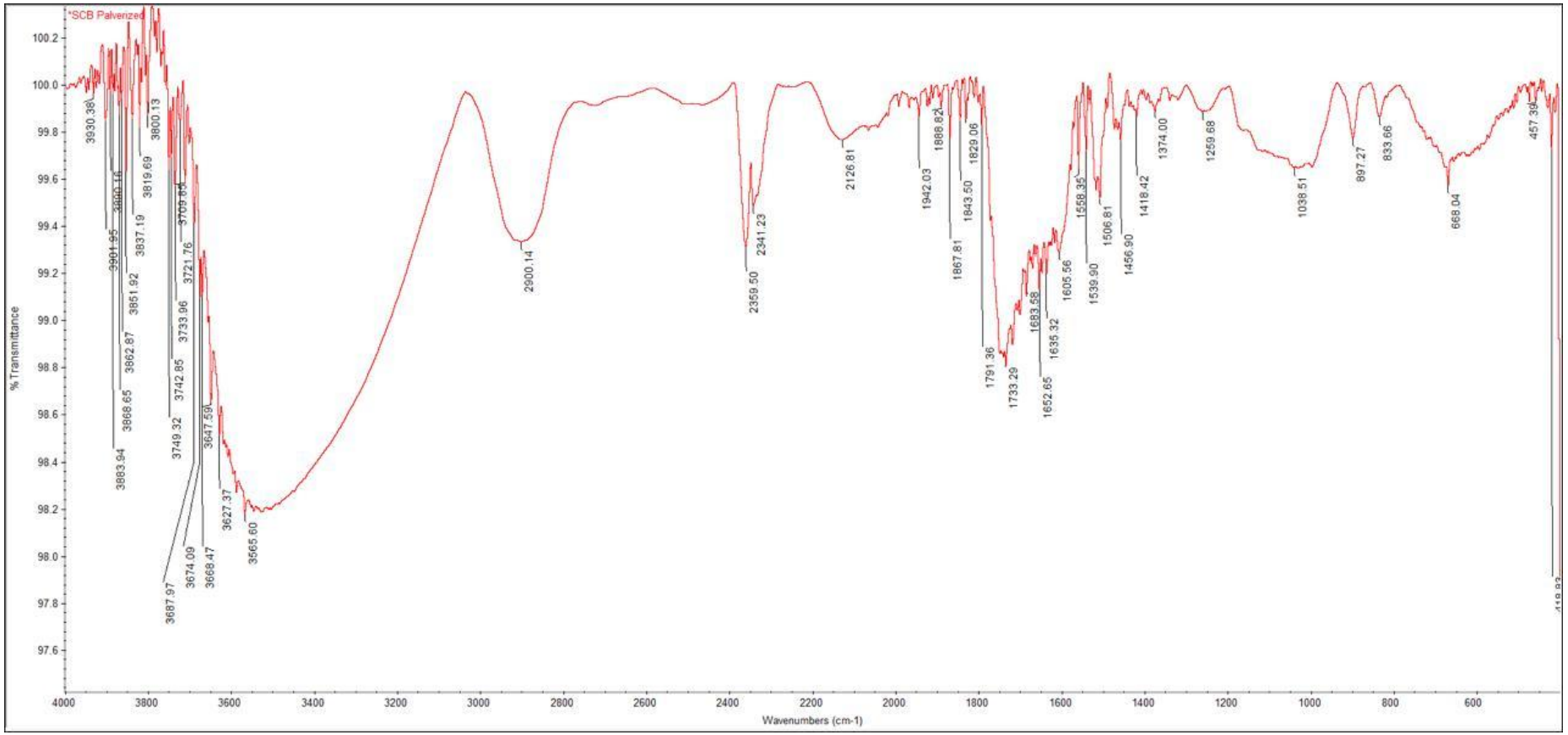


Figure 4-5: Spectrum of Fourier Transform Infrared Spectroscopy

4.2 Discussion

4.2.1 Overview of the findings

SCB is a biodegradable, readily available, and cost-effective adsorbent that can be used for removing heavy metals from mine-impacted wastewater. Pristine, pulverised, and gas pre-treated SCB samples were used in this study, and the following observations were made:

- Pristine SCB was only effective in the removal of copper (16% at pH 2), nickel (44% at pH 4.5) and zinc (39% at pH 4.5).
- Pulverised SCB was effective in removing iron (86% at pH 4.5) and zinc (71% at pH 4.5). At pH 9, nickel removal was at 81%, and zinc increased to 93%.
- SCB pre-treated in oxygen at 120 °C was effective in removing iron (95% at pH 4.5) and manganese (85% at pH 4.5). The highest amount of zinc (85% at pH 4.5) was removed at 25 °C.
- SCB pre-treated in nitrogen at 25 °C only removed 61% nickel. Increasing the temperature of the fluidised reactor to 180 °C, iron (85% at pH 4.5), and nickel (66% at pH 4.5) were removed.
- SCBA was effective in removing 60% copper and 20% nickel at pH 4.5.

SCB has been used successfully to remove heavy metals from industrial wastewater with carboxylic acids and oxidants in acid-based solutions and at hot temperatures. A study conducted by Iwuzor *et al*. (2022) aimed at enhancing the removal of chromium in water bodies achieved removal efficiencies of 28.8% Cu(II), 8.29% Cd(II), 0.395% Cr(III), 1.67% Ni, 70% Pb (II), and 20% Zn(II) using modified sugarcane bagasse. This study could not establish the removal of manganese and iron as compared to the unmodified SCB. Although results confirm the effectiveness of SCB in removing chromium, cadmium and lead, which could not be achieved using unmodified SCB, this study has established that pristine SCB and gas pre-treated SCB can remove heavy metals from mine wastewater at ambient temperature without chemical modification, achieving up to 65% zinc and 48% copper.

Many of the studies have primarily concentrated on the removal of individual heavy metals. For instance, a study by Lumadede *et al*. (2022) demonstrated that cadmium

could be removed from an aqueous solution by adding 0.1 M hydrochloric acid at a temperature of 800 °C. While the researchers managed to remove cadmium, the addition of acid and high temperature to roast the SCB remains an environmental concern, introducing issues such as volatilisation of fumes, which may affect the air quality, while acid decreases the pH of water sources, promoting dissociation of heavy metal ions. Most of the experiments conducted for this research were executed at ambient temperature, except where the temperature of the fluidised reactor was adjusted to a maximum of 180 °C for nitrogen pretreatment. This is due to a change in the physical state of SCB, where it was powdered during pulverisation, making it easy to burn at a high temperature. At 25 °C, SCB still yielded up to 95% removal of iron, for example. This illustration reveals that SCB can work at low temperature and unadjusted pH.

Ion exchange methods using physical and chemical methods, such as chelating resins and zeolite, in the removal of heavy metals from wastewater depend on the pH of a solution, selectivity, material origin, and activation process involving acids and alkalis, which, in most cases, do not support green chemistry (Wong *et al.,* 2018). This research has shown that SCB, while selective in certain conditions, plays an active role in extracting heavy metals from mining wastewater. The findings emphasise that the removal efficiency is influenced by factors such as the pH of the solution, temperature, and the activation process, with the gas-pre-treated SCB demonstrating the highest effectiveness.

Studies conducted on bio-adsorbents to reduce toxic metals from wastewater concluded that the adsorption of heavy metals such as cadmium and lead using SCB depends on the ionic strength of the metals (Thanki *et al.,* 2021), which is inversely proportional to the adsorption capacity, while being directly proportional to temperature. This is due to the lack of uniformity in the concentration of contaminants in wastewater, leading pollutant species to compete for active sites during the adsorption process. In this research, it was noted that SCB was not successful in the removal of chromium, cobalt and lead from wastewater, which confirms that the ionic strength of these heavy metals was not strong enough to stick to the surface area of the SCB.

Literature revealed that SCB has been used to remove heavy metals from aqueous solutions and other industrial waste, such as oil refineries, electroplating, textiles, palm oil, paint, ceramic and steel industries (Karri *et al.,* 2020). However, nothing has been documented relevant to studies involving the use of SCB for heavy metal removal from mining wastewater. This study has established that SCB, pristine and gas pre-treated, can treat mining wastewater as well as it treats another industrial wastewater.

4.2.2 Background on Adsorbent Performance

The efficiency of adsorption in hydrometallurgy and various scientific methods that employ adsorbents is influenced by several important factors. These factors encompass the adsorbent's surface area, the starting concentration of the adsorbate, the adsorbate properties, the pH of the solution, temperature, the quantity of adsorbent applied, pressure, and the contact time. In this research, these environmental conditions were studied as follows:

4.2.2.1 The Temperature of The Solution

Pristine and pulverised SCB were used at 25 °C indicate some level of adsorption for different heavy metals, such as copper at forty-eight per cent (48%) and nickel at forty-four per cent (44%). Increased temperature in a fluidized reactor during oxygen pretreatment of SCB enhanced the removal efficiency for manganese to over 80% and over 90% for iron at 120 °C, showing more selectivity for iron.

SCB pre-treated with nitrogen at 25 °C only removed (60%) nickel from the mining wastewater, and increasing the temperature to 60 °C did not yield any heavy metal removal. At 120 °C, nickel decreased by almost half, but the removal efficiency for manganese and iron was the highest. An increased temperature to 180 °C achieved eighty per cent (80%) of iron recovery; therefore, increased temperature enhanced the selectivity of gas pre-treated SCB in heavy metal removal and not the temperature of the solution or wastewater.

4.2.2.2 Contact Time and Feed Concentration

Time is directly proportional to the efficiency of adsorption, the longer the contact time, the better the adsorption. A study conducted by Karri *et al*. (2022) indicates that maximum chromium adsorption of 87% was obtained at 10 mg/l feed concentration,

while 75% chromium adsorption was obtained at a higher feed concentration of 30 mg/L. Also, the higher the residence time (irrespective of initial feed concentration), resulted in higher the chromium removal. Furthermore, the study revealed that the optimum contact time for SCB in a homogenous mixture to remove heavy metals was 60, 120, and 180 minutes.

These observations align with this research. In this study, it was observed that heavy metals in mining wastewater were effectively removed within the first two hours. The highest removal efficiencies achieved were 95% for iron, 85% for manganese, and 66% for nickel. It was also found that extending the residence time led to some desorption in the samples examined.

4.2.2.3 Surface Area of Adsorbent

In adsorption, surface area plays a significant role because the larger the surface area, the more molecules of adsorbate interact with the adsorbent, allowing molecules to adhere to the surface (Aljamali *et al.,* 2021). Increasing surface area means the number of sites for adsorption also increases. Both physical and chemical adsorption are affected by the surface area of the adsorbent. The same phenomenon has been observed during this study, where pristine SCB did not extract a lot of heavy metals from the mining wastewater. An example of this concept is revealed where only 48% of copper was removed from the mine wastewater at pH 4.5, whereas 60% of copper was removed from the mine wastewater using SCBA.

4.2.2.4 pH of the solution

Ezeonuegbhu *et al.* (2021) conducted a study for the removal of heavy metals such as lead and nickel from aqueous solution using SCB. Conditions for the removal efficiencies of lead (89 %) and Ni (96 %) were a pH of 6.0, a temperature of 30 °C, and a contact time of 90 minutes. The maximum monolayer adsorption capacities of Pb (II) and Ni (II) were 1.61 mg/g and 123.46 mg/g, respectively. Although pH 6 is less acidic, it has achieved the highest removal efficiency of 96.3% for nickel, whereas in this study, pH 4.5 remained the most effective pH for nickel removal, with up to 66% removal even at 25 °C. Also, as observed throughout the study, the removal of heavy metals occurred within the first two hours of the experimental work, which is comparable to 90 min according to Ezeonuegbhu *et al.* (2021).

4.2.3 Selectivity of SCB

Homagai (2018) evaluated the uptake performance of SCB for the removal of heavy metal ions such as cadmium, lead, copper, nickel and zinc from aqueous solution. The performance of SCB significantly changed with pH, concentration of metal ions and temperature. The selectivity order in the removal of heavy metals at pH around 4 follows the order lead> copper > nickel > cadmium >zinc. A change in condition leads to a change in the order of selectivity to lead > cadmium > zinc > nickel>copper.

In this study, it was observed that the selectivity of pulverised SCB at pH 4.5 was iron (86%)> manganese (80%) > zinc (71), whereas at pH 9, manganese was not removed at all, and the selectivity changed to iron (86%)> nickel (81%) > zinc (71) instead.

4.2.4 Purification of contaminated SCB

Most studies were successful in the use of SCB for the removal of heavy metals from wastewater; however, the heavy metal-loaded or impregnated SCB is normally not addressed properly, or there is not enough documented evidence on the process. This study established that the impregnated SCB can be exposed to hydrometallurgical processes for the removal of heavy metal traces before being used as fertilisers by farmers or can be washed before being taken for future use in the agricultural sector, using acetic acid, commonly known as vinegar, to remove the heavy metals from the SCB. Since most sugar processing companies burn SCB to generate electricity, heavy metal-loaded SCB may be burned for similar purposes. Another option is to introduce the heavy metal-loaded SCB to high-temperature technology, which involves roasting the material to ash in a controlled area to prevent volatilisation of harmful substances into the atmosphere. The ash containing heavy metals can further be processed for metal recovery using hydrometallurgical techniques. The study has established that the adsorption of heavy metal ions using SCB was successful.

The adsorption of anions such as nitrates, sulphates, and cyanide species has not yet been assessed; therefore, this study can be used as a basis for further investigations involving the removal of anions such as chlorides, nitrates, sulphates, cyanate, etc., using SCB, while analysing the concentration of such using UV-VIS and a segmented flow injection analyser for cyanide species. Also, radioactive materials such as uranium and thorium were not within the scope of this research; however, future work

involving the use of SCB to remove such material, including arsenic, can be explored and analysed using X-ray methods. Future perspectives on the application of SCB as a natural coagulant in the removal of various other pollutants, such as colour, biochemical oxygen demand, and heavy metals from sources of wastewater, can further be investigated.

4.2.5 Comparative studies between SCB and other water treatment methods

Copper is the most extensively researched heavy metal in various industries, serving as a benchmark for comparing the efficiency of different methods used to recover or remove heavy metals, as illustrated in Table 4-11.

Table 4-11: Comparison of SCB and other treatment methods in the removal of heavy metals from industrial wastewater

Treatment Method	Heavy metal removed	% Removal	SCB
Ion Exchange	Cu	64 – 69	16 – 60
Electrochemistry	Cu	91 – 99	16 – 60
Chemical Precipitation	Cu	99	16 – 60
Adsorption	Cu	88 – 98	16 – 60
Biotechnology	Cu	95	16 – 60

Ion-exchange methods: In a study conducted to recover Cu (II) using resins, a recovery of between 64 – 99% was achieved; however, resins do not have long-term reusability and the possibility of recovering the target compounds from the regenerated solution remains a limitation to the application of ion exchange material such as zeolite. (Yu *et al*., 2019).

Electrochemistry: Electrochemical cells have been used by Salonen *et al*. (2018) in the recovery of copper and the results obtained were between 91 and 99%.

Precipitation: Shan *et al*. (2013) used chemical methods such as precipitation to remove copper from wastewater and obtained 99% recovery.

Adsorption methods: The use of agricultural waste in the removal of copper has been studied by Pfeifer *et al*. (2012), and 88% recovery was obtained, while the use of zeolite and steel slag achieved the highest of 99% recovery.

Biotechnology: The use of algae in the removal of copper has been studied by Tam *et al*. (1998), achieving the highest removal efficiency of 95%.

The efficiency of all copper removal from the various wastewater using methods as described in Table 4-11 cannot be disputed. However, the highest efficiencies obtained cannot replace the environmental and other challenges associated with the use of such methods when dealing with copper.

This research shows the use of SCB, obtaining the highest recovery efficiency of only 60% copper under pH 4.5. Although the removal efficiency is low when compared to the methods described in Table 4-11, SCB is still a prospective adsorbent in the removal of heavy metals from industrial wastewater because it not only removes copper, but also other heavy metals such as iron, manganese, nickel and zinc. Although the highest removal of manganese, nickel, iron and zinc was obtained in this research, the reusability of SCB did not form part of the study.

5. CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study focused on using SCB as an ion exchange process to treat wastewater from the mining industry according to the listed objectives. The hypothesis assessed the application of SCB as an adsorbent for heavy metals from mineral-impacted wastewater and is hereby accepted as successful.

Based on the results, the following objectives have been achieved.

Objective one: To establish the effectiveness of sugarcane bagasse (SCB) as an alternative material in purifying mining wastewater. Based on the analytical results, the following outcomes have been achieved.

- Pristine SCB sample removed 16% copper at pH 2 and 48% copper, 44% nickel and 39% zinc from the mining wastewater at pH 4.5.
- Pre-treated SCB using oxygen and nitrogen, at 25,120 and 180 °C in a fluidized reactor, achieved the highest efficiency of heavy metal removal, such as 95% iron, 85% manganese, 66% nickel, and 85% zinc at pH 4.5.

The samples assessed (pristine, pulverised, and the gas-pre-treated SCB) were effective in the removal of heavy metals from mining wastewater. Although recent studies indicate the use of chemically modified SCB for the removal of heavy metals from variable aqueous solutions, this study has established that SCB can work without chemical modification and once implemented successfully by industries, it would eliminate the use of selective polymer resins, chemical fertilisers and chemicals such as lime. It was observed that SCB is a prospective adsorbent in the removal of heavy metals from the mine-impacted wastewater. From studies involving the use of chemical precipitation, adsorption methods using biochar, activated carbon and other exchange methods, although they are effective in removing heavy metals from industries such as oil refinery, paint and steel manufacturing, they face environmental challenges such as handling, storage, and disposal. Although the study focused on mine wastewater, since it was successful in the removal of heavy metals with minimal environmental concerns, it can be implemented in these industries.

Objective two: To compare the effectiveness of pristine and gas pre-treated SCB using oxygen, nitrogen, or air in removing heavy metals such as iron, manganese, nickel, and zinc from the mining wastewater.

From the analytical results, pristine SCB only removed 48% copper, while pulverised SCB samples that were pre-treated at 25 °C show a significant removal of zinc (93%), manganese (85%), and nickel (68%) at a pH of 4.5. For the oxygen pre-treated SCB, only nickel (81%) adsorption occurs. For the nitrogen pre-treated SCB, it can be concluded that gas pretreatment of SCB enhanced the removal efficiency of heavy metals from mine wastewater using SCB. It displayed some degree of selectivity because pristine SCB removed copper, but pulverised SCB removed iron, manganese, nickel, and zinc.

Objective three: To establish the effectiveness of sugarcane bagasse ash (SCBA) as an alternative material to SCB in purifying mining wastewater.

From the analytical results, SCB removed 48% copper while SCBA removed 60% copper and 12% nickel at pH 4.5. Therefore, SCBA can be used instead of SCB in the removal of copper from mining wastewater.

Objective four: To compare treated water to the standards set for drinking water by South African National Standards (SANS 241), and water quality guidelines for industrial effluents as determined by the Department of Agriculture and Forestry, and the City of Johannesburg Municipal bylaws.

Water quality standards benchmarked are: The SANS241 drinking water standard, Drinking water and human health, Organisms Freshwater Quality Criteria, Aquatic organism saltwater quality, Agriculture Irrigation, Agriculture livestock, Recreational, Aquaculture and Industrial water quality standards, as well as the Johannesburg municipal bylaws. Mine wastewater treated using SCB was compared to these water quality standards, and the analytical results indicate the following:

- All heavy metal concentrations meet the requirements for the city of Johannesburg municipal bylaws for effluent, with 50 µg/L chromium, 300 µg/L iron, 10 µg/L lead, 50 µg/L manganese, and 20 µg/L nickel.

- Iron remains the most extracted heavy metal (at 95% efficiency), but it does not meet the requirements of many water quality guidelines except for irrigation and livestock.
- Zinc and copper concentrations meet the SANS 241 standard for drinking water, human health, livestock, irrigation, and recreation purposes.
- The concentrations of nickel and manganese remaining in the mine's wastewater effluents examined in this study fell short of the established water quality guidelines.
- From the outcome stated above, it can be deduced that SCB produced water that meets the requirements of the SANS 241 drinking water standard, agricultural livestock, recreational, and the city of Johannesburg municipal bylaws.

Other conclusions, based on the outcome of this study and the analytical results, are that:

- SCB did not work well for the removal of cobalt, chromium, and lead.
- SCBA only worked in the removal of copper at pH 4.5.

5.2 Recommendations

Since the present study has established SCB as an alternative adsorbent material for wastewater purification, mining companies can.

- Avoid the use of chemicals to neutralize the effluent produced from mining, mineral processing, and metallurgical processes.
- To implement this on a large scale, a pilot campaign may be required, involving different experts such as chemists, metallurgists, engineers, and other professionals. Once the effectiveness of SCB has been established on a large scale, process engineers may design proper columns and sequence them properly for the removal of target heavy metals.
- This will assist mining companies in meeting their environmental compliance obligations while minimizing the use of polymer resins that continue to pose waste management concerns. Successful implementation of SCB as a

purification method would help to save water that can be used for other purposes and avoid contaminating the river water with heavy metals.

- The water produced using SCB can be used for different purposes, assisting organizations to meet the strategic UN-SDG obligations while supporting circular economies. Water produced through treatment by SCB has been found to meet the municipal bylaw requirements of the City of Johannesburg, and mining companies may enhance their compliance obligations by introducing the use of SCB.
- Elimination of polymer resins by mining companies would minimize waste management and disposal costs while fostering a partnership between the farmers and sugarcane processing companies. Since SCB is cost-effective, the cost associated with the use of non-biodegradable polymer resins, activated carbon, and calcium carbonate would also be eliminated.

5.3 Future Work

Further research studies involving experts, such as process engineers, can design columns for SCB to be used in a large-scale pilot campaign targeting the removal of heavy metals from mine wastewater, as indicated in Figure 5-1:

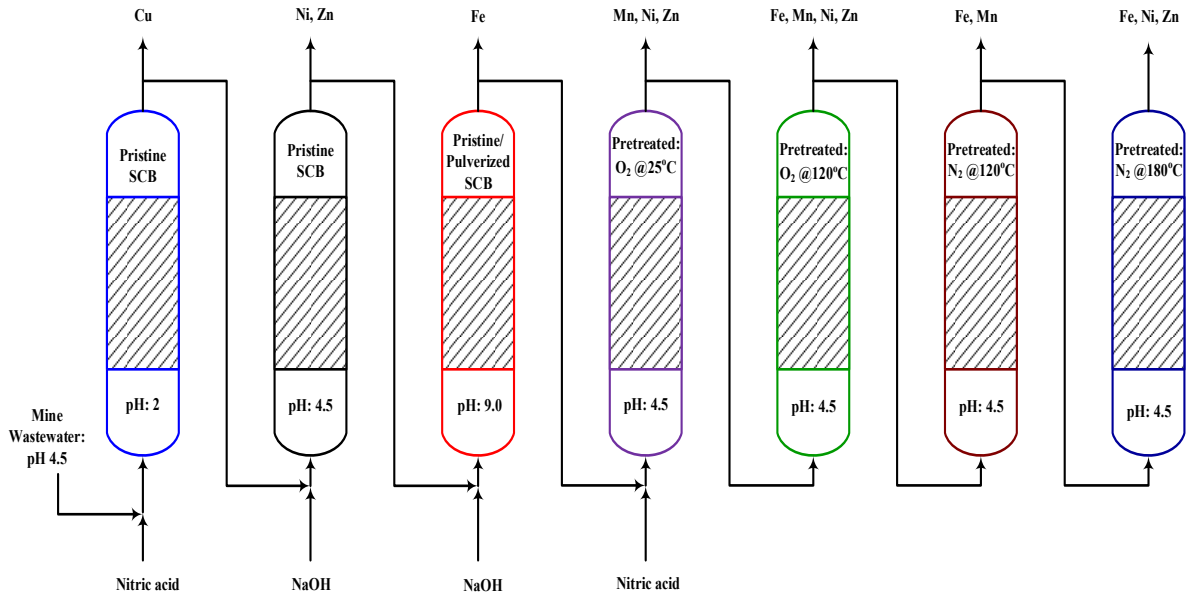


Figure 5-1: Possible sequencing of columns for heavy metal removal from mine wastewater using SCB under different conditions.

From the diagram in Figure 5-1, the sequencing of columns can be done in such a way as to suit the specific needs of the mining company. For example, column three can be put at the end since it indicates the highest pH, depending on the target heavy metal. The graphical schematic suggests a column sequencing that can be applied to extract most of the heavy metal ions and then leach individually using hydrometallurgy processing for metal recovery before SCB is taken to the farmers to be used as a fertiliser.

Certain parameters to be investigated by engineers, metallurgists, and scientists may include, among other things, water flow rate through the column per hour, the amount of SCB required to treat the required amount of wastewater, SCB reusability, and regeneration. Although SCB produces water that meets certain requirements for specific water quality guidelines, there may be a need for further treatment, such as membrane filtration, based on the need for specific water use. For mining companies to save fresh water, the water produced using SCB can be reused for irrigation, animal husbandry, and other purposes, such as cleaning.

5.4 Aesthetic, decaying and other considerations of using raw SCB in wastewater treatment

The study has established that SCB can remove heavy metals from mining wastewater and the treated water is potable however there are aesthetic concerns associated with the application of raw sugarcane bagasse in wastewater treatment may have the following:

1. Particulate accumulation: physical breaking of fragments that can either float or settle in basins. This can be remediated by extra filtration at the end of the treatment process

2. Increase turbidity: analytical results of the final treated wastewater will indicate the level of turbidity and suitability of the water use where turbidity is not an issue. Although potable water is a target in this research, there are many other water uses that can be profitable as indicated in appendices, pages 99 to 104.

3. Water discolouration: raw bagasse contains brownish colour which can turn water into yellowish colour. Since this is not harmful, the water can be used in agricultural activities such as irrigation. For drinking water, introduction of coagulants such as ferric or ferrous chloride, can be used for the treatment of dye and pigment wastewater. Previous studies reveal the addition of coagulants is essential for reduction of chemical oxygen demand, colour, turbidity, and total suspended solids from the wastewater

Decaying of raw SCB in wastewater treatment can be a serious concern. However, further studies such as reusability of SCB will determine the frequency of SCB changed during the process.

The regeneration and reusability of SCB have not been established in this research, and further work covering that aspect may be necessary.

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7. APPENDICES

7.1 List of Tables for Water Quality Standards

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Appendix 1 Chemical, physical, and aesthetic determinants of requirements for drinking water, Courtesy of SANS 241:2015

Determinant	Unit of measure	Standard limit/criteria
pH @ 25 ^{O}C	pH units	5≤ 9.7
Electrical Conductivity @ 25 ^{O}C	mS/m	≤ 170
Total Dissolved Solids	mg/L	≤ 1200
Chlorine	mg/L	≤ 300
Sulphate	mg/L	≤ 250
Fluoride	mg/L	≤ 1.5
Nitrate	mg/L	≤ 11
Free Cyanide	µg/L	≤ 2000
Chromium(Total)	µg/L	≤ 50
Copper	µg/L	≤ 2000
Iron	µg/L	≤ 300
Manganese	mg/L	≤ 100
Arsenic	µg/L	≤ 10
Lead	µg/L	≤ 10
Calcium	mg/L	≤ 150
Magnesium	mg/L	≤ 70
Sodium	mg/L	≤ 200

Appendix 2 Chemical Constituents Requirements for Drinking Water and Human Health Criteria

Determinant	Unit	Standard limit/ criteria
Copper	mg/L	20
Chromium	mg/L	10
Iron	mg/L	50
Lead	mg/L	5
Zinc	mg/L	30

Manganese	mg/L	-
Nickel	mg/L	5

Appendix 3 Chemical determinant requirements for the City of Johannesburg Municipal Bylaws

Determinant	Unit of measure	Standard limit/Criteria
Chromium (total)	µg/L	50
Cobalt	µg/L	-
Copper	µg/L	1000
Iron	µg/L	300
Lead	µg/L	10
Manganese	µg/L	50
Nickel	µg/L	20

Appendix 4 Chemical Constituents Requirements for Aquatic Organisms Freshwater Quality Criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium (VI)	µg/L	11
Cobalt	µg/L	-
Copper	µg/L	-
Iron	µg/L	1000
Lead	µg/L	-
Manganese	µg/L	370
Nickel	µg/L	-
Zinc	µg/L	-

Appendix 5 Chemical Constituents Requirements for Aquatic Organisms Saltwater Quality Criteria

Metal/Metalloid	Unit of measure	Standard limit /criteria
Chromium III	µg/L	27.4
Chromium VI	µg/L	4.4
Cobalt	µg/L	-
Copper	µg/L	3.2
Iron	µg/L	-
Lead	µg/L	8.1
Manganese	µg/L	-
Nickel	µg/L	70
Zinc	µg/L	15

Appendix 6 Chemical Determinants Requirements for Agriculture- Irrigation Water Quality Criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium(Total)	µg/L	100
Cobalt	µg/L	50
Copper	µg/L	200
Iron	µg/L	5000
Lead	µg/L	200
Manganese	µg/L	200
Nickel	µg/L	200
Zinc	µg/L	2000

Appendix 7 Chemical Determinants Requirements for Agriculture- Livestock Water Quality Criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium(Total)	µg/L	100
Cobalt	µg/L	50
Copper	µg/L	200
Iron	µg/L	5000
Lead	µg/L	200
Manganese	µg/L	200
Nickel	µg/L	200
Zinc	µg/L	2000

Appendix 8 Chemical determinants and requirements for aquaculture water quality criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium(VI)	µg/L	100
Cobalt	µg/L	-
Copper	µg/L	-
Iron	µg/L	10
Lead	µg/L	-
Manganese	µg/L	10
Nickel	µg/L	100
Zinc	µg/L	5

Appendix 9 Chemical Determinants Requirements for Recreational Water Quality Criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium(Total)	µg/L	50
Cobalt	µg/L	-
Copper	µg/L	1000
Iron	µg/L	300
Lead	µg/L	10
Manganese	µg/L	100
Nickel	µg/L	40
Zinc	µg/L	3000

Appendix 10 Chemical Constituents Requirements for Industrial Water Quality Criteria

Metal/metalloid	Unit of measure	Standard limit/criteria
Chromium(Total)	µg/L	100
Cobalt	µg/L	-
Copper	µg/L	-
Iron	µg/L	10
Lead	µg/L	-
Manganese	µg/L	10
Nickel	µg/L	100
Zinc	µg/L	5

7-2 Figures as Referred to in the Text.



Appendix 11 The shaking table used in the experimental work with roller bottles loaded with SCB.



Appendix 12 A column loaded with pulverised SCB inside the Fluidised reactor.



Appendix 13 The fluidized reactor is connected to a fuel source, with O_2, N_2, H_2, and Air for the pretreatment of pulverised SCB. The fuel source is passed through a column loaded with SCB at a flow rate of 400 m^3/s at different temperature ranges.



Appendix 14 BET analyser for surface area /porosity of pulverised SCB



Appendix 15 FTIR equipment was used for the characterisation of SCB.



Appendix 16 Handheld Hitachi XRF in the hydrometallurgy laboratory at MC-Y, used to analyse raw bagasse before pulverization or use.



Appendix 17 SCB sample from the column exposed to temperatures exceeding 180 ^{O}C in different gases

7.3 Chemical Analytical Results

7.3.1 Appendix 18: XRF results

Date	Mode	Sample name	Unit	Ca	Ti	Fe	Y
########	Soil	no label	PPM	4426	614	5612	ND
########	Soil	no label 1	PPM	4152	582	5595	ND
########	Soil	no label 2	PPM	4402	650	5649	ND
########	Soil	Illovo A unprocessed	PPM	558	93	1609	ND
########	Soil	Illovo A unprocessed 1	PPM	601	106	1639	ND
########	Soil	Illovo A unprocessed 2	PPM	477	113	1693	ND
########	Soil	UGL sample	PPM	1341	159	2303	ND
########	Soil	UGL sample 1	PPM	1325	175	2283	ND
########	Soil	UGL sample 2	PPM	1296	169	2302	ND

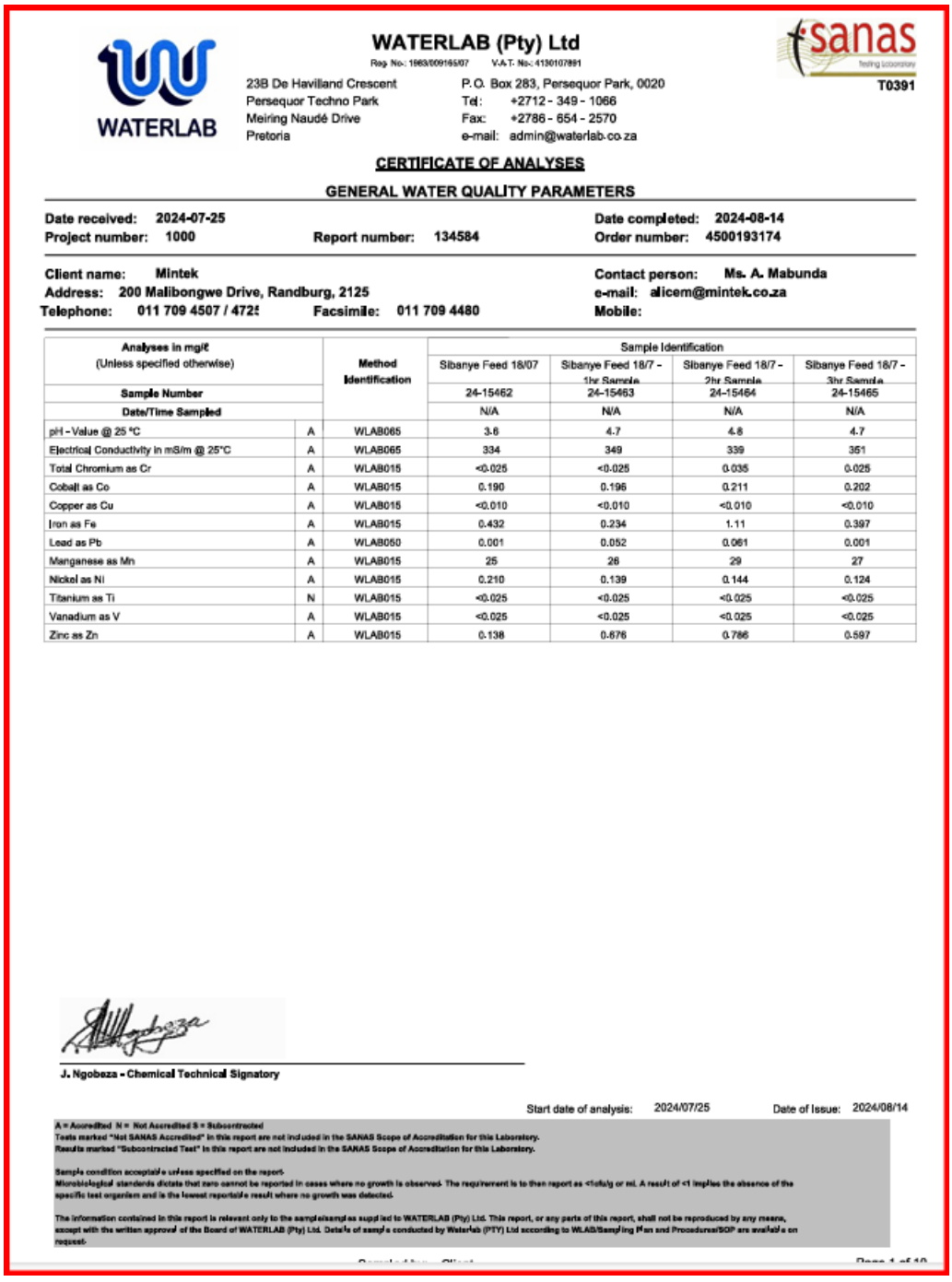
P	S	Cl	K	V	Cr	Mn	Co	Ni
ND	1708	ND	2393	25	53	288	ND	ND
ND	1435	ND	2439	35	60	283	ND	ND
ND	1461	ND	2490	22	56	275	ND	ND
ND	407	459	1128	6,6	53	90	ND	ND
ND	499	385	1126	6,1	52	95	ND	ND
ND	487	393	1173	ND	48	94	ND	ND
ND	702	185	1261	7,5	45	126	ND	ND
ND	544	129	1287	5,7	45	128	ND	ND
ND	527	264	1289	ND	46	124	ND	ND

Cu	Zn	As	Se	Rb	Sr	Zr	Nb	Mo
ND	36	ND	ND	17,3	19	115	53	ND
ND	41	ND	ND	16	22	110	49	6
ND	35	ND	ND	17,6	20	109	54	ND
ND	31,7	ND	ND	12,6	18,3	10,1	44,7	3,8
ND	30,9	ND	ND	12,4	18	12,7	44,7	3
8	30,3	ND	ND	12,4	16,7	12,6	46,1	3,7
ND	13,2	ND	ND	11,8	8,9	17,1	44,6	4,4
ND	11,4	ND	ND	11,9	10,1	16,8	40,7	5,1
ND	12,1	ND	ND	10,6	9,9	19,2	40,2	3,8

Ag	Cd	Sn	Sb	Ba	La	Ce	Pr	Nd
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND
ND	ND	ND	ND	ND	ND	ND	ND	ND

Ta	W	Hg	Pb	Bi	Th	U
41	ND	ND	26	ND	ND	ND
38	ND	ND	34	ND	ND	ND
32	ND	ND	30	ND	ND	ND
23	ND	ND	34	ND	ND	ND
21	ND	ND	36,5	ND	ND	ND
21	ND	ND	36,2	ND	ND	ND
22	ND	ND	19	ND	ND	ND
22	ND	ND	17,7	ND	ND	ND
20	ND	ND	16	ND	ND	ND

7.3.2 Appendix 19: Analytical Results from the Testing Lab



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CERTIFICATE OF ANALYSES

GENERAL WATER QUALITY PARAMETERS

Date received: 2024-07-25 **Date completed:** 2024-08-14
Project number: 1000 **Report number:** 134584 **Order number:** 4500193174

Client name: Mintek **Contact person:** Ms. A. Mabunda
Address: 200 Malibongwe Drive, Randburg, 2125 **e-mail:** alicem@mintek.co.za
Telephone: 011 709 4507 / 4725 **Facsimile:** 011 709 4480 **Mobile:**

Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			Sibanye Feed 18/07	Sibanye Feed 18/7 - 1hr Sample	Sibanye Feed 18/7 - 2hr Sample	Sibanye Feed 18/7 - 3hr Sample
Sample Number			24-15462	24-15463	24-15464	24-15465
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	3.6	4.7	4.8	4.7
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	334	349	339	351
Total Chromium as Cr	A	WLAB015	<0.025	<0.025	0.035	0.025
Cobalt as Co	A	WLAB015	0.190	0.196	0.211	0.202
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	0.432	0.234	1.11	0.397
Lead as Pb	A	WLAB060	0.001	0.052	0.061	0.001
Manganese as Mn	A	WLAB015	25	26	29	27
Nickel as Ni	A	WLAB015	0.210	0.139	0.144	0.124
Titanium as Ti	N	WLAB015	<0.025	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Zinc as Zn	A	WLAB015	0.138	0.676	0.786	0.597

J. Ngobeza - Chemical Technical Signatory

Start date of analysis: 2024/07/25 Date of Issue: 2024/08/14

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Analyses in mg/l (Unless specified otherwise)		Method Identification	Sample Identification			
			Sibanye Feed 18/7 - 4hr Sample	Thungela Feed 18/7	Thungela Feed 18/7 - 1hr Sample	Thungela Feed 18/7 - 2hr Sample
Sample Number			24-15466	24-15467	24-15468	24-15469
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	4.7	2.6	3.5	3.6
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	334	503	394	417
Total Chromium as Cr	A	WLAB015	0.058	<0.025	0.063	0.081
Cobalt as Co	A	WLAB015	0.221	0.245	0.275	0.285
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	2.51	69	10	10
Lead as Pb	A	WLAB050	0.003	0.003	0.006	0.006
Manganese as Mn	A	WLAB015	30	12	16	18
Nickel as Ni	A	WLAB015	0.155	0.375	0.397	0.432
Titanium as Ti	N	WLAB015	0.037	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	<0.025	0.026	<0.025	<0.025
Zinc as Zn	A	WLAB015	0.789	0.869	2.06	2.04

J. Ngobeza - Chemical Technical Signatory

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Telephone: 011 709 4507 / 4725 **Facsimile:** 011 709 4480 **Mobile:**

Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			Thungela Feed 18/7 - 3hr Sample	Thungela Feed 18/7 - 4hr Sample	N2 Feed 22/7	N2 25 C 1hr 22/7 - 2hr Sample
Sample Number			24-15470	24-15471	24-15472	24-15473
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	3.6	3.6	7.4	5.5
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	426	410	45.7	77.9
Total Chromium as Cr	A	WLAB015	0.098	0.101	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.268	0.263	0.122	0.067
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	0.050
Iron as Fe	A	WLAB015	11	11	0.408	1.24
Lead as Pb	A	WLAB050	0.004	0.001	0.050	0.012
Manganese as Mn	A	WLAB015	17	17	0.136	2.77
Nickel as Ni	A	WLAB015	0.423	0.412	1.04	0.434
Titanium as Ti	N	WLAB015	<0.025	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	<0.025	<0.025	0.029	0.037
Zinc as Zn	A	WLAB015	2.06	2.09	0.058	0.265

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CERTIFICATE OF ANALYSES

GENERAL WATER QUALITY PARAMETERS

Date received: 2024-07-25 **Date completed:** 2024-08-14
Project number: 1000 **Report number:** 134584 **Order number:** 4500193174

Client name: Mintek **Contact person:** Ms. A. Mabunda
Address: 200 Malibongwe Drive, Randburg, 2125 **e-mail:** alicem@mintek.co.za
Telephone: 011 709 4507 / 4725 **Facsimile:** 011 709 4480 **Mobile:**

Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			N2 25 C 3hr 22/7 - 2hr Sample	N2 25 C 1hr 22/7 - 4hr Sample	N2 25 C 3hr 22/7 - 4hr Sample	N2 120 C 1hr 22/7 - 2hr Sample
Sample Number			24-15474	24-15475	24-15476	24-15477
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	5.0	4.7	4.8	6.2
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	67.8	85.1	67.1	75.0
Total Chromium as Cr	A	WLAB015	<0.025	<0.025	<0.025	0.037
Cobalt as Co	A	WLAB015	0.064	0.058	0.058	0.075
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	1.04	2.46	2.37	1.60
Lead as Pb	A	WLAB050	0.009	0.012	0.016	0.020
Manganese as Mn	A	WLAB015	2.01	2.61	1.78	2.91
Nickel as Ni	A	WLAB015	0.477	0.414	0.406	0.542
Titanium as Ti	N	WLAB015	0.049	0.034	0.080	<0.025
Vanadium as V	A	WLAB015	0.034	0.040	0.027	0.029
Zinc as Zn	A	WLAB015	0.098	0.265	0.157	0.216

J. Ngobeza - Chemical Technical Signatory

Start date of analysis: 2024/07/25 Date of Issue: 2024/08/14

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			N2 120 C 1hr 22/7 - 4hr Sample	N2 180 C 1hr 22/7 - 2hr Sample	N2 180 C 1hr 22/7 - 4hr Sample	Feed 23/7
Sample Number			24-15478	24-15479	24-15480	24-15481
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	6.0	6.9	7.0	7.0
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	94.3	74.4	43.7	44.2
Total Chromium as Cr	A	WLAB015	0.043	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.092	0.196	0.158	0.095
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	1.72	0.956	0.944	0.220
Lead as Pb	A	WLAB050	0.017	0.012	0.014	0.046
Manganese as Mn	A	WLAB015	3.75	2.24	1.83	0.412
Nickel as Ni	A	WLAB015	0.894	0.372	0.288	0.855
Titanium as Ti	N	WLAB015	0.043	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	0.036	0.048	<0.025	0.026
Zinc as Zn	A	WLAB015	0.448	0.133	0.123	0.075

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Analyses in mg/l (Unless specified otherwise)		Method Identification	Sample Identification			
			Blank 25 C 2hr 23/7	O2 25 C 1hr 23/7 - 2hr Sample	O2 25 C 3hr 23/7 - 2hr Sample	O2 25 C 3hr 23/7 - 4hr Sample
Sample Number			24-15482	24-15483	24-15484	24-15485
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	6.2	5.4	6.0	5.7
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	101	85.0	102	102
Total Chromium as Cr	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.193	0.140	0.187	0.181
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	0.289	0.808	0.352	0.754
Lead as Pb	A	WLAB050	0.001	0.003	0.001	0.002
Manganese as Mn	A	WLAB015	2.64	2.55	2.37	2.27
Nickel as Ni	A	WLAB015	0.695	0.601	0.635	0.618
Titanium as Ti	N	WLAB015	<0.025	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	<0.025	<0.025	<0.025	<0.025
Zinc as Zn	A	WLAB015	0.410	0.498	0.397	0.496

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
Sample Number			O2 25 C 1hr 23/7 - 4hr Sample 24-15486	O2 Blank 25 C 23/7 - 4hr Sample 24-15487	N2 30 C 1hr 23/7 - 2hr Sample 24-15488	N2 30 C 1hr 23/7 - 4hr Sample 24-15489
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	5.1	5.7	7.4	7.2
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	83.7	104	45.9	49.9
Total Chromium as Cr	A	WLAB015	0.064	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.350	0.178	0.059	0.037
Copper as Cu	A	WLAB015	0.087	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	2.04	0.201	<0.025	<0.025
Lead as Pb	A	WLAB050	0.050	0.002	0.001	0.002
Manganese as Mn	A	WLAB015	6.16	2.41	0.493	0.455
Nickel as Ni	A	WLAB015	1.31	0.612	0.484	0.391
Titanium as Ti	N	WLAB015	<0.025	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	0.041	<0.025	<0.025	<0.025
Zinc as Zn	A	WLAB015	3.46	0.587	0.043	<0.025

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			Effluent Feed 24/7	UCL 24/7 - 1hr Sample	UCL 24/7 - 2hr Sample	UCL 24/7 - 3hr Sample
Sample Number			24-15494	24-15495	24-15496	24-15497
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	6.6	5.7	5.5	5.4
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	83.7	124	111	112
Total Chromium as Cr	A	WLAB015	0.671	0.054	0.030	0.050
Cobalt as Co	A	WLAB015	0.555	0.192	0.203	0.265
Copper as Cu	A	WLAB015	0.516	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	24	3.84	1.10	2.31
Lead as Pb	A	WLAB050	0.284	0.007	0.002	0.004
Manganese as Mn	A	WLAB015	1.37	4.04	3.57	4.97
Nickel as Ni	A	WLAB015	1.90	0.672	0.711	0.959
Titanium as Ti	N	WLAB015	0.045	0.098	<0.025	0.066
Vanadium as V	A	WLAB015	<0.025	0.025	0.038	0.031
Zinc as Zn	A	WLAB015	6.45	1.47	1.10	1.82

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			UCL 24/7 - 4hr Sample	Sibanye Feed 25/7	Thungela Feed 25/7	Mintek Feed 25/7
Sample Number			24-15498	24-15499	24-15500	24-15501
Date/Time Sampled			N/A	N/A	N/A	N/A
pH - Value @ 25 °C	A	WLAB065	5.7	3.6	2.7	6.5
Electrical Conductivity in mS/m @ 25°C	A	WLAB065	117	321	450	81.1
Total Chromium as Cr	A	WLAB015	0.062	<0.025	<0.025	<0.025
Cobalt as Co	A	WLAB015	0.187	0.193	0.253	0.305
Copper as Cu	A	WLAB015	<0.010	<0.010	<0.010	<0.010
Iron as Fe	A	WLAB015	3.62	0.232	20	<0.025
Lead as Pb	A	WLAB050	0.006	0.002	0.004	<0.001
Manganese as Mn	A	WLAB015	3.82	25	12	0.500
Nickel as Ni	A	WLAB015	0.655	0.208	0.382	1.20
Titanium as Ti	N	WLAB015	0.184	<0.025	<0.025	<0.025
Vanadium as V	A	WLAB015	0.038	0.042	0.033	0.037
Zinc as Zn	A	WLAB015	1.34	0.153	0.938	1.08

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GENERAL WATER QUALITY PARAMETERS

Date received: 2024-04-29 **Date completed:** 2024-05-10
Project number: 1000 **Report number:** 131766 **Order number:** PO4500192908

Client name: Mintek **Contact person:** Ms. A. Mabunda
Address: 200 Malibongwe Drive, Randburg, 2125 **e-mail:** alicem@mintek.co.za
Telephone: 011 709 4507 / 4725 **Facsimile:** 011 709 4480 **Mobile:**

Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			PH2 + Temp - 0Hour	PH2 + Temp - 1Hour	PH2 + Temp - 2Hours	PH2 + Temp - 3Hours
Sample Number			24-06447	24-06448	24-06449	24-06450
Date/Time Sampled			N/A	N/A	N/A	N/A
Total Chromium as Cr	A	WLAB015	0.186	0.206	0.286	0.496
Cobalt as Co	A	WLAB015	0.074	0.059	0.080	0.092
Copper as Cu	A	WLAB015	0.315	0.195	0.167	0.175
Iron as Fe	A	WLAB015	6.68	8.39	15	29
Manganese as Mn	A	WLAB015	2.47	2.43	2.96	4.57
Nickel as Ni	A	WLAB015	1.63	1.73	1.90	2.87
Zinc as Zn	A	WLAB015	1.78	1.86	2.19	2.74

E. Nkabinde - Chemical & Microbiological Technical Signatory

Start date of analysis: 2024/04/29 Date of Issue: 2024/06/03

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			PH2 + Temp - 4Hours	PH9 - 1Hour	PH9 - 2Hours	PH9 - 3Hours
Sample Number			24-06451	24-06452	24-06453	24-06454
Date/Time Sampled			N/A	N/A	N/A	N/A
Total Chromium as Cr	A	WLAB015	0.598	0.050	0.060	0.096
Cobalt as Co	A	WLAB015	0.121	0.038	0.036	0.070
Copper as Cu	A	WLAB015	0.216	0.100	0.066	0.077
Iron as Fe	A	WLAB015	34	0.912	0.807	0.943
Manganese as Mn	A	WLAB015	5.45	0.608	0.549	0.634
Nickel as Ni	A	WLAB015	3.42	0.180	0.145	0.156
Zinc as Zn	A	WLAB015	3.50	0.198	0.146	0.151

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Analyses in mg/ℓ (Unless specified otherwise)		Method Identification	Sample Identification			
			PH9 - 4Hours	PH9 + Temp - 0Hour	PH9 + Temp - 1Hour	PH9 + Temp - 2Hours
Sample Number			24-06455	24-06456	24-06457	24-06458
Date/Time Sampled			N/A	N/A	N/A	N/A
Total Chromium as Cr	A	WLAB015	0.138	0.080	0.061	0.046
Cobalt as Co	A	WLAB015	0.081	0.073	0.046	0.042
Copper as Cu	A	WLAB015	0.095	0.086	0.092	0.086
Iron as Fe	A	WLAB015	0.990	0.866	0.846	1.20
Manganese as Mn	A	WLAB015	0.492	0.703	1.22	3.40
Nickel as Ni	A	WLAB015	0.142	0.342	0.167	0.394
Zinc as Zn	A	WLAB015	0.167	0.490	0.307	1.54

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The information contained in this report is relevant only to the sample/samples supplied to WATERLAB (Pty) Ltd. This report, or any parts of this report, shall not be reproduced by any means, except with the written approval of the Board of WATERLAB (Pty) Ltd. Details of sample conducted by Waterlab (PTY) Ltd according to WLAB/Sampling Plan and Procedures/SOP are available on request.

WATERLAB (Pty) Ltd

Reg. No.: 1993/009185/07 V.A.T. No.: 4130107891

23B De Havilland Crescent
Persequor Techno Park
Meiring Naudé Drive
Pretoria

P.O. Box 283, Persequor Park, 0020
Tel: +2712 - 349 - 1066
Fax: +2786 - 654 - 2570
e-mail: admin@waterlab.co.za

T0391

CERTIFICATE OF ANALYSES

GENERAL WATER QUALITY PARAMETERS

Date received: 2024-04-29 **Date completed:** 2024-05-10
Project number: 1000 **Report number:** 131766 **Order number:** PO4500192908

Client name: Mintek **Contact person:** Ms. A. Mabunda
Address: 200 Malibongwe Drive, Randburg, 2125 **e-mail:** alicem@mintek.co.za
Telephone: 011 709 4507 / 4725 **Facsimile:** 011 709 4480 **Mobile:**

Analyses in mg/l (Unless specified otherwise)		Method Identification	Sample Identification		
			PH9 + Temp - 3Hours	PH9 + Temp - 4Hours	Feed Sample
Sample Number			24-06459	24-06460	24-06461
Date/Time Sampled			N/A	N/A	N/A
Total Chromium as Cr	A	WLAB015	0.046	0.049	<0.025
Cobalt as Co	A	WLAB015	0.178	0.079	0.030
Copper as Cu	A	WLAB015	0.088	0.390	0.037
Iron as Fe	A	WLAB015	1.34	1.04	0.888
Manganese as Mn	A	WLAB015	3.76	4.67	0.194
Nickel as Ni	A	WLAB015	0.741	0.652	0.885
Zinc as Zn	A	WLAB015	2.09	1.76	0.203

E. Nkabinde - Chemical & Microbiological Technical Signatory

Start date of analysis: 2024/04/29 Date of Issue: 2024/06/03

A = Accredited N = Not Accredited S = Subcontracted
Tests marked "Not SANAS Accredited" in this report are not included in the SANAS Scope of Accreditation for this Laboratory.
Results marked "Subcontracted Test" in this report are not included in the SANAS Scope of Accreditation for this Laboratory.

Sample condition acceptable unless specified on the report.
Microbiological standards dictate that zero cannot be reported in cases where no growth is observed. The requirement is to then report as <1cfu/g or ml. A result of <1 implies the absence of the specific test organism and is the lowest reportable result where no growth was detected.

The information contained in this report is relevant only to the sample/samples supplied to WATERLAB (Pty) Ltd. This report, or any parts of this report, shall not be reproduced by any means, except with the written approval of the Board of WATERLAB (Pty) Ltd. Details of sample conducted by Waterlab (PTY) Ltd according to WLAB/Sampling Plan and Procedures/SOP are available on

7.4 Approval Letters

7.4.1 Appendix 20: Approval Letters from the SCPC A



MINTEK
A global leader in mineral and metallurgical innovation

ISO 9001 QUALITY MANAGEMENT SYSTEM
ISO 17025 TESTING AND CALIBRATION LABORATORY
ISO 14001 ENVIRONMENTAL MANAGEMENT SYSTEM
ISO 45001 OCCUPATIONAL HEALTH AND SAFETY MANAGEMENT SYSTEM

200 Malibongwe Drive
Randburg.
2194
20 February 2025

To: The Registrar

University of South Africa(UNISA)

Re: Permission to conduct the study at MINTEK

This letter confirms that Ms Tsakani Alice Mukhabele, student ID 44916604, is currently enrolled in the Master of Science program in Environmental Science for the academic year 2025. The dissertation: "**Sugarcane bagasse, an alternative ion exchange material for the removal of heavy metals from mine wastewater**" is under review for submission at the University of South Africa (UNISA). MINTEK management has approved the collection of data at the wastewater treatment plant and the use of laboratories and other resources relevant to the study, including travelling to source bagasse samples from UCL in Mooi River and Illovo in Sezela, KZN province.

For further information, please do not hesitate to contact the HR department representative.

Puso Thulo |

Human Resources

200 Malibongwe Drive, Randburg, South Africa
T: 011 709 4701 | E: pusot@mintek.co.za
www.mintek.co.za

"Your partner in unlocking mineral wealth."

7.4.2 Appendix 21: Approval Letter from MC- X



UCL COMPANY (PTY) LTD
Registration No.: 2005/017711/07

Telephone: +27 33 501 1600

Address: 16 Noodsberg Road, Dalton
Postal: P.O. Box 1, Dalton, KwaZulu-Natal, 3236, South Africa

Website: www.ucl.co.za

17 February 2025

Department of Environmental Science
Office 136
Calabash Building

To Whom It May Concern

RE: Permission to Conduct an Academic Research Project in UCL Sugar Factory

We will gladly accommodate Ms Tsakani Alice Mukhabele, ID No.7904220371088, Student No. 44916604, from UNISA to visit UCL Sugar Factory on the 11 March to see the sugar mill process and collect the 5kg of sugarcane bagasse for her research study.

On your arrival request to see Sindile Matsobane at the Training Centre, from where you will be breathalysed at the factory gate before entering, and undergo the visitors' safety induction.

It will be your duty to enforce all recognised safety regulations. Note that you must provide your own long trousers and closed shoes, safety boots will be preferable.

Yours faithfully,
UCL COMPANY PTY LTD

CLINTON VERMEULEN
GENERAL MANAGER: OPERATIONS

7.4.3 Appendix 22: Approval Letter from MC- Y.

Sibanye Gold Academy Proprietary Limited
Registration No. 2004/006126/07

Business Address:
349 Rietkloof
Glenharvie
1786
Postal Address:
Bag X11
Westonaria
1780

Tel +27 11 752 1145
Fax +27 11 752 1372

30 May 2025

TA Mukhabele

University of South Africa (UNISA)/ MINTEK

Student No 44916604

Dear Ms. Mukhabele,

APPLICATION TO CONDUCT RESEARCH AT SIBANYE-STILLWATER

Research Topic: Sugarcane Baggasse, an alternative ion exchange method for purification of wastewater from the mining industry.

Your application for conducting research at Sibanye-Stillwater has been approved.

You will be required to furnish Sibanye-Stillwater with your ethical clearance documentation and number, as well as Non-Disclosure Agreement prior to commencing with research.

Kind regards,

Signed by:Denis James Mc Dougall
Signed at:2025-05-30 14:25:29 +02:00
Reason:I approve this document

D McDougall

Manager Technical Training

7.5 Appendix 23: Editor's Certificate

Private Bag X2046, Mmabatho
South Africa 2735
Tel: +2718 389-2328
Fax: +2708 606-8714
Dave.Kawadza@nwu.ac.za
Web: http://www.nwu.ac.za

Language Editing Certificate

Date: 31st January 2026

This serves to confirm that I have read and edited the Master's (Environmental Science) dissertation of Tsakani Alice **MUKHABELE** (Student number: **44916604**) entitled:

Sugarcane bagasse: an alternative ion exchange method for removal of heavy metals from toxic wastewater from the mining industry

The candidate corrected the language errors identified.

The document is of an acceptable scientific and linguistic standard.

Best regards.

Dr T.D. Kawadza
Language Editor
Faculty of Natural and Agricultural Sciences

Original details: (16232461) C:\Users\16232461\Documents\ MUKHABELE TA\Ledit.mm.docm
31 January 2026

7.6 Appendix 24: Ethics Clearance Certificate

UNISA university of south africa

College of Agriculture and Environmental Sciences_Health REC

NHREC Registration # : REC-170616-051
Ref #: 2025/CAES_HREC/5921
Name: Ms TSAKANI ALICE MUKHABELE
Student #: 44916604

Date: 01/04/2025

Dear: Ms TSAKANI ALICE MUKHABELE

Decision: Ethics Approval from 01/04/2025 to 31/03/2028

Researcher: Ms TSAKANI ALICE MUKHABELE
44916604@mylife,unisa,ac,za 0832740010

Supervisor: Mr Ntsako Baloyi baloynd@unisa,ac,za

Sugarcane Baggasse, an alternative ion exchange method for purification of wastewater from the mining industry

Qualification: MSc Environmental Sciences

Thank you for the application for research ethics clearance by the College of Agriculture and Environmental Sciences_Health REC for the above mentioned research study. Ethics approval is granted for three years, **subject to submission of yearly progress reports. Failure to submit the progress report will lead to withdrawal of the ethics clearance until the report is submitted.**

Due date for progress report: 31 March 2026

The **low risk application** was **reviewed** by College of Agriculture and Environmental Sciences_Health REC on 31 March 2025 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics,
2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the College of Agriculture and Environmental Sciences_Health REC.
3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003,
6. Only de-identified research data may be used for secondary research purposes in future on condition that the

Page 1 of 2

7.7 Appendix 25: Standard Operating Procedure for SCB experimental work

Effective date	06 July 2024
Reviewed by	Sazini Mashaba
Next review date	06 July 2025
Approved by	Dr Gebhu Ndlovu
Document number	SOP- MIN-005 Rev 1
Revision number	1

Title: Preparation, handling and use of SCB for the adsorption laboratory test work

Purpose: To establish the safe production of ground bagasse to be used for lab experiments

Scope: This SOP applies to all technicians, scientists, and metallurgists working in the sample preparation and other science laboratories

Responsibilities

Operator: To ensure all required equipment is available and in good working condition and to escalate all equipment malfunctions and anomalies.

SHE Officer: To ensure all employees have access to the required PPE, and to enforce SHEQ compliance in the laboratory, including waste management

Supervisors: To ensure all employees working in the laboratory adhere to this procedure

Definitions:

SOP- standard operating procedure

PPE: Personal protective equipment.

SDS: Safety data sheet

SCB: Sugarcane bagasse

Required PPE: Safety gloves

Safety goggles

Dust musk

Lab coat/ overall

Procedure

1. **Sample preparation (SCB grinding)**

- Ensure the right PPE is available for use before work commences.
- Avoid using compressed air to clean the grinding area; this may introduce cross-contamination**.**
- Ensure the correct grinder is clean before use to prevent cross-contamination
- Grind at least 100g of sugarcane bagasse at a time
- After grinding, screen the SCB using a 75-micron sieve and put it in a clean zip plastic bag.

2. **SCB preparation at the fluidised reactor**

    - Ensure the person operating the fluidised reactor is trained and there is supervision
    - Ensure the correct gas is connected for the experiment
    - Set the instrument parameters temperature and gas flow) as per the recommendations of the supervisor and according to the user manual.

3. **Experimental work**

    - Verify the calibration of the weighing scale using mass pieces before weighing the SCB sample
    - Weigh 20g the ground SCB into a crucible and transfer the material into clearly labelled Scotch bottles.
    - Add 100ml of wastewater into each bottle and place it in a shaking table to allow SCB contact with the wastewater.
    - Ensure the table is running at a constant speed, avoiding over-shaking.
    - Do not leave the shaking table unattended
    - Using a timer, take out each bottle hourly and filter the slurry using the available gravity filtration system.
    - Take the solids and place them in a waste bin clearly labelled as a hazardous waste bin
    - Using pill vials, label the profile samples as follows
    - Date:
    - p H of the wastewater
    - Pristine/ Pre- treated SCB
    - Temperature of pre-treated SCB

- Time: 1 hour, 2 hours, 3 hours, etc
- Record the filtrate volume and wash the bottles before each use.
- Repeat the above step for p H 2, 4.5, 7 and 9, adjusting to the required p H using acetic acid to decrease and sodium hydroxide to increase accordingly.
- Send them to a testing laboratory, preferably a SANAS-accredited lab