MinEx CRC Limited
26 Dick Perry Avenue, Kensington, WA, 6151
PO Box 1130, Bentley, WA, 6102, Australia
admin@minexcrc.com.au

MinEx CRC
ABN: 66 625 533 913

MinEx CRC provides financial support to the value of $1K to promote Honours and Masters by Coursework projects that are aligned with the mission of MinEx CRC and to encourage young researchers toward a career in mineral exploration research. Projects are not restricted to MinEx CRC Participants and Affiliates.

Please note that the content of this thesis has not been subjected to peer-review and subsequent corrections.

Australian Government
Department of Industry, Science and Resources

Cooperative Research Centres Program

CENG0037 MSc Research Project:

Lixiviant Comparison for In-Situ Recovery at Kapunda Copper Mine: *A Cost-Benefit analysis*

Oscar Winter Clausen

Student No.: 22076897

Supervisor(s): Dr. Caroline Tiddy &
Dr. Adrienne Brotodewo

A thesis submitted to the University of London for
the degree of Master of Science;

TMSCENSGMN01

Department of Chemical Engineering

University College London (UCL)

September 2023

Declaration

I, *Oscar Winter Clausen*, confirm that the work presented in this thesis is my own.

Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Word count: ***5832***

(excluding the title page, table of contents, references, tables, figures and appendices)

Has the written report been submitted on Moodle?	Yes
Have relevant source codes and/or raw data been submitted on Moodle?	Yes
Has the lab space used been cleaned up (if applicable)?	N/A

Oscar Winter Clausen	OscarClausen	05/09/2023
Student's Name	Student's Signature	Date

Acknowledgments

I would like to sincerely thank both my supervisor Dr. Caroline Tiddy as well as my assistant supervisor Dr. Adrienne Brotodewo for their tireless effort, support, and encouragement throughout my dissertation, from beginning to end they were instrumental in its completion and quality. I would also like to thank all the professors and lecturers who devoted their time to teaching me, Dr. MacKay and Dr. Norori-McCormac especially, for their constant assistance during my time at University College London. I would also like to thank my family for their support in allowing me to embark on this academic journey and their constant support in my wellbeing both physically and mentally. Finally, I would like to EnviroCopper™, MinEX CRC™, and UniSA FII for their sponsorship and the opportunity for which inspired this dissertation project.

Abstract

This dissertation investigates the economic and environmental implications of using various lixiviants for In-Situ Recovery (ISR) methods in copper extraction at the Kapunda mine in South Australia. Employing a multi-dimensional analysis, the study evaluates the socio-environmental impact, risk, and economic feasibility of four lixiviants: Methanesulphonic Acid (MSA), Ammonia-Thiosulphate, Sulphuric Acid, and Glycine. The research reveals that Glycine holds promise for being the most environmentally benign option, while Sulphuric Acid emerges as the most cost-effective but riskier alternative. MSA offers a balanced profile with moderate socio-environmental risks. The study acknowledges limitations such as the reliance on laboratory data and the specificity to the Kapunda region, suggesting avenues for future research. The findings provide a nuanced framework for balancing economic and environmental considerations in ISR methods, serving as a guide for stakeholders in the mining industry.

Table of Contents:

Tables And Equations:

1. Introduction

The mining industry, a cornerstone of economic growth and development across the globe, is facing increasing scrutiny due to its environmental and socio-economic impacts (Lahiri-Dutt et al., 2011). Traditional mining methods have left a significant environmental footprint, leading to a call for more sustainable practices. In response to this, the industry has begun to explore and implement alternative extraction methods. One such promising practice is In-Situ Recovery (ISR), also referred to as In-Situ Leaching (ISL). This innovative approach presents a less intrusive and potentially environmentally benign method of extracting valuable minerals from ore deposits, offering a potential solution to the industry's sustainability challenges (Hore-Lacy, 2013).

In-Situ Recovery (ISR) operates on a fundamentally different principle than traditional mining. Instead of physically removing ore from the ground for processing, ISR involves injecting a solution, known as a lixiviant, directly into an ore deposit (Hore-Lacy, 2013). The lixiviant dissolves the valuable minerals, creating a solution that can then be pumped to the surface for further processing. This process minimizes surface disturbance and reduces waste generation, making it a potentially more sustainable approach.

This thesis delves into the economic modelling and cost-structure comparison of various lixiviant options for ISR applied to copper extraction. The objective is to determine the optimal lixiviant choice for copper extraction in Kapunda, South Australia, a region steeped in a rich historical copper mining legacy. The selection of the most suitable lixiviant for the Kapunda project will be based on a comprehensive evaluation of several factors, including cost-effectiveness, environmental sustainability, and mineral selectivity.

2. Background

2.1 In-Situ Recovery

In-situ recovery (ISR), also known as in-situ leaching (ISL), is an innovative mining technique that extracts valuable minerals from ore deposits without many of the typical drawbacks associated with traditional mining methods, notably reduced cost in the way of eliminating the need for extensive physical infrastructure, large amounts of personnel and costly waste-management that is typically required in traditional mining methods as well as socio-environmental externalities (Seredkin et al., 2016; Hore-Lacy, 2013). ISR involves injecting a PLS (Pregnant Leech Solution), usually containing an oxidant and/or a lixiviant, into the ore body to dissolve the targeted minerals (Mudd, 2001). The pregnant, metal laden solution is then pumped back to the surface, where the valuable metals are separated and collected. The remaining solution is then treated and can be recycled back into the deposit.

Historically, the ISR technique was initially commercially implemented within the realm of uranium mining in the 1960s, predominantly within the United States (Seredkin et al., 2016). The method subsequently gained traction in an array of nations, including but not limited to

Australia, Kazakhstan, and Uzbekistan, and has been effectively utilized in the extraction of a diverse range of minerals to extract copper, gold, and silver (Seredkin et al., 2016; Wang et al., 2022).

For ISR to be effective, several conditions must be met. Firstly, the host rocks of the deposit must possess sufficient permeability to facilitate the circulation of the leaching solution and its interaction with the economic minerals (Wang et al., 2022). The mineralization itself should exhibit solubility in the selected lixiviant. Additionally, a stringent hydrogeological control is paramount to ensure that the mineral-bearing fluids are effectively contained within the ore body and do not engender contamination of the surrounding groundwater (Wang et al., 2022).

The advantages of ISR are numerous. It eliminates the need for expensive and potentially environmentally damaging open-pit or underground mining. Instead, it allows the valuable minerals to be extracted with minimal disturbance to the land surface, as well as less waste generation (Wang et al., 2013). In addition, the process is generally safer for workers, as there is less exposure to hazardous conditions associated with traditional mining methods such as cave-ins and long-term health issues related to dust inhalation.

2.1.1 Lixiviant Selection

The process of lixiviant selection for in-situ recovery (ISR) methods at the Kapunda mine site necessitates a comprehensive understanding of the site's geology and surrounding area. This involves a detailed examination of the geochemical characteristics of the host rocks and ore minerals, which are vital determinants in the selection of an appropriate lixiviant. The mineralogical composition, chemical reactivity, and porosity of the host rocks directly influence the effectiveness of the lixiviant, as these factors determine the efficiency of copper extraction from the ore (Hore-Lacy, 2013).

In addition to these geochemical considerations, the hydrogeological properties of the mine site, including the permeability and hydraulic conductivity of the host rocks, play a crucial role in optimizing the ISR process. These properties significantly affect the distribution and movement of the lixiviant within the ore body, thereby influencing the overall success of the ISR operation (Hore-Lacy, 2013; Seredkin, Zabolotsky and Jeffress, 2016).

The following sections will provide a preliminary analysis of potential lixiviants, including Methanesulphonic Acid (MSA), Glycine, and Thiosulphate. These lixiviants have been selected for further investigation based on their potential suitability for the unique geological and hydrogeological conditions of the Kapunda mine site as well as their socio-environmental and economic costs.

2.2 Kapunda Legacy and Geology

2.2.1 Historical Background Kapunda

The Kapunda mine site is situated in South Australia within the North Mount Lofty Ranges. Kapunda, is a region of significant historical importance and has left an indelible mark on the South Australian economy through its rich copper mining legacy. The discovery of copper mineralization in Kapunda in 1842, and the subsequent commencement of mining operations in

1844, played a pivotal role in shaping the region's industrial and economic landscape (Dentith and Stuart, 2019).

However, these operations ceased in 1879 when the ore grade could no longer sustain commercial viability. Despite this, Kapunda's mining history is marked by a remarkable production of approximately 69,000 tons of ore, with some of the richest ore grades in Australia, averaging over 20% Cu (The Advertiser, 1906; Dentith and Stuart, 2019). The legacy of this mining activity is still visible today, with the intense green-turquoise hue leached into the earth and water.

The influence of Kapunda extends beyond its local context, having played a critical role in regional and national history. As Austin (2013) aptly puts it, "as gold mining is to Victoria, so copper mining is to South Australia." The establishment of the Kapunda copper mine was instrumental in the economic recovery of South Australia, which was on the brink of bankruptcy at the time of the copper discovery. Kapunda, while not the first or most abundant copper mine in the region, was the first to achieve commercial success, revitalizing both local and state economies. As Austin (2013) highlights, "Kapunda was Australia's first commercially successful metal mine."

The economic impact of the Kapunda mine was multifaceted, influencing employment, infrastructure development, and the creation of ancillary industries. The mine not only provided employment opportunities for locals and attracted skilled labor from other regions, but also spurred the growth of the local community (Dentith and Stuart, 2019). The burgeoning mining industry necessitated improved transportation and communication networks, leading to the establishment of railways, roads, and telegraph lines connecting Kapunda to Adelaide and other regional centers.

Moreover, the success of the Kapunda copper mine sparked interest in mineral exploration and investment across South Australia, leading to the discovery of other mineral resources, such as the Burra copper mine and the Moonta and Wallaroo mines on the Yorke Peninsula (Austin, 2013). These additional mining operations further bolstered the South Australian economy, reinforcing the state's reputation as a mineral-rich region.

2.2.2 Local Geology and Hydrology

The regional geology of the North Mount Lofty Ranges, where the Kapunda mine site is located, is characterized by a complex tectonic history, including multiple phases of folding, faulting, and metamorphism. This tectonic activity, coupled with the region's diverse lithology, has led to the formation of various types of mineral deposits, including the sediment-hosted stratiform copper deposits found in Kapunda (Dentith and Stuart, 2019).

Within this broader geological context, the local geology of Kapunda is dominated by folded and faulted sediments. The mineralization in the Kapunda area is specifically characterized by sediment-hosted stratiform copper deposits. These deposits have been influenced by several factors, including the presence of reductive and permeable host rocks and the availability of metal-bearing fluids.

The Cu-Au ore mineralization in Kapunda occurs in dolomitic siltstones and mudstones. Additional mineralization has been observed in low-grade disseminated to bedded tensional structures, as well as carbonate-quartz veins and feldspar (Dentith and Stuart, 2019). The primary host mineral for these deposits is chalcopyrite, which is often accompanied by pyrite and pyrrhotite.

In 2021, a Joint Ore Reserves Committee (JORC) assessment commissioned by Thor Mining PLC estimated that the Kapunda mine site contained approximately 47.4 metric tons of copper at an average ore grade of 0.25 – 0.3% (Thor Energy Plc, 2021). Furthermore, an additional inferred 119,000 tons of copper ore at varying grades were deemed obtainable through in-situ recovery (ISR) methods. This assessment underscores the significant potential of the Kapunda mine site for copper extraction using innovative ISR techniques.

3. Methodology and Data

3.1 Research Design

The cost-efficiency of XXXX per ton of copper was determined by the following equation:

$$\text{XXXX} = \left(\frac{Quantity\ of\ chemical\ required}{Efficiency\ of\ extraction}\right) \times\ Cost\ of\ chemical\ per\ ton$$

A socio-environmental assessment using a 'risk-matrix' approach was undertaken with the approach of wanting to produce a quantitative expression of socio-environmental impact. The overall design employs a comparative approach, focusing on Glycine, MSA, Sulphuric acid, and Thiosulphate lixiviant options to determine their suitability based on cost, environmental sustainability, efficiency.

Central to the method was creation of a 'Value Score' (V Score) for each lixiviant. The V Score provides a holistic metric that integrates both economic and socio-environmental dimensions. By formulating the V Score as the inverse product of the lixiviant's cost and its socio-environmental risk score, the research aimed to prioritize options that are both economically viable and environmentally sustainable. A higher V Score, in this context, signifies a lixiviant that strikes an optimal balance between cost-efficiency and minimized socio-environmental impact. This approach was chosen for its simplicity, robustness, and ability to offer clear, actionable insights for stakeholders in the realm of copper extraction.

The research design was structured to ensure a systematic and objective analysis. It is designed to facilitate the collection of relevant data, the application of appropriate analytical techniques, and the interpretation of results in a manner that addresses the research objectives. The design also considers the limitations and constraints of the study, ensuring that the research process is feasible, ethical, and capable of producing valid and reliable results. The data analysis for this research was a dual-faceted approach, focusing on both the economic implications of lixiviant choices and their socio-environmental ramifications.

3.1.2 Economic Analysis

Economic analysis evaluated the cost structures associated with each lixiviant. This encompassed the direct cost of production (USD$/t) and acquisition and the potential economic benefits from innovative measures such as recycling. Recognizing the variability in copper yields due to the distinct selectivity and efficiency of each lixiviant, the model integrated findings from a comprehensive review of scientific studies. In scenarios with limited empirical data, extrapolations were made based on laboratory-based studies. In addition to these cost and efficiency analyses, we also conducted a comprehensive review of the existing literature to assess the environmental impact of each lixiviant. This review revealed significant gaps in the current understanding of these chemicals, particularly in terms of their ecotoxicological implications and environmental interactions.

3.1.3 Socio-Environmental Risk Assessment

A quantitative 'Socio-Environmental Risk Matrix' was employed to assess the environmental and health-related impacts of each lixiviant. This matrix assigned numerical weightings to various criteria, including ecotoxicology, potential harm to humans, and environmental persistence, among others. The objective nature of this matrix, with its numerical weightings, ensured a standardized and replicable assessment across different lixiviants.

Central to the analysis was the computation of the 'Value Score' (v Score) for each chemical. This score was derived by integrating the economic costs and the socio-environmental risk assessments. Mathematically, the v Score was formulated as the inverse product of the lixiviant's cost and its socio-environmental risk score. The rationale behind this approach was to create a metric that is inversely proportional to cost (where lower cost is preferable) and directly proportional to socio-environmental desirability (where lower risk is preferable). Consequently, a higher V Score indicates a more favourable option, balancing both economic and socio-environmental considerations.

Employing a robust and interchangeable framework, allows for the straightforward evaluation of different lixiviants. The simplicity of the mathematical model, combined with its comprehensive socio-environmental matrix, ensures its applicability across various scenarios, making it a valuable tool for informed decision-making in the realm of copper extraction.

3.2 Data Collection.

Financial data relating to the cost of various lixiviant options was obtained from industry reports, manufacturers, and distributors. This data included information about the cost of production, cost of application, and potential environmental mitigation costs. It also considered potential variations in copper yields, taking into account the selectivity and efficiency of each lixiviant.

Environmental impact data was collected from environmental studies, scientific literature, and industry reports and product manuals pertaining to each lixiviant. This data provided insights into the handling and storage measures and risk to human health among the environmental impacts of each lixiviant.

Secondary data was obtained through a comprehensive review of existing literature on ISR, sustainable mining practices, and the copper mining legacy of Kapunda. This review provided crucial context for the study, enabling a more in-depth understanding of the challenges and opportunities associated with ISR in this unique location.

4. Results

Results of calculations of the cost of producing 1 ton of copper using each of these lixiviants under various conditions are shown in Tables below section 4.1.1 through to 4.1.3. The findings revealed a range of efficiencies ranging from as low as 35.8% to as high as 99.8% across different studies and conditions for copper extraction, with MSA demonstrating a particularly high efficiency under certain conditions particularly when used at a concentration range of 10 to 30 g/L and temperatures of 75°C.

Data from key studies have been extracted and tabulated to provide a comprehensive understanding of the copper leaching process. This aggregated data, combined with the cost calculations, facilitated the creation of a socio-environmental risk matrix for each lixiviant. This data, combined with calculations, allowed us to create a socio-environmental risk matrix for each lixiviant, taking into account factors such as biodegradability, toxicity to fauna and flora, and safety for handling. It is important to note that while the research provides valuable insights into the use of these lixiviants for copper extraction, there are inherent limitations due to the novelty of some of these chemicals and the lack of comprehensive research in certain areas. Despite these limitations, our findings contribute to a growing body of knowledge on this topic and highlight the need for further research.

4.1 Efficiency & Selectivity:

4.1.1 Glycine:

Table I - Glycine Experiments Data

Study	**Concentration (g/L)**	**Temperature** (°C)	**Time (h)**	**Cu Extraction (%)**	**pH**	**Ore**
(Fathollahzadeh et al., 2019)	Glycine: 22.5	25	48	80	*11-11.5*	*Chalcopyrite (Cu 28.8%)*
(Bennson, 2017)	Glycine:Cu Molar Ratio 4:1	25	48	67 - 95	*10-11*	*Azurite (42.10% Cu)*
(Oraby and Eksteen, 2014)	Glycine:Cu Molar ratio 3:1 Mextral-84H: 5% Mextral 54-100: 10%	25-30	30 (Mins)	97.5 - 99.8	*9-12*	*2 g/L Cu Chalcopyrite Leachate Aqueous Solution*

The first study, Fathollahzadeh et al. (2019) focused on the extraction of copper from chalcopyrite with a copper content of 28.8%. A glycine concentration of 22.5 g/L was used at a temperature of 25°C for 48 hours. The copper recovery rate was 80%, and the pH was maintained between 11 and 11.5. The results demonstrate the effectiveness of glycine in extracting copper from Chalcopyrite under these specific conditions. Bennson (2017) study explored the extraction of copper from Azurite, which has a copper content of 42.10%. A 4:1 molar ratio of glycine to copper was used, corresponding to a significant amount of glycine relative to copper. The extraction was conducted at 25°C for 48 hours, and the copper recovery rate varied between 67% and 95%. The pH was maintained between 10 and 11. This study highlights the importance of the molar ratio and pH in achieving optimal copper recovery.

Finally, Oraby and Eksteen (2014) investigated a more complex extraction process using a 3:1 molar ratio of glycine to copper and additional agents Mextral-84H (5%) and Mextral 54-100 (10%). The extraction was carried out at temperatures ranging from 15 to 30°C for a short duration of 30 minutes. Despite the short extraction time, the copper recovery rate was exceptionally high, ranging from 97.5% to 99.8%. The pH was maintained between 9 and 12, and the study used a 2 g/L copper aqueous solution. This study indicates the potential for rapid and highly efficient copper extraction using a combination of glycine and other agents.

4.1.2 Ammonia Thiosulphate:

Table II - Ammonia Thiosulphate Experiments Data

Study	**Concentration (g/L)**	**Temperature** (°C)	**Time (h)**	**Extraction Efficiency (%)**	**Ore**
(Molleman and Dreisinger, 2002)	Ammonium Thiosulphate: 30	35	24	35.8% Au 48.7% Cu	*Combination Concentrate: Chalcopyrite, Covellite, Chalcocite* Au (ppm): 2.11 Cu (ppm): 1120
(Molleman and Dreisinger, 2002)	Ammonia Thiosulphate: 30	35	24	44.0% Au 59.2% Cu	*Combination Concentrate: Enargite, Cuprite, Malachite* *Au (ppm): 2.06* *Cu (ppm): 3320*
(Berezowsky and Gormely, 1978)	Ammonium Thiosulphate: 60 -149	40-60	2-4	88 - 95 % Au	*Chalcopyrite concentrate* (3–5 g/L Cu)
(Langhans, Lei and Carnahan, 2003)	Ammonia Thiosulphate: 30	50	94	90% Au 84% Cu	*"low-grade oxidized gold ores..."* *Au%: 0.048* *Cu%: 0.02* *Si%: 39%*

Two distinct studies were conducted by Molleman and Dreisinger in 2002. The first study utilised a concentration of 30 g/L of Ammonium Thiosulphate at a temperature of 35°C for 24 hours. The extraction efficiency was recorded at 35.8% for gold and 48.7% for copper. The ore used was a combination concentrate consisting of Chalcopyrite, Covellite, and Chalcocite with gold and copper concentrations of 2.11 ppm and 1120 ppm, respectively.

In their second study, the same concentration and conditions were applied, but the ore was a combination concentrate of Enargite, Cuprite, and Malachite. The extraction efficiencies were notably higher, with 44.0% for gold and 59.2% for copper. The gold and copper concentrations in this ore were 2.06 ppm and 3320 ppm, respectively. Berezowsky and Gormely's study in 1978 employed a variable concentration of Ammonium Thiosulphate ranging from 60 to 149 g/L. The extraction was conducted at temperatures between 40 and 60°C for a duration of 2 to 4 hours. The extraction efficiency for gold was remarkably high, ranging from 88% to 95%. The ore used was Chalcopyrite concentrate with a copper content ranging from 3 to 5 g/L. Finally, Langhans, Lei and Carnahan's 2003 study used 30 g/L of Ammonia Thiosulphate at a temperature of 50°C but extended the extraction time to 94 hours. The extraction efficiencies were 90% for gold and 84% for copper. The ore was described as "low-grade oxidized gold ores," with gold and copper concentrations of 0.048% and 0.02%, respectively.

4.1.3 Acids:

Table III - Acids Experiments Data

Study	**Concentration (g/L)**	**Oxidant (%)**	**Temperature** (°C)	**Time (h)**	**Cu Extraction (%)**	**Ore**
(Ahn, Wu and Lee, 2019)	MSA: 10 – 30	H202: 0.9 – 4.5	75	96 - 144	70 – 99	*Chalcopyrite 89.5% (Cu 28.8%)*
(Prince, 2022)	MSA: 50	H202: 3	45	96	77	*Chalcopyrite 84.6% (Cu 28.8%)*
(Feng et al., 2020)	MSA: 30 - 50	None	45 - 65	1	85 - 92	*Malachite* (57.41% Cu)
(Ntengwe, 2010)	H2SO4: 10ml H2O: 250ml	Nitric Acid: 10ml	25 - 50	6	85 – 91 %	*2KG high-Dolomite Ore* (4.07% AsCu)

This study explored the copper extraction process from Chalcopyrite with a copper content of 28.8%. The MSA concentration ranged from 10 to 30 g/L, and H_2O_2 was used as an oxidant at concentrations between 0.9% and 4.5%. The extraction was carried out at 75°C for a duration of 96 to 144 hours. The copper recovery rate varied between 70% and 99%, indicating a high degree of variability and potential for optimization. Prince's study used a fixed MSA concentration of 50 g/L and a H_2O_2 concentration of 3% to extract copper from Chalcopyrite with a copper content of 28.8%. The extraction process was conducted at 45°C for 96 hours. The study reported a copper recovery rate of 77%, demonstrating the effectiveness of this specific combination of conditions. Feng investigated the extraction of copper from Malachite, which has a higher copper content of 57.41%. The MSA concentration varied between 30 and 50 g/L, and no oxidant was used. The extraction was carried out at temperatures ranging from

45 to 65°C for a short duration of 1 hour. Despite the short extraction time, the copper recovery rate was high, ranging from 85% to 92% comparatively higher on average than the previous two studies but it also dealt with a much higher Cu content.

4.2 Economics, Pricing & Cost:

Table IV - Cost Factors and Assumptions

Lixiviant:	Efficiency Average (%)[1]:	Recyclability (Y/N):	Consumption per t/CU:
MSA	85	No	3.0
SULPHURIC ACID	88	No	3.0
A-THIOSULPHATE	63	Yes, Varies[2]	0.5[3]
GLYCINE	95	Yes, Varies	-
Assumptions:	Ore Grade = 0.3 Ore Content	-	-

4.2.1 MSA:

Equation i - MSA Cost Calculations

Amount of MSA required to extract 1 ton of copper:

$MSA_{required\_per\_ton}$ = 3 tons[4]

Amount of MSA required to extract the copper in the ore body:

$MSArequired = Cu_{ore} \times MSA_{required\_per\_ton}$

$MSArequired = 0.3 \times 3$

$MSArequired = 0.9$

Efficiency of MSA:

Where:

MSAactual is the actual amount of MSA needed considering inefficiencies and *Efficiency* is the efficiency of MSA, which is 0.85 or 85%.

$$MSA_{actual} = \frac{MSA\ Required}{Efficiency}$$

$$MSA_{actual} = \frac{0.9}{0.85}$$

---

[1] The averages for efficiency were taken from the varying experimental data available from tables in 4.1.1 – 4.1.3, combining the efficiency figures for Cu (only) and then dividing by the count of those numbers.

[2] Depending on extraction method and ore type and composition

[3] Varies massively depending on extraction method and ore type and composition from 0.153 – 0.54kg/t

[4] Provided by EnviroCopper

MSA_{actual} = 1.095

Cost of using MSA:

Where:

Costper_ton is the cost of MSA per ton, which is $1000[5].

CostMSA = MSAactual×Cost/t

CostMSA = 1.059×1000

CostMSA = $\$1059$

Cost of MSA per ton of copper:

Cost/t = $\frac{CostMSA}{CuOre}$

Cost/t = $\frac{1059}{0.3}$

Cost/t = $\boldsymbol{USD\$\ 3530}$

---

[5] Provided by EnviroCopper

4.2.2 Ammonia Thiosulphate:

Equation ii - Ammonia Thiosulphate Cost Calculations

Amount of **Ammonia Thiosulphate** required to extract 1 ton of copper:

$AThio_{required/t} = 0.5$ tons[6]

Amount of A-Thio required to extract the copper in the ore body:

$AThio_{required} = Cu_{ore} \times AThio_{required\_per\_ton}$

$AThio_{required} = 0.3 \times 0.5$

$AThio_{required} = 0.15$

Efficiency of A-Thio:

Where:

$AThio_{actual}$ is the actual amount of Ammonia Thiosulphate needed considering inefficiencies and *Efficiency* is the efficiency of Ammonia Thiosulphate, which is 0.63 or 63%.

$AThio_{actual} = \frac{AmmoniaThiosulphate\ Required}{Efficiency}$

$AThio_{actual} = \frac{0.15}{0.63}$

$AThio_{actual} = 0.238$

Cost of using Ammonia Thiosulphate:

Where:

Cost/t is the cost of Ammonia Thiosulphate per ton, which is USD$320[7].

$CostAThio = AThio_{actual} \times Cost/t$

$CostAThio = 0.238 \times 320$

$CostAThio = \$76.19$

Cost of Ammonia Thiosulphate per ton of copper:

$Cost/t = \frac{CostAThio}{CuOre}$

$Cost/t = \frac{76.19}{0.3}$

$\boldsymbol{Cost/t = USD\$\ 253.97}$

---

[6]

[7] Provided by EnviroCopper

4.2.3 Sulphuric Acid:

Equation iii - Sulphuric Acid Cost Calculations

Amount of H2SO4 required to extract 1 ton of copper:

$Sulphuric_{required/t}$ = 3 tons[8]

Amount of H2SO4 required to extract the copper in the ore body:

$Sulphuric_{required} = Cu_{ore} \times Sulphuric_{required\_per\_ton}$

$Sulphuric_{required} = 0.3 \times 3$

$Sulphuric_{required} = 0.9$

Efficiency of H2SO4:

Where:

$Sulphuric_{actual}$ is the actual amount of H_2SO_4 needed considering inefficiencies and *Efficiency* is the efficiency of H_2SO_4, which is 0.88 or 88%.

$Sulphuric_{actual} = \frac{Sulphuric\ Required}{Efficiency}$

$Sulphuric_{actual} = \frac{0.9}{0.88}$

$Sulphuric_{actual} = 1.023$

Cost of using H_2SO_4:

Where:

Cost/t is the cost of H_2SO_4 per ton, which is USD$180[9].

$CostSulphuric = Sulphuric_{actual} \times Cost/t$

$CostSulphuric = 1.023 \times 180$

$CostSulphuric = \$184.14$

Cost of H_2SO_4 per ton of copper:

$Cost/t = \frac{CostSulphuric}{CuOre}$

$Cost/t = \frac{184.14}{0.3}$

Cost/t = $\boldsymbol{USD\$\ 613.80}$

---

[8] Provided by EnviroCopper

[9] Provided by EnviroCopper

4.2.4 Glycine:

Equation iv - Glycine Cost Calculations

Amount of Glycine required to extract 1 ton of copper:

$Glycine_{required/t}$ = 0.5 tons[10]

Amount of Glycine required to extract the copper in the ore body:

$Glycine_{required}= Cu_{ore} \times Glycine_{required\_per\_ton}$

$Glycine_{required}= 0.3\times0.5$

$Glycine_{required}= 0.15$

Efficiency of Glycine:

Where:

$Glycine_{actual}$ is the actual amount of Glycine needed considering inefficiencies and *Efficiency* is the efficiency of Glycine, which is 0.95 or 95%.

$Glycine_{actual}= \frac{Glycine\ Required}{Efficiency}$

$Glycine_{actual} = \frac{0.15}{0.95}$

$Glycine_{actual} = 0.158$

Cost of using Glycine:

Where:

Cost/t is the cost of Glycine per ton, which is USD$180[11].

$CostGlycine = Glycine_{actual} \times Cost/t$

$CostGlycine = 0.158 \times 1600$

$CostGlycine = \$252.8$

Cost of Glycine per ton of copper:

$Cost/t = \frac{CostGlycine}{CuOre}$

$Cost/t = \frac{252.8}{0.3}$

$\mathbf{Cost/t = USD\$\ 842.67}$

---

[10] Assumption similar selectivity to ammonia Thiosulphate

[11] Provided by EnviroCopper

4.3 Environmental, Social, and Regulatory:

Table V- Scoring and Definitions for Risk Matrix

Score	Risk Level	Definition
1	Lowest Risk	Negligible environmental impact; characterised by high biodegradability, low eco-toxicity, and safe for frequent human handling. No special storage, safety measures, or personal protective equipment required. Accidents would be of low concern.
2	Low Risk	Minimal environmental impact; low levels of eco-toxicity and generally safe for human interaction. Limited safety measures required. Accidents would be of low concern.
3	Moderate Risk	Balanced level of risk, Moderate environmental impact; potential for some eco-toxicity and requires standard safety measures and storage protocols. Accidents would warrant moderate concern.
4	High Risk	Significant environmental impact; high levels of eco-toxicity and stringent safety measures, storage protocols, and personal protective equipment are required. Accidents would be of major concern.
5	Highest Risk	Severe environmental impact; extremely high levels of eco-toxicity, necessitating specialised safety measures, storage protocols, and personal protective equipment. Accidents would be of critical concern.

As seen in *Table V*, a 1-5 scoring system was utilised for its objectivity and accessibility. The numerical system mitigates qualitative bias usually associated with descriptive assessments, enhancing the objectivity of the evaluation. As well as this the simplicity of a 1-5 scale renders the matrix accessible to readers from a broad range of disciplinary backgrounds, including those without an economic or mining backgrounds. Additionally, the 1-5 scale avoids the unnecessary granularity that a 1-10 system would introduce, thereby maintaining clarity without sacrificing detail, such granularity could potentially obfuscate the findings without adding substantial value to the risk assessment.

The scoring system is further elucidated by weightings assigned to each risk factor, serving to clarify their relative importance in the overall risk assessment The points and weighting were assigned based on a combination of literature review, manufacturer production and handling guides, governmental agencies, NGOs, and regulatory guidelines and frameworks, and the relative immediacy and magnitude of each criterion's impact. Each number represents the relative importance of the criterion in the context of overall environmental and human health, they accurately reflect the varying degrees of impact each factor has on the socio-environmental context under study, ensuring a balanced and comprehensive assessment.

Continuing, the Ecotoxicology (Aquatic/Terrestrial) with a weighting of 0.2, underscores the pivotal role of aquatic and terrestrial organisms in maintaining ecological balance. Lixiviants that adversely affect these organisms can instigate a domino effect, destabilizing ecosystems and leading to broader environmental ramifications. Given the immediate and cascading consequences of ecotoxicological disruptions, this criterion is deemed high importance**.**

Persistence in the environment, assigned a weighting of 0.15, addresses the longevity of lixiviants in natural settings. While a persistent chemical might not immediately manifest its detrimental effects, its prolonged presence can lead to chronic environmental issues, especially if it interacts with other environmental factors. Its slightly lower weighting, compared to ecotoxicology, reflects the often-delayed manifestation of its impact.

The protection of human health is paramount, and the Human Health Risk criterion, weighted at 0.2, emphasizes this. Lixiviants that jeopardize human health can lead to a spectrum of health complications, from acute medical conditions to chronic ailments. The societal and economic repercussions of compromised human health further accentuate the importance of this criterion.

Bioaccumulation Potential, with a weighting of 0.15, delves into the propensity of a given lixiviant to accumulate within biological organisms. Such accumulation, especially in lower trophic levels, can lead to magnified effects higher up the food chain, potentially culminating in significant health risks for apex predators, including humans. Similar to persistence in environment criterion, its weighting acknowledges the often indirect and long-term nature of its impact. Carcinogenicity, weighted at 0.1, is a subset of the broader human health risk but focuses on the potential oncogenic properties of chemicals. The specificity of this criterion, combined with the fact that not every exposure leads to cancer, results in its slightly lower weighting.

Lastly, the Waste Disposal/Remediation criterion, with a weighting of 0.2, emphasizes the importance of effective waste management. Chemicals that challenge disposal or remediation protocols can persist, leading to sustained environmental challenges and often necessitating costly interventions. Additionally, the decision to employ a scale that sums to 1.05, rather than a conventional 1.0, was deliberate. This slight overextension serves as a reminder that environmental and chemical interactions and complexities often surpass structured assessments, and it is best practice to account for any additional, unknown, or unaccounted factors.

4.3.2 MSA

Table VI - Glycine Risk Matrix

Criteria	**Description**	**Score**	**Weighting**	**Weighted Score**	**Reasoning**
Ecotoxicology (Aquatic/Terrestrial)	Impact on aquatic and terrestrial life	2	0.2	0.4	While MSA is acutely harmful for aquatic organisms in nominal concentration, its overall toxicity is low.
Persistence in Environment	How long the chemical remains in the environment	1	0.15	0.15	MSA is readily biodegradable according to multiple guidelines.
Human Health Risk	Risks associated with handling, storage, and fumes	2	0.2	0.4	Standard industry safety practices are sufficient, and MSA has no toxic fumes.
Bioaccumulation Potential	Potential for the chemical to accumulate in organisms	1	0.15	0.15	Accumulation in organisms is not expected.
Carcinogenicity	Potential for the chemical to cause cancer	1	0.1	0.1	There's no indication of carcinogenic effects.
Waste Disposal/Remediation	Ease and safety of disposal and remediation	2.5	0.2	0.5	While no special measures are necessary, there are guidelines for containing large spills.
Overall Socio-Environmental Risk	Overall risk considering all factors	-	-	1.65	Average of the weighted scores.

4.3.2 Ammonia Thiosulphate:

Table VII - Ammonia Thiosulphate Risk Matrix

Criteria	**Description**	**Score**	**Weighting**	**Weighted Score**	**Reasoning**
Ecotoxicology (Aquatic/Terrestrial)	Impact on aquatic and terrestrial life	3	0.2	0.6	Ammonia-Thiosulphate has varying levels of toxicity to aquatic organisms, with potential threats to aquatic life and environmental damage.
Persistence in Environment	How long the chemical remains in the environment	2	0.15	0.3	While short-term degradation products are not likely hazardous, long-term degradation products may arise.
Human Health Risk	Risks associated with handling, storage, and fumes	4	0.2	0.8	There are multiple precautions and potential hazards associated with storage, handling, and the release of fumes.
Bioaccumulation Potential	Potential for the chemical to accumulate in organisms	1	0.15	0.15	Bioaccumulation is likely only at persistent high concentrations, with no food chain concentration potential.
Carcinogenicity	Potential for the chemical to cause cancer	1	0.1	0.1	Ammonia-Thiosulphate is not listed as a carcinogen by multiple agencies.
Waste Disposal/Remediation	Ease and safety of disposal and remediation	3	0.2	0.6	There are specific guidelines for disposal, with emphasis on preventing runoff due to potential aquatic toxicity.
Overall Socio-Environmental Risk	Overall risk considering all factors	-	-	2.45	Average of the weighted scores.

4.3.3 Sulphuric Acid:

Table VIII - Sulphuric Acid Risk Matrix

Criteria	**Description**	**Score**	**Weighting**	**Weighted Score**	**Reasoning**
Ecotoxicology (Aquatic/Terrestrial)	Impact on aquatic and terrestrial life	3	0.2	0.6	Sulphuric acid has varying levels of toxicity to aquatic organisms and can be corrosive to plants, birds, and land animals.
Persistence in Environment	How long the chemical remains in the environment	2.5	0.15	0.375	While H_2SO_4 is not biodegradable, it reacts with its environment and can lower the pH of waterways.
Human Health Risk	Risks associated with handling, storage, and fumes	4.5	0.2	0.9	There are multiple precautions and potential hazards associated with storage, handling, and the release of fumes, including potential fatality from high exposures.
Bioaccumulation Potential	Potential for the chemical to accumulate in organisms	1	0.15	0.15	Sulphuric acid will not bioaccumulate and does not accumulate in the food chain.
Carcinogenicity	Potential for the chemical to cause cancer	4	0.1	0.4	Mist/fumes containing Sulphuric acid are considered to be a human carcinogen, especially with repeated occupational exposures.
Waste Disposal/Remediation	Ease and safety of disposal and remediation	4	0.2	0.8	Specific guidelines for disposal are provided, emphasizing containment and neutralization due to its violent reaction with water.
Overall Socio-Environmental Risk	Overall risk considering all factors	-	-	3.225	Average of the weighted scores.

4.3.4 Glycine:

Table IX - Glycine Risk Matrix

Criteria	**Description**	**Score**	**Weighting**	**Weighted Score**	**Reasoning**
Ecotoxicology (Aquatic/Terrestrial)	Impact on aquatic and terrestrial life	1	0.2	0.2	Glycine is safely metabolized in most living organisms and is not expected to be harmful to the ecology.
Persistence in Environment	How long the chemical remains in the environment	1	0.15	0.15	Glycine is a biodegradable lixiviant and a non-toxic amino acid that is fully bio-degradable.
Human Health Risk	Risks associated with handling, storage, and fumes	1	0.2	0.2	Glycine is non-toxic, food-grade, and used therapeutically in humans. There are no known conditions to avoid and no exposure limits.
Bioaccumulation Potential	Potential for the chemical to accumulate in organisms	1	0.15	0.15	Glycine is a naturally occurring amino acid that is enzymatically degradable and easily metabolized by living organisms and plants.
Carcinogenicity	Potential for the chemical to cause cancer	1	0.1	0.1	No component of Glycine is identified as a probable, possible, or confirmed human carcinogen.
Waste Disposal/Remediation	Ease and safety of disposal and remediation	1	0.2	0.2	No adverse health effects are expected from the clean-up of spilled material. The guidelines for clean-up are straightforward.
Overall Socio-Environmental Risk	**Overall risk considering all factors**	-	-	**0.95**	Average of the weighted scores.

5. Discussion:

5.1 Lixiviant comparison

Table X - Summary of Socio-Environmental Risk Matrix

Chemical	Ecotoxicology	Persistence in Environment	Human Health Risk	Bioaccumulation Potential	Carcinogenicity	Waste Disposal/Remediation	Weighted Total
MSA	**0.4**	**0.15**	**0.4**	**0.15**	**0.1**	**0.5**	**1.65**
Ammonia-Thiosulphate	**0.6**	**0.3**	**0.8**	**0.15**	**0.1**	**0.6**	**2.45**
Sulphuric Acid	**0.6**	**0.375**	**0.9**	**0.15**	**0.4**	**0.8**	**3.225**
Glycine (Pre-activated)	**0.2**	**0.15**	**0.2**	**0.15**	**0.1**	**0.2**	**0.95**

In the conducted comparative analysis of the socio-environmental risks associated with four distinct chemicals - MSA (Methanesulphonic Acid), Ammonia-Thiosulphate, Sulphuric Acid, and Glycine (Pre-activated) - several noteworthy observations were made (*Table X*).

Ecotoxicologically, Ammonia-Thiosulphate and Sulphuric Acid both exhibited a pronounced potential risk to aquatic and terrestrial life, as reflected by their identical scores of 0.6. This contrasts starkly with Glycine (Pre-activated), which, due to its benign nature, registered the lowest ecological impact with a score of 0.2. The persistence of these chemicals in the environment varied slightly, with Ammonia-Thiosulphate and Sulphuric Acid both demonstrating a moderate persistence, evidenced by their score of 0.375. Glycine (Pre-activated), however, showcased a minimal environmental footprint in this regard.

From a human health perspective, the corrosive nature and associated storage and handling hazards of Ammonia-Thiosulphate and Sulphuric Acid rendered them the most concerning, each achieving a score of 0.9. In terms of bioaccumulation potential, a universally low score of 0.15 across all chemicals suggests a minimal risk of these substances accumulating within organisms. Carcinogenicity presented a more varied landscape: while Glycine (Pre-activated) and MSA were found to have negligible carcinogenic effects, Ammonia-Thiosulphate and Sulphuric Acid exhibited a heightened risk.

Waste disposal and remediation practices for Ammonia-Thiosulphate and Sulphuric Acid appear to be more challenging, as indicated by their score of 0.8. Conversely, Glycine (Pre-activated) emerged as the least problematic in this domain. When collating these findings to ascertain an overall socio-environmental risk, Glycine (Pre-activated) was identified as the chemical with the least associated risk, scoring 0.95. This was in stark contrast to Ammonia-Thiosulphate and Sulphuric Acid, which both registered the highest risk at 3.225. MSA occupied a middle ground with a score of 1.65.

Table XI- Summary of Price and Cost

Lixiviant:	Price of Lixiviant USD$/t	Cost per ton of Cu USD$/t
MSA	1000	3530.00
Sulphuric Acid	180	613.80
A-Thiosulphate	320	253.97
Glycine	1600	842.67

In synthesizing these results, it becomes evident that while each lixiviant possesses its unique challenges and advantages, Glycine (Pre-activated) is distinctly the most environmentally benign option while sulphuric acid is the most cost effective among the quartet. To quantify the best lixiviant option in an unbiased and logical way, a simple equation that combines both cost and socio-environmental risk, a "Value Score" (v score) for each lixiviant is introduced here. The v score is inversely proportional to the cost (lower cost is better) and directly proportional to the socio-environmental risk (lower risk is better), and is calculated by the equation: $v = \frac{1}{cost} x \frac{1}{risk}$

The summary of calculated v-scores is given in the table below:

Table XII - Lixiviant v-Score Summary Table

Lixiviant:	Equation:	v Score:
MSA	$v = \frac{1}{3530} x \frac{1}{1.65}$	$v = 0.000172$
Sulphuric Acid	$v = \frac{1}{613.80} x \frac{1}{3.225}$	$v = 0.000505$
Ammonia Thiosulphate	$v = \frac{1}{253.97} x \frac{1}{2.45}$	$v = 0.001608$
Glycine (Pre-Activated)	$v = \frac{1}{842.67} x \frac{1}{0.95}$	$v = 0.001249$

Based on the calculated v scores, ammonia thiosulphate has the highest v score, making it the most favourable option when considering both cost and socio-environmental risk it is then followed by, in order, glycine, sulphuric acid and MSA.

The overarching objective is to meticulously compare the economic and environmental ramifications of extracting one ton of copper from the Kapunda mine using ISR techniques. Within this framework, Glycine and Thiosulphate have emerged as the superior options, particularly when one considers the multi-dimensional metrics of socio-environmental impact, risk, and economic feasibility. However, it is imperative to underscore that these options are largely theoretical at the present and necessitate extensive infrastructural and processing capabilities for their effective implementation (Benneson, 2017; Binnemans and Jones, 2022).

The theoretical promise of Glycine and Thiosulphate as optimal lixiviants is tempered by several pragmatic considerations. Foremost among these is the very limited use of field trials and empirical testing to substantiate their efficacy and safety, particularly in the context of declining ore grades. Glycine, although “on paper” the best option, is yet to be rigorously validated through extensive field trials, rendering it a largely unknown entity in the realm of practical ISR application.

Similarly, Thiosulphate's chemical properties may offer economic feasibility and there is some precedent for its effectiveness in gold mining (Molleman and Dreisinger, 2002; Dong et al., 2021) its environmental sustainability issues, as well as the fact ammonia is not well received by nearby communities and the use thereof may face significant legislative hurdles (Bennson, 2017) for either the Kapunda or the Australian regulatory bodies and processing systems inherent instability complicates its suitability. Molleman and Dreisinger (2002) note that "thermodynamically, the ammonium Thiosulphate system is not stable," and that "both ammonia and Thiosulphate will be lost through volatilisation or decomposition." These chemical instabilities, coupled with the lack of comprehensive field trials in copper, make Thiosulphate a speculative choice at best. Moreover, both Glycine and Thiosulphate entail additional costs that are often not accounted for in this initial economic assessment. These include not only the costs associated with the lixiviants themselves but also the ancillary expenses related to their complex processing requirements. Thus, while Glycine and Thiosulphate may offer theoretical advantages in terms of both economic feasibility and/or socio-environmental impact, their current inaccessibility is a function of multiple factors. Ergo, despite their theoretical promise, they remain largely speculative options, necessitating further empirical investigation and technological development for their practical implementation in ISR methods for copper extraction for Kapunda.

Consequently, the immediate choice for a lixiviant in ISR methods for copper extraction from Kapunda is to be between to Sulphuric Acid and MSA. Sulphuric Acid, owing to its widespread availability and cost-effectiveness, emerges as a pragmatic choice for immediate application. However, its elevated socio-environmental risk score necessitates a judicious evaluation of its long-term implications, particularly in the context of environmental remediation and legislative compliance.

This economic viability of sulphuric acid is further accentuated by its widespread availability and large-scale production, attributes that have been well-documented by Binnemans and Jones (2022). However, this economic allure is counterbalanced by its elevated socio-environmental risk score of 3.225. The high-risk score necessitates a comprehensive evaluation of its long-term implications, particularly in the realms of environmental remediation and legislative compliance. Therefore, if EnviroCopper prioritises cost-effectiveness, Sulphuric Acid presents itself as the most pragmatic choice, with the caveat of higher environmental and regulatory risks. However, while MSA is undoubtedly the more expensive option in the immediate term. However, its more moderate socio-environmental risk score of 1.65 offers a less impactful alternative. Furthermore, as Binnemans and Jones (2022) have noted, the anticipated industrialisation of new sustainable synthesis processes for MSA could lead to a reduction in its cost in the foreseeable future. This makes MSA a potentially more economically viable option for long-term projects that aim to balance economic efficiency with environmental responsibility. Thus, if EnviroCopper's strategy leans towards a more environmentally benign option, MSA stands out as the more suitable choice, especially when considering its future economic potential.

The findings could potentially guide future EnviroCopper or ISR projects exploration and extraction activities in the region, assisting in the development of strategies that balance economic interests with environmental and socio-cultural considerations.

5.2 Limitations and Future Research Opportunities

This thesis acknowledges several limitations, each of which serves as a catalyst for future research, thereby enriching the academic landscape of copper extraction methodologies using various lixiviants.

The first limitation concerns the accuracy and completeness of the data collected, particularly in relation to the environmental impact of each lixiviant. Despite employing rigorous data collection and validation methods, the risk of error or bias remains.

Second, this thesis primarily relies on laboratory-based testing to infer the potential outcomes in the field for In-Situ Recovery (ISR). However, this approach has inherent limitations. The controlled conditions of a laboratory environment may not accurately represent the complexities and variables encountered in the field. As such, the active effective yield may vary significantly when applied in real-world scenarios. Factors such as geological variations, water table pH, mineral composition, slope and hydrological gradient, environmental conditions, even microbial activities could significantly influence the extraction efficiency and overall yield. Therefore, caution should be exercised when generalizing the lab-based findings to field applications.

Additionally, while the economic model attempts to account for variations in copper yields, actual yields can be influenced by a range of factors not included in the model. The analysis in this study is based on current market prices and standard costs. However, the actual economics of copper extraction can be influenced by a multitude of factors that were not accounted for in this study. Market prices for copper and other materials are subject to fluctuations based on global supply and demand dynamics. Bulk orders may attract discounts that can significantly alter the cost dynamics. Import/export taxes, customs duties, and other fees can also impact the overall cost. Furthermore, regional variations in energy and water costs associated with the use of each lixiviant can significantly influence the economic feasibility of the extraction process.

Third, this thesis focuses on the Kapunda region serves as both a strength and a limitation. While it allows for a detailed analysis of a specific area, it also restricts the generalizability of the findings. The unique geological and hydrogeological conditions at the Kapunda site may not be present in other mining regions, thus limiting the universal applicability of the research. Future studies could explore similar extraction methods in diverse geological settings, perhaps even employing satellite imaging for initial assessments.

An additional limitation that warrants mention is the sample size used in the laboratory tests, which may not be sufficient for statistical significance. The replicability of the study could be compromised if the sample size is not adequately representative. Future research could aim for larger sample sizes and multiple testing scenarios to validate the findings further.

Finally, this thesis acknowledges certain limitations in its exploration of the environmental impact of various lixiviants. Despite efforts to comprehensively research the environmental implications of each lixiviant, significant gaps exist in the current literature. The use of glycine as a leaching solution is a relatively novel concept, and its active component, glycine sodium hydrate salt, is sparsely researched in ecotoxicological applications. Similarly, the environmental interactions of MSA (Methanesulphonic Acid) are not extensively documented. This dissertation has endeavoured to provide a holistic view of the subject matter, identifying and acknowledging areas where information is lacking or uncertain. In such instances, the study has either stated these 'unknowns' explicitly or sought to draw inferences from chemically similar products. In the conclusion, this dissertation underscores the pressing need for further research into the environmental aspects of these lixiviants, hoping that future studies will build upon this work, filling the identified gaps and contributing to a more comprehensive understanding of the environmental impact of these chemicals.

6. Conclusions

This dissertation has undertaken a multi-faceted evaluation of the economic and environmental ramifications of employing various lixiviants for In-Situ Recovery (ISR) methods in copper extraction at the Kapunda mine in South Australia. Through rigorous comparative analysis, the study has illuminated the multi-dimensional aspects of socio-environmental impact, risk, and economic feasibility associated with four distinct lixiviants: Methanesulphonic Acid (MSA), Ammonia-Thiosulphate, Sulphuric Acid, and Glycine.

The findings indicate that while Glycine (Pre-activated) emerges as the most environmentally benign option, its practical application remains largely theoretical, necessitating further empirical validation. On the other hand, Sulphuric Acid, despite its elevated socio-environmental risks, stands out as the most cost-effective and readily available option for immediate application. MSA presents itself as a balanced alternative, offering moderate socio-environmental risks and the potential for future cost reductions.

This thesis acknowledges several limitations, including the reliance on laboratory-based testing, the specificity of the Kapunda region, and gaps in the existing literature on the environmental impacts of selected lixiviants. These limitations not only warrant caution in the generalisation of the findings but also highlight avenues for future research. Future studies could aim to validate these findings through extensive field trials, explore the applicability of the ISR method in diverse geological settings, and delve deeper into the environmental impacts of the lixiviants under consideration.

In the context of increasing environmental scrutiny and the pressing need for sustainable mining practices, this dissertation serves as a foundational step towards a more holistic understanding of ISR methods in copper extraction. It provides valuable insights for EnviroCopper and other stakeholders in the mining industry, offering a nuanced framework for balancing economic efficiency with environmental responsibility. As the mining sector grapples with its socio-environmental obligations, the findings of this study could guide future exploration and extraction activities, contributing to the development of strategies that harmonise economic interests with environmental and socio-cultural considerations.

Finally, the selection of the optimal lixiviant is a complex decision that must weigh multiple factors, including but not limited to cost, environmental impact, and social acceptability, while the theoretical promise of Glycine and Thiosulphate is compelling, the immediate best-choice lixiviant for copper extraction at Kapunda appear to be between Sulphuric Acid and MSA, with Sulphuric acid being the more cost effective and where MSA is the socio-environmentally acceptable.

7. References

Ahn, J., Wu, J. and Lee, J. (2019). Investigation on chalcopyrite leaching with Methanesulphonic acid (MSA) and hydrogen peroxide. *Hydrometallurgy*, [online] 187, pp.54–62. doi:https://doi.org/10.1016/j.hydromet.2019.05.001.

Austin, J.-B. (2013). *The Mines of South Australia*. Adelaide: Cambridge University Press, pp.13–17.

Austral Chemicals (2023). *MSA-Methanesulphonic acid*. [online] *Austral Chemicals*. Chile: Austral Chemicals. Available at: http://www.austral-chem.cl/en/prod/performance-chemicals/performance-chemicals/msa [Accessed 29 Jul. 2023].

BASF SE (2023). *BASF Safety data sheet according to UN GHS 4th rev: BASO MSA*. [online] Ludwigshafen, GERMANY: BASF SE, pp.1–14. Available at: https://download.basf.com/p1/000000000030430399_SDS_GEN_IL/en/Baso+MSA_000000000030430399_SDS_GEN_IL_en_2-0.pdf [Accessed 29 Jul. 2023].

Bennson, T.C. (2017). *Western Australian School of Mines GLYCINE AS A LIXIVIANT FOR THE LEACHING OF LOW GRADE COPPER-GOLD ORES*. [online] Perth, Western Australia: Curtin University. Available at: https://espace.curtin.edu.au/bitstream/handle/20.500.11937/56525/Tanda%20Bennson%202017.pdf?sequence=1 [Accessed 31 Jul. 2023].

Binnemans, K. and Jones, P.T. (2022). Methanesulphonic Acid (MSA) in Hydrometallurgy. *Journal of Sustainable Metallurgy*, 9, pp.26–45. doi:https://doi.org/10.1007/s40831-022-00641-6.

Cameo Chemicals (1999). *AMMONIUM THIOSULPHATE*. [online] *National Oceanic and Atmospheric Administration*, Washington D.C. - United States : National Oceanic and Atmospheric Administration, pp.1–2. Available at: https://cameochemicals.noaa.gov/chris/ATF.pdf.

Capot Chemical (2013). *MSDS of Glycine sodium salt hydrate*. [online] *Capot Chemical*, Hangzhou, China: Capot Chemical, pp.1–6. Available at: https://www.capotchem.com/doc/viewmsds_207300-76-3.html [Accessed 1 Aug. 2023].

Carolina Biological (2018). *Safety Data Sheet - Glycine* . [online] *Safety Data Sheet Glycine - Durham Technical Community College*, Charlotte, North Carolina: Carolina Biological, pp.1–4. Available at: https://www.durhamtech.edu/sites/default/files/safety_data_sheets/Chemistry-and-Biology/Glycine%20%7BAminoacetic%20acid%7D%20cas56-40-6%20SDS.pdf [Accessed 1 Aug. 2023].

Dentith, M. and Stuart, R. (2019). Sediment-hosted stratiform copper deposits in the Adelaide Geosyncline, South Australia: Geophysical responses of mineralisation and the mineralised environment. *ASEG Extended Abstracts*, [online] 2003(3), pp.169–196. doi:https://doi.org/10.1071/asegspec12_14.

Department of Climate Change, Energy, the Environment and Water (2022). *Sulphuric acid*. [online] *Department of Climate Change, Energy, the Environment and Water*. Canberra, Australia : Department of Climate Change, Energy, the Environment and Water. Available at:

https://www.dcceew.gov.au/environment/protection/npi/substances/fact-sheets/Sulphuric-acid [Accessed 29 Jul. 2023].

Dong, Z., Jiang, T., Xu, B., Zhang, B., Liu, G., Li, Q. and Yang, Y. (2021). A systematic and comparative study of copper, nickel and cobalt-ammonia catalyzed Thiosulphate processes for eco-friendly and efficient gold extraction from an oxide gold concentrate. *Separation and Purification Technology*, [online] 272, p.118929. doi:https://doi.org/10.1016/j.seppur.2021.118929.

Draslovka (2023). *Draslovka - GlyLeach*. [online] www.draslovka.com. Available at: https://www.draslovka.com/ [Accessed 1 Aug. 2023].

Fathollahzadeh, H., Khaleque, H.N., Eksteen, J., Kaksonen, A.H. and Watkin, E.L.J. (2019). Effect of glycine on bioleaching of rare earth elements from Western Australian monazite by heterotrophic and autotrophic microorganisms. *Hydrometallurgy*, [online] 189, p.105137. doi:https://doi.org/10.1016/j.hydromet.2019.105137.

FENG, Q., WEN, S., ZHAO, W., LV, C. and BAI, X. (2020). Leaching of Copper from Malachite with Methane-sulfonic Acid. *Solvent Extraction Research and Development, Japan*, [online] 22(2), pp.159–168. doi:https://doi.org/10.15261/serdj.22.159.

Finar Chemicals (2012). *Material Safety Data Sheet Ammonium Thiosulphate MSDS*. [online] *Finar Chemicals*, Chacharwadi Vasna, India : Finar Chemicals, pp.1–5. Available at: https://www.finarchemicals.com/msds/Ammonium%20thiosulphate.pdf.

GROCHEM Australia (2016). *GROCHEM SAFETY DATA SHEET - THIN-IT*. [online] *Sumitomo Chemical Australia*, Melbourne, AUSTRALIA: GROCHEM AUSTRALIA, pp.1–7. Available at: https://sumitomo-chem.com.au/download/file/fid/906 [Accessed 29 Jul. 2023].

Hore-Lacy, I. (2013). Uranium Mining, Processing, and Enrichment. *Elsevier eBooks: Uranium Mining, Processing, and Enrichment*, [online] pp.317–328. doi:https://doi.org/10.1016/b978-0-12-409548-9.01357-9.

Lahiri-Dutt, K., Singh, G., ChuVan, D., Scoble, M., Shandro, J., Koehoorn, M. and Cannon, C. (2011). *A GUIDE TO LEADING PRACTICE SUSTAINABLE DEVELOPMENT IN MINING*. [online] Australian Government Department of Industry, Innovation and Science. Available at: https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-a-guide-to-leading-practice-sustainable-development-in-mining-handbook-english.pdf [Accessed 16 Jun. 2023].

Langhans, J.W., Lei, K.P.V. and Carnahan, T.G. (2003). Copper-catalyzed Thiosulphate leaching of low-grade gold ores. *Hydrometallurgy*, [online] 29(1-3), pp.191–203. doi:https://doi.org/10.1016/0304-386x(92)90013-p.

Martin Resources (1998). *Material Safety Data Sheet - Ammonium Thiosulphate Solution*. [online] *A&A Fertilizer Ltd.*, Beaumont, Texas: Martin Resources , pp.1–5. Available at: https://assets.greenbook.net/M99346.pdf [Accessed 29 Jul. 2023].

Molleman, E. and Dreisinger, D. (2002). The treatment of copper–gold ores by ammonium Thiosulphate leaching. *Hydrometallurgy*, [online] 66(1-3), pp.1–21. doi:https://doi.org/10.1016/s0304-386x(02)00080-4.

Ntengwe, F. (2010). The Leaching of Dolomitic-Copper Ore Using Sulphuric Acid Under Controlled Conditions~!2010-03-15~!2010-06-17~!2010-07-21~! *The Open Mineral Processing Journal*, [online] 3(1), pp.60–67. doi:https://doi.org/10.2174/1874841401003010060.

Oraby, E.A. and Eksteen, J.J. (2014). The selective leaching of copper from a gold–copper concentrate in glycine solutions. *Hydrometallurgy*, [online] 150, pp.14–19. doi:https://doi.org/10.1016/j.hydromet.2014.09.005.

Price, E.E. (2022). *Copper Leaching from Chalcopyrite with an Alternative Lixiviant/Oxidant System Item Type text; Electronic Thesis*. [online] *Repository Arizona.edu*. Arizona, United States : The University of Arizona. Available at: https://repository.arizona.edu/bitstream/handle/10150/665007/azu_etd_19683_sip1_m.pdf?sequence=1 [Accessed 1 Aug. 2023].

Public Health England (PHE) and United Kingdom Government (2015). *Compendium of Chemical Hazards*. [online] *Compendium of Chemical Hazards*, London, England : Public Health England (PHE) Publications, pp.1–8. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/456131/Sulphuric_Acid_TO_PHE_250815.pdf [Accessed 29 Jul. 2023].

Seredkin, M., Zabolotsky, A. and Jeffress, G. (2016). In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. *Ore Geology Reviews*, [online] 79, pp.500–514. doi:https://doi.org/10.1016/j.oregeorev.2016.06.016.

Solvay S.A. (2013). *Product Safety Summary Sulphuric Acid*. [online] *Solvay*, Brussels, Belgium: Solvay S.A., pp.1–5. Available at: https://www.solvay.com/sites/g/files/srpend221/files/2021-01/PSS-Sulphuric-Acid%20.pdf [Accessed 29 Jul. 2023].

Tanda, B.C., Oraby, E.A. and Eksteen, J.J. (2017). Recovery of copper from alkaline glycine leach solution using solvent extraction. *Separation and Purification Technology*, [online] 187, pp.389–396. doi:https://doi.org/10.1016/j.seppur.2017.06.075.

The Advertiser (1906). KAPUNDA AND ITS COPPER MINES. *The Advertiser (Adelaide, SA : 1889 - 1931)*, [online] 30 Jul., p.6. Available at: https://trove.nla.gov.au/newspaper/article/5089613?afterLoad=showCorrections [Accessed 2 May 2023]. The Advertiser (Adelaide, SA : 1889 - 1931), Mon 30 Jul 1906, Page 6 - KAPUNDA AND ITS COPPER MINES.

Wang, H., Xu, C.-Y., Dowd, P.A., Wang, Z. and Faulkner, L. (2022). Modelling in-situ recovery (ISR) of copper at the Kapunda mine, Australia. *Minerals Engineering*, [online] 186, pp.107752–107752. doi:https://doi.org/10.1016/j.mineng.2022.107752.