

The Use of *Aspergillus niger* for the Removal of Phosphorous and Potassium from the Iron Ore Concentrate of the Sishen Iron Ore Mine, South Africa

CHAPTER 7

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The editorial style of the *Hydrometallurgy* was followed in this chapter

7.1 Abstract

The depletion of the richer iron ore worldwide has made it necessary to process lower quality iron ore. Certain alkali substances, such as phosphorous (P) and potassium (K), contained within the iron ore have a detrimental effect on the smelting process during steel manufacturing. Therefore, international steel making companies charge penalties when purchasing iron ore concentrates containing high concentrations of P and K. It has, therefore, become necessary to develop an economically viable and environmentally friendly process to reduce the high P and K concentrations contained in the iron ore concentrate of the Sishen Iron Ore Mine. Conventional bioleaching refers to the microbial conversion of insoluble metals into soluble forms, however, the P and K contained within the iron ore concentrate are in non-sulphidic phases, and therefore, conventional bioleaching processes are not viable for their removal from the ore. Therefore, the use of an alternative bioleaching microorganism has to be investigated to remove the undesirable P and K from the iron ore concentrate. The objective of this study is, therefore, to investigate the possible use of *A. niger* in a bioleaching process for the economic removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine. During this study different pulp densities [bioleaching solution (ml)/iron ore (g)] were compared for the removal of P and K from the iron ore concentrate using *A. niger* as the bioleaching microorganism. A pulp density of 33% proved to be most efficient in terms of citric acid production, producing a maximum of 52.06 g.l⁻¹ of citric acid at 30°C after 96 h. In addition, the 33% pulp density resulted in the maximum P and K removal of 23.53% and 17.65% respectively, and therefore, *A. niger* can be considered as a

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suitable bioleaching candidate for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine.

Key words: *Aspergillus niger*, bioleaching, iron ore concentrate, phosphorous, potassium

7.2 Introduction

The processing of lower quality iron ore has become necessary due to the rapid depletion of the richer iron ore bodies worldwide as a result of the advancing global technologies and civilisation (Jian and Sharma, 2004). Alkali compounds, such as P and K, contained within the lower quality iron ore have a detrimental effect on the smelting process during steel making in blast furnaces (Yusfin *et al.*, 1999). These alkali compounds are deposited on the surface of the coke, where they act as a catalyst in the gasification of carbon in the presence of carbon dioxide (CO₂) (Yusfin *et al.*, 1999). The presence of especially K in the coke leads to the formation of K₂O.SiO₂ and K₂O.Al₂O₃.2SiO₂, which leads to an increase in the coke volume and its subsequent fracture (Yusfin *et al.*, 1999). In addition, K penetrates the monolithic aluminosilicate lining of the furnace, resulting in the formation of silicide or leucite, and the subsequent rearrangement of the crystalline lattice of the refractories (Yusfin *et al.*, 1999). This results in the creation of stresses that cause cracks to form in the refractory lining, leading to its subsequent destruction (Yusfin *et al.*, 1999). Therefore, as a result of the negative financial impact due to the destruction of the refractory lining, the steel making companies charge penalties when purchasing iron ore concentrates containing high concentrations of P and K. The limits on alkali concentrations range from 0.25% mass in Japan to 0.55% mass in Switzerland (Yusfin *et al.*, 1999).

In the past, lower quality iron ore was blended with high quality ore to “dilute” the P and K concentrations in the final iron ore product, which is exported to the international steel making plants (Dukino *et al.*, 2000). To date, the blending of different quality iron ores has minimised the penalties charged by the steel making companies, however, the ratio of low quality iron ore to high quality iron ore is increasing, and thus becoming an

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escalating problem within the economic functioning of the Sishen Iron Ore Mine. It has, therefore, become important to develop an economically viable and environmentally friendly process to reduce the high P and K concentrations contained within the iron ore concentrate to improve the quality of ore that is being exported to the international steel making companies.

Various technologies developed in the last couple of decades include microbial use for the extraction of different valuable metals, which is commonly known as bioleaching (Gilbertson, 2000; Rohwerder *et al.*, 2002). Conventional bioleaching, also known as biooxidation, refers to the microbial conversion of insoluble metals (e.g. metal sulphides such as CuS, NiS and ZnS) into soluble forms (usually metal sulphates such as CuSO₄, NiSO₄ and ZnSO₄) (Sand, 2001; Rawlings, 2002, Roberto, 2002). The basic fundamentals of conventional bioleaching may, therefore, be used for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine. The P and K contained within the iron ore concentrate are, however, in non-sulphidic phases, and therefore, the use of an alternative bioleaching microorganism has to be investigated to remove the undesirable P and K from the iron ore concentrate.

Metals in certain non-sulphide minerals, such as the iron ore concentrate of the Sishen Iron Ore Mine, may be solubilised by a process of complexation using organic acids, such as citric and oxalic acid (Rawlings, 2005). These organic acids are typically produced by certain types of fungi, such as *A. niger* (Jianlong, 2000; Vandenberghe *et al.*, 2000; Rawlings, 2005). Citric acid contains several carboxyl groups, which tend to donate protons (H⁺), resulting in negatively charged carboxyl groups that are capable of forming stable complexes with several cations (Sayer and Gadd, 2001). Therefore, it would be possible that these negatively charged carboxyl groups might form stable complexes with the positively charged K cations present, and at the same time the release of H⁺ ions may result in a hydrolysis reaction involving the P contained in the iron ore, resulting in the subsequent P and K removal from the iron ore concentrate.

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The objective of this study is, therefore, to investigate the possible use of *A. niger* in a bioleaching process for the economic removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine.

7.3 Materials and Methods

7.3.1 Microorganism and Preparation of Inoculum

A freeze-dried sample of *Aspergillus niger* NRRL 567 was obtained from the American Type Culture Collection (ATCC, Rockville, MD, USA) and stored at 4°C. *A. niger* spores were produced on Potato Dextrose Agar (PDA) (Merck Laboratories, Darmstadt, Germany) (Appendix A) at 30°C and were sub-cultured at bi-weekly intervals. Spores were harvested after 7 days of incubation by adding 10 ml of 0.1% Tween 80 (Merck) solution to each plate. Spore inoculates of 1.0×10^7 spores.ml⁻¹ were prepared using a haemocytometer.

7.3.2 Iron Ore Concentrate Sample Selection

Iron ore concentrate samples (-5+1mm particle size) were collected by Kumba Iron Ore, Ltd. at the Sishen Iron Ore Mine, South Africa.

7.3.3 Bioleaching Fermentation Medium

The fermentation medium was prepared using distilled water (dH₂O) and contained the following (Appendix A): 150 g.l⁻¹ D-glucose, 2.5 g.l⁻¹ (NH₄)₂SO₄, 0.5 g.l⁻¹ MgSO₄.7H₂O, 2.0 KH₂PO₄, 0.1×10^{-3} g.l⁻¹ Fe₂(SO)₄.24H₂O, 0.1×10^{-3} g.l⁻¹ ZnSO₄.7H₂O and 0.06×10^{-3} g.l⁻¹ CuSO₄.5H₂O.

7.3.4 Bioleaching Conditions for the Removal of Phosphorous and Potassium from the Iron Ore Concentrate

Bioleaching was conducted in 11 Erlenmeyer flasks. Briefly, three separate 500 g iron ore concentrate samples were mixed with 100 ml, 250 ml and 500 ml of fermentation medium respectively. Each flask was inoculated with 1 ml of *A. niger* NRRL 567

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inoculum (1.0×10^7 spores.ml⁻¹). The Erlenmeyer flasks and their contents were incubated at 30°C for 10 days. The bioleaching procedures were conducted in duplicate.

7.3.5 Analytical Procedure

The analytical procedure entailed the aseptic extraction of 5 ml of the fermentation medium from each flask. The extracted medium was filtered through a 0.45µm syringe filter (Millipore), followed by the analyses for pH and citric acid quantification. The abovementioned analyses were performed daily for 10 days.

7.3.6 Citric Acid Concentration Analysis

Citric acid concentrations were determined by spectrophotometry at 420nm after adding pyridine and acetic anhydride as described by Marier and Boulet (1958). Briefly, 1 ml of the sample was added to a test tube containing 1.3 ml of pyridine (C₅H₅N) (Merck), followed by the addition of 5.7 ml of acetic anhydride (C₄H₆O₃) (Merck). The contents of the test tube was mixed by swirling the tube and immediately placed in a constant-temperature (22°C) water bath. Colour development was allowed for 30 min, followed by reading the colour intensity at 420nm with the blank set on 100% transmission. The citric acid concentration was determined by referring to a standard curve for citric acid concentration. Citric acid concentrations were expressed in g.l⁻¹.

7.3.7 Chemical Analysis of the Treated Iron Ore Concentrate

The chemical content of the treated iron ore concentrate was analysed after the 10 day bioleaching process by the Department of Geology, University of Pretoria, Pretoria, South Africa, using XRF spectrometry of the major elements. Briefly, the samples were ground to <75µm in a Tungsten Carbide milling vessel, roasted at 1000°C, followed by the fusing of 1g of sample and 9g Li₂B₄O₇ into a glass bead. Major element analysis was executed on the fused bead using a ARL9400XP+ spectrometer. Another aliquot of the sample was pressed into a powder briquette for trace element analysis.

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7.4 Results and Discussion

The citric acid concentrations produced using different pulp densities [bioleaching solution (ml)/iron ore (g)] (1/1, 1/2, and 1/5) of fermentation medium is illustrated in Figure 7.1. It was evident that the presence of the iron ore concentrate in the fermentation flasks had a negative effect on the citric acid production, as lower concentrations of citric acid (30.45 – 52.06 g.l⁻¹) were detected compared to fermentation without the presence of iron ore concentrate, where the maximum citric acid concentration was 102.3 g.l⁻¹ after 96 h (Williams and Cloete, 2008). This phenomenon may be as a result of the inhibitory effect which iron may have on the metabolism of *A. niger*.

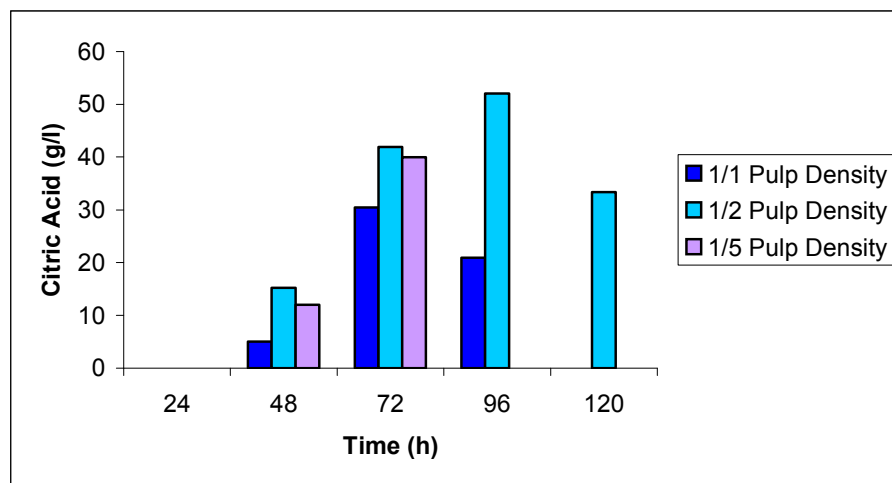


FIGURE 7.1

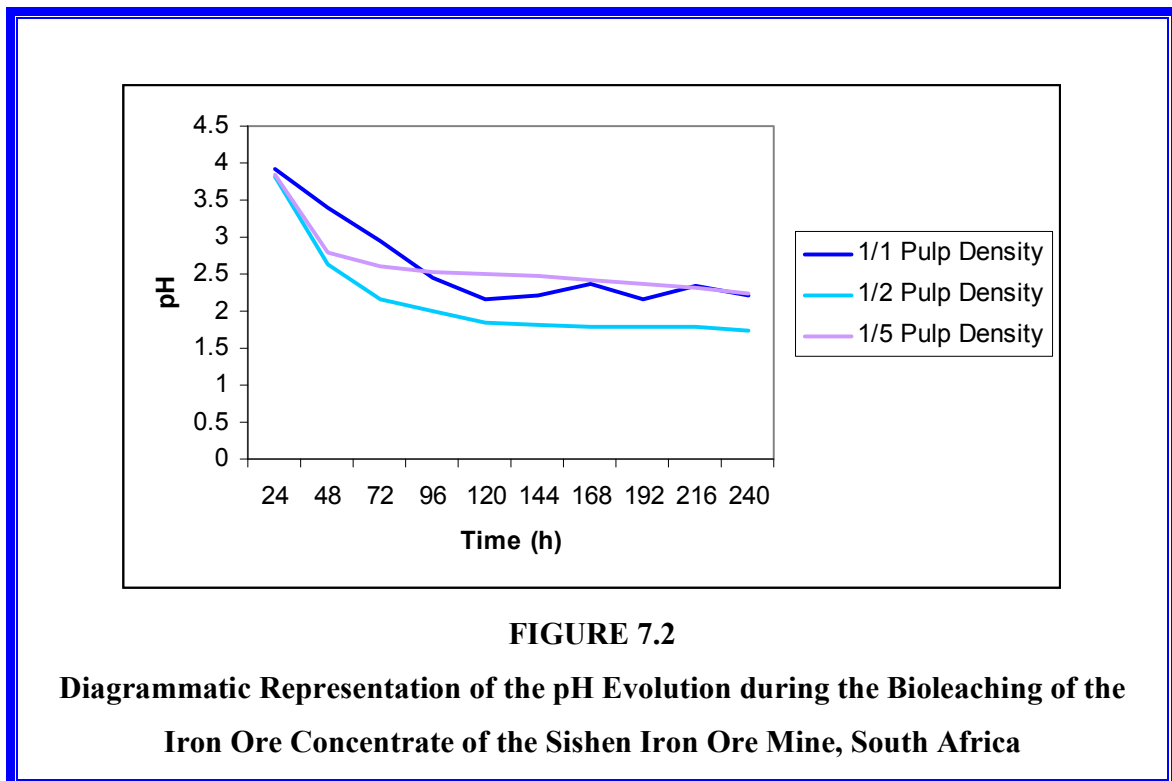
Diagrammatic Representation of the Citric Acid Production during Bioleaching by *Aspergillus niger* NRRL 567 at 30°C

In addition, the pulp density also had an effect on the citric acid production. A 1/2 pulp density proved to be most efficient for citric acid production, producing a maximum citric acid concentration of 52.06 g.l⁻¹ after 96 h of fermentation, whereas the 1/1 and 1/5 pulp

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densities produced maximum citric acid concentrations of 30.45 g.l⁻¹ and 39.99 g.l⁻¹ after 72 h respectively. No citric acid could be detected in the bioleaching solution after 96 h using a 1/5 pulp density compared to the 1/1 and 1/2 pulp densities where the citric acid disappeared from the solutions after 120 h and 144 h respectively. Similar patterns of citric acid reduction were observed during citric acid production by *A. niger* (Williams and Cloete, 2008).

The pH evolution using different pulp densities (1/1, 1/2, and 1/5) is illustrated in Figure 7.2. The pH of the bioleaching solutions using all three pulp densities rapidly decreased during the first 72 h of fermentation, followed by the pH stabilization from 96 h onwards. The pH of the 1/2 pulp density proved to reach the lowest levels of the pulp densities tested, stabilizing to an average of 1.79 from 120 h onwards, while the 1/1 and 1/5 pulp densities stabilized to an average of 2.24 and 2.38 in the same period. The maximum reduction in pH of 2.26 was achieved by using a pulp density of 1/2, while the maximum reduction of pH for the 1/1 and 1/5 pulp densities were 1.85 and 1.76 respectively.



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In addition to citric acid production, *Aspergillus niger* is able to produce other organic acids such as oxalic acid, which may explain the low pH throughout the bioleaching process, in spite of the citric acid depletion from the bioleaching solution after 96-144 h (Jianlong, 2000; Vandenberghe *et al.*, 2000; Rawlings, 2005).

The chemical composition of the untreated iron ore concentrate of the Sishen Iron Ore Mine is given in Table 6.1. XRF spectrometry of the iron ore concentrate revealed a P concentration of 0.17 % mass, a K concentration of 0.17 % mass and a Fe concentration of 96.90 % mass.

Major Elements (Oxides)	% Mass
Silica (SiO ₂)	1.89
Titanium (TiO ₂)	0.08
Aluminium (Al ₂ O ₃)	1.18
Iron (Fe ₂ O ₃)	96.90
Potassium (K ₂ O)	0.17
Phosphorous (P ₂ O ₅)	0.17

The average percentage removal of the major elements from the iron ore concentrate of the Sishen Iron Ore Mine by bioleaching for 10 days using *A. niger* at different pulp densities is given in Table 7.2. The maximum P removal of 23.53±5.88% could be achieved using a pulp density of 1/2, while a maximum P removal of 11.76±6.79% and 5.88±5.88% was achieved using 1/1 and 1/5 pulp densities respectively. As a result of data scatter due to sampling and assay variation, however, the actual maximum P removal may be as low as 6.67% using a pulp density of 1/2. At the same time a maximum K removal of 17.65±5.88% was also achieved using a pulp density of 1/2, while only 5.88±5.88% K removal was possible for both the 1/1 and 1/5 pulp densities.

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The maximum K removal however, may be as low as 6.25% using a pulp density of 1/2 as a result of data scatter due to sampling and assay variation. All bioleaching tests in this study proved to be relatively non-reactive towards the iron contained within the ore, as could be seen by the low levels (0.46% - 0.63%) of iron removal from the ore (Table 7.2).

Major Elements	1/1 Pulp Density	1/2 Pulp Density	1/5 Pulp Density
Iron (Fe ₂ O ₃)	0.53	0.63	0.46
Potassium (K ₂ O)	5.88	17.65	5.88
Phosphorous (P ₂ O ₅)	11.76	23.53	5.88

In a previous study by Williams and Cloete (2008) (Chapter 6), chemical leaching using a 1M solution of citric acid at 30°C achieved a maximum P and K removal of 17.65% after a 5 day leaching period, while a 0.75M solution of citric acid at 60°C achieved a P removal of 35.29% and K removal of 17.65% after a 5 day leaching period. The abovementioned results are similar to that reported in this study using a pulp density of 1/2 at 30°C for 10 days. This indicates that by adding *A. niger* to create a bioleaching process, it is not necessary to increase the leaching temperature to 60°C as required by chemical leaching, and also that similar results to what was reported by Williams and Cloete (2008) (Chapter 6) at 30°C was possible at a much lower concentration of citric acid (~0.25M vs 1M).

7.5 Conclusions

Compared to chemical leaching, which requires high concentrations of citric acid and/or high leaching temperatures (Williams and Cloete, 2008) (Chapter 6), this bioleaching process offers a more economical method with similar efficiency for the removal of P and

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K from the iron ore concentrate of the Sishen Iron Ore Mine. This bioleaching process using *A. niger* NRRL 567 requires a pulp density [bioleaching solution (ml)/iron ore (g)] of 1/2 for the most efficient removal of P and K from the iron ore concentrate at 30°C, as the most P (23.53±5.88%) and K (17.65±5.88%) was removed from the iron ore concentrate with only a negligible amount of iron lost due to acid corrosion. Therefore, it is suggested that bioleaching using *A. niger* NRRL 567 is a feasible process for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine.

7.6 References

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CHAPTER 8

CONCLUSIONS

As the progressive depletion of high-grade iron ore deposits, due to the advancing global technologies and civilisation, have been observed throughout the world, it has become necessary to process lower-grade iron ore bodies (Torma, 1986; Ehrlich, 1999; Costa *et al.*, 2003; Jian and Sharma, 2004). Impurities, such as phosphorous (P) and potassium (K), contained within the lower-grade iron ore have a detrimental effect on the steel-making process by damaging the refractory linings of blast furnaces (Yusfin *et al.*, 1999). Steel-making companies in the leading industrial nations have, therefore, established limits on the concentration of alkali's (such as K_2O) in the charge material without changing the smelting practice (Yusfin *et al.*, 1999). Therefore, it has become important to develop an economically viable and environmentally friendly process to reduce the high P and K levels contained in the ore to improve the quality of iron ore that is being exported from the Sishen Iron Ore Mine. Currently such an economically viable biotechnological process for the reduction of P and K present in iron ore does not exist, and would therefore give Sishen Iron Ore Mine a competitive advantage in the international iron ore arena.

Chapter 3

The first step in developing a process for the removal of P and K from the iron ore concentrate was to conduct a population study of the process- and ground water, as well as the iron ore of the mine that would give insight into the microorganisms present in the mine environment. These microorganisms could prove to be useful in the removal of the P and K from the iron ore, as they may have novel metabolic properties, which could enable them to produce acids that may prove invaluable when applied in industrial practice (Gupta and Sharma, 2002; Lesniak *et al.*, 2002). It is hypothesised that indigenous microorganisms already living in the Sishen Iron Ore Mine environment are capable of using the P and K in the iron ore as structural components for their cell walls

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and membranes, as well as many other metabolic processes, such as organic acid production, since the environment selects for them to do so. A community study of the process- and ground water of the Sishen Iron Ore Mine showed the presence of various bacterial species, including *Aeromonas hydrophila*, *Alcaligenes faecalis*, *Brevundimonas vesicularis*, *Acinetobacter junii*, *Pantoea* spp., *Flavobacterium meningosepticum*, *Chryseomonas luteola*, *Enterobacter sakazakii*, *Pseudomonas aeruginosa* and *Herbaspirillum* spp. All of the abovementioned microorganisms have previously been associated with aquatic systems (Pellett *et al.*, 1983; Aspinall and Graham, 1989; Havelaar *et al.*, 1990; Morais and da Costa, 1990; Davis *et al.*, 1994; Römling *et al.*, 1994; Nishio *et al.*, 1998; Squier *et al.*, 2000; Chauret *et al.*, 2001; Lynch *et al.*, 2002; Bomo *et al.*, 2004; Kim *et al.*, 2004; Ozdemir and Baysal, 2004; Connon *et al.*, 2005; Vacca *et al.*, 2005; Canals *et al.*, 2006; Chale-Matsau and Snyman, 2006; Joo *et al.*, 2007). Except for *C. luteola* which may be used for the biosorption of chromium from waste water, there is no indication of bioleaching properties for any of the microorganisms isolated in the process- and ground water systems, and therefore, they should be excluded as bioleaching candidates for the removal of undesirable substances from the iron ore of the Sishen Iron Ore Mine.

Chapter 4

The community study of the iron ore concentrate of the Sishen Iron Ore Mine revealed several bacterial and fungal species present in the Sishen Iron Ore Mine environment. According to phylogeny, the bacterial isolates were closely related to *Herbaspirillum* species, as well as *Acidithiobacillus ferrooxidans*, while the fungal isolates were closely related to *Aureobasidium pullulans*, *Phaeosphaeria nodorum*, *Aspergillus fumigatus*, and *Candida parapsilosis*. The most likely candidate for the removal of P and K from the iron ore concentrate would seem to be *Acidithiobacillus ferrooxidans*, however, this bacterium produces sulphuric acid, which is undesired in the iron ore industry due its corrosive properties. Furthermore, the P and K contained in the iron ore is in a non-sulphidic phase, and therefore, the use of organic acids, such as citric acid, for the removal of these contaminants may have potential (Rawlings, 2005). These organic acids are typically produced by certain types of fungi, such as *Aspergillus niger* (Jianlong,

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2000; Vandenberghe *et al.*, 2000; Rawlings, 2005). Although *A. niger* was not isolated from the iron ore/soil of the Sishen Iron Ore Mine, isolating *A. fumigatus* may indicate that *A. niger* may have the potential to adapt to the environment that prevails at the mine. This would allow the application of *A. niger* for the production of citric acid, which in turn may be used for the removal of P and K from the iron ore concentrate.

Chapter 5

Conventional bioleaching involves the oxidation of insoluble metal sulphides to form corresponding soluble metal sulphates, enabling their removal from complex ore bodies (Rohwerder *et al.*, 2002; Rawlings, 2005). The P and K contained within the iron ore concentrate are, however, in non-sulphidic phases, and therefore, conventional bioleaching processes are not viable for their removal from the ore. Metals in certain non-sulphide minerals, such as the iron ore concentrate of the Sishen Iron Ore Mine may be solubilised by a process of complexation using microbially produced inorganic or organic acids (Rawlings, 2005). Citric acid seemed to be the best leaching candidate for the removal of P and K from the iron ore of the Sishen Iron Ore Mine. Although no P was removed by citric acid during this investigation, further analyses are needed to determine whether higher leaching temperatures would play a role in the removal of P from the iron ore. Organic acids, such as citric acid produced by *Aspergillus niger*, possess several carboxyl groups, and therefore can act as chelating agents (Sayer and Gadd, 2001). These carboxyl groups tend to donate protons (H^+), resulting in negatively charged carboxyl groups that are capable of forming stable complexes with several metal cations, such as copper and zinc (Sayer and Gadd, 2001). Therefore, it is possible that these negatively charged carboxyl groups are able to form stable complexes with the K^+ cations present, while the H^+ cations are able to react with the negatively charged phosphorous, resulting in their removal from the iron ore concentrate.

Chapter 6

Solid substrate- and submerged fermentation using *Aspergillus niger* were compared for the production of citric acid, which is to be used for the chemical leaching of P and K from the iron ore concentrate. During solid substrate- and submerged fermentation using

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A. niger a high concentration of glucose was required to ensure that citric was excreted from the fungal mycelia. The maximum citric acid yield of 54.2 g.kg⁻¹ DPM by solid substrate fermentation and 102.3 g.l⁻¹ by submerged fermentation was attained after a period of 96 h in both processes. The fermentation media of both solid substrate- and submerged fermentation contained similar constituents, with the difference that the submerged fermentation medium contained less of each constituent. In addition, solid substrate fermentation required peat moss as a solid substrate, which increases the costs incurred by using this fermentation process. Therefore, taking all the variable factors into account it is suggested that submerged fermentation be used for citric acid production by *A. niger*, as this fermentation process was found to be more economical and produced more citric acid in the same time.

Chemical leaching of the iron ore concentrate was compared to “heap leaching” of the iron ore, whereby iron ore concentrate was mixed with fermentation medium inoculated with *A. niger* with a v/m ratio of 1/10. Chemical leaching of the iron ore concentrate proved to be more efficient than “heap leaching”, as more P and K was removed from the iron ore concentrate, as well as in a shorter time frame. In addition, using “heap leaching” technology proved to be uneconomical in this case, as growth medium will have to be added every 5 days to enhance the fungal growth. It is suggested that a 1M citric acid leaching solution be used at 60°C for the chemical leaching process, as the most P and K is removed from the iron ore concentrate using these leaching conditions. Therefore, the most economical and efficient chemical leaching process for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine, involves a two-stage process whereby citric acid is produced by *A. niger*, followed by the chemical leaching of the P and K from the iron ore concentrate using a 1M citric acid leaching solution at 60°C.

Chapter 7

Various technologies developed in the last couple of decades include microbial use for the extraction of different valuable metals, which is commonly known as bioleaching (Gilbertson, 2000; Rohwerder *et al.*, 2002). Conventional bioleaching, also known as

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biooxidation, refers to the microbial conversion of insoluble metals into soluble forms (Sand, 2001; Rawlings, 2002, Roberto, 2002). The P and K contained within the iron ore concentrate are, however, in non-sulphidic phases, and therefore, conventional bioleaching processes are not viable for their removal from the ore. Therefore, the use of an alternative bioleaching microorganism was investigated to remove the undesirable P and K from the iron ore concentrate.

The possibility to use *A. niger* as a bioleaching microorganism was investigated, due to its ability to produce organic acids, such as citric acid, which has the ability to remove P and K from the iron ore concentrate by chemical leaching (Chapter 6). Compared to chemical leaching, which requires high concentrations of citric acid and/or high leaching temperatures (Williams and Cloete, 2008) (Chapter 6), bioleaching using *A. niger* offers a more economical method with similar efficiency for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine. This bioleaching process using *A. niger* NRRL 567 requires a pulp density [bioleaching solution (ml)/iron ore (g)] of 1/2 for the most efficient removal of P and K from the iron ore concentrate at 30°C, as the most P (23.53%) and K (17.65%) was removed from the iron ore concentrate with only a negligible amount of iron lost due to acid corrosion. Therefore, it is suggested that bioleaching using *A. niger* NRRL 567 is a feasible process for the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine.

With all results taken into account, the best results in terms of the removal of P and K from the iron ore concentrate of the Sishen Iron Ore Mine was obtained by the chemical leaching of P and K from the iron ore concentrate using a 1M solution of citric acid, which was produced by *A. niger*, at 60°C for 5 days. This method, however, may prove to be uneconomical due to the energy costs involved to maintain the 60°C temperature required for this process. The most economically viable process, although not as efficient as the abovementioned process for the removal of P and K from the iron ore concentrate, proved to be the bioleaching process using *A. niger* NRRL 567 with a bioleaching pulp density of 1/2 at 30°C for 10 days. This is the first report of the use of *A. niger* for use in any bioleaching process.

Conclusions

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