CHAPTER FOUR

DISCUSSIONS ON ISSUES RAISED BY THE ARTICLES

4.1 The Concept of the Thesis

The concept of a “thesis” in its narrower meaning, is a hypothetical proposition that advances and offers to maintain, or which is actually maintained by argument. In the context of a doctoral thesis in a scientific subject as an original set of scientific findings to be defended, suggest an orientation within the traditional approach to science: it requires a set of hypotheses to be tested or research questions to be answered (Thompson, 2004). While thesis in other disciplines relates to a "question" to be answered, engineering theses are however, "problem solving” oriented. Incorrect assumptions during process design which usually have disastrous consequences in hydrometallurgical processing of complex sulphide ore. This thesis provides a problem-solving mineralogical approach for understanding the behavior of low-grade complex sulphide ore during biohydrometallurgical processing and further investigates the mechanisms by which microwave processing improves microbial recovery.

This Chapter discusses each of the articles and their interrelationship as they logically accomplished the objectives of this study. A recap of the rationale of each article is made, and their contributions to achieving the objective of the study and to knowledge are summarized. Arguments for the novelty and contribution of this study to the existing knowledge of process mineralogy as to solving problems associated with biohydrometallurgical processing and microwave treatments of complex sulphide ores are also provided.
4.2 Argument for Research Novelty and Contributions to Knowledge

As indicated in Chapter 1, the primary aim of this research is to provide a mineralogical basis for understanding the biohydrometallurgical route for processing sulphide ores and understanding of the means by which microwave processing improves microbial recovery, using a low-grade Nigerian complex sulphide ore as a case study. To this end, principal issues raised by the articles, as they accomplish the objectives of this study, are discussed in this section.

4.2.1 Applied Mineralogical Studies

Published articles relating applied mineralogical studies comprise articles 1 to 3. Article 1 was aimed at providing information on process mineralogy as applied to the processing of complex sulphide ores and about how it could be used in improving the recovery of sulphide ores. A detailed mineralogical study of the complex sulphide ore deposit located at Ishiagu in the South Eastern part of Nigeria and used in this study was reported in Article 2. This article was aimed at providing relevant mineralogical information on which the processing of the ore could easily be achieved. Article 3 utilized and interpreted mineralogical data on size reduction characteristics, size distribution pattern, degree of mineral liberation, mineralogical and elemental distribution among different size fractions for predicting parameters for which optimal hydrometallurgical recovery of constituent metals could be obtained from low grade complex sulphide ores.

It was found from Article 1 that process mineralogy is an integral part of all the various processing stages and for improving efficiency during ore processing and recovery. It was concluded from this article, that improving recovery should involve interaction and communication between the processor and the mineralogist at each stage of the recovery processes in understanding feed response and product behaviour. For effective communication of information between the mineralogist and the extractive metallurgist for subsequent process optimization, two major issues should be reconciled in accordance with de Vaux (2005). The mineral processor/extractive metallurgist should know more about mineralogy, so that correct questions can be asked thereby assisting the
mineralogist to provide relevant answers that are of use. The mineralogist should also learn more about mineral processing so that efforts can be directed to looking for information that is relevant and not just throw the mineralogical book at a problem.

The need to have a full understanding of mineralogical knowledge of ore deposit, feed material and material flow during processing is concluded in this article to be imperative to developing and employing a sustainable, effective and relatively economical recovering route, and to improving the recovery of the existing process. Despite the array of available techniques (XRD, SEM, XRF, EPMA, LA-ICP-MS, MLA, QEMSCAN, ICP-MS, ICP-OES, etc.) co-existing for process mineralogical studies; this article concluded that not all of them are very suitable for sulphide ore analysis with high accuracy. Although, no single characterization technique can satisfy all the goals and requirements for achieving the absolute mineralogical characterization during sulphide ore processing and recovery, it was found that it is of little use and uneconomical to adopt all characterization techniques for mere comparison of results and effectiveness. This article recommended that a combination of those techniques suitable for improving and optimising base and precious minerals recovery processes should be selected and adopted.

**Article 2** addressed a major problem facing the minerals industry in Nigeria. A large deposit of over 20 million tonnes of complex sulphide minerals is available in Nigeria, especially in Ishiagu (South Eastern part of Nigeria) where this study was carried out. Although sustainable development in the minerals sector has been a serious concern in Nigeria, the mere existence of mineral deposits in this part of the world does not however justify the hope of exploitation and development of the Nigerian solid minerals. Despite concerted efforts being made by the Nigerian government to invite and encourage private sector participation and joint ventures to develop, exploit and stake concessions on these mineral deposits (Ekaette, 2003), not much positive responses have been received. The only few responses are centered on their exploitation and conveyance abroad for processing. Some are semi-processed and exported; while many of those being beneficiated, especially through small-scale illegal mining, have much of their valuable metals lost in tailings.
To a large extent, the processing technologies adopted by the few minerals beneficiation and extractive industries in Nigeria have been unable to give very high concentrate yields and metal recoveries respectively. With the technologies adopted by these few processing industries, a huge amount of valuable metals are also lost in tailings and sludge without paying serious attention to the economic impact these losses have on the country. The non-effective exploitation and processing technologies of these minerals have therefore made them a burden instead of a blessing (Adekoya, 1995). This resulted from the fact that attention has not been paid by the small scale exploiting entrepreneurs to the study, determination and evaluation of the mineralization of these ores at various locations. The underlying mineralogical principles for understanding the recovery processes were not fully understood for process optimization and effectiveness.

The detailed mineralogical study of the deposit reported in this article is therefore, a significant contribution to knowledge as it revealed interesting and valuable information on the type of sulphide ores occurring in this part of the world, which has not been known before. This information would thus provide useful guide for designing effective processing techniques for the ore deposit and to aid the understanding of the recovery processes of its constituent metals. It is also of very high value to the Nigerian Government, in enhancing sustainable development in the minerals industry.

Article 3 investigated an important aspect of applied mineralogy which is often not considered important during mineralogical studies. Most mineralogical studies often involve particle size analysis and liberation studies, while studies on elemental distribution amongst varying particle size ranges are however not often given much consideration. Particle size analysis is very relevant and is of great importance in the design of an optimal process for mineral processing and extraction. Several studies are still under investigation to determine its effects on hydrometallurgical recovery processes (Ozcán et al., 2000; Hossain et al., 2004; Deveci, 2004; Muñoz et al., 2007; Jorjani et al., 2007; Mellado and Cisternas, 2008; Demir and Dönmez, 2008; Kasaini et al., 2008). However, particle size alone may not reveal relevant and mineralogical information
required for process optimization. Particle size analysis offers little information about the
breakage characteristics of the material within the comminution system (Fuerstenau et al.,
1999). Moreover, particle size does not provide detailed information on the distribution of
the constituent minerals and elements within the various size ranges to ascertain the
degree of the reduction of specified minerals.

This study therefore contributed to the understanding on the role played by applied
mineralogy in determining an optimal hydrometallurgical recovery process for base
metals from complex sulphide ores. It also revealed that the choice of a grinding route for
an ore is largely determined by the mineralogical properties of the ore. Since mineral
dissolution behaviour depends mostly on their chemical and mineralogical compositions,
owing to the differences in the electrochemical galvanic interactions, as galvanic
interactions depend on the mineralogical association between the phases present (Cruz et
al., 2005), this article provided a mineralogical basis for which the recovery at any given
particle size could be determined and to ascertain relative recovery of the specified metal.
Minerals and elemental distribution among the various particle sizes provided information
on which a hydrometallurgist could base his choice of extraction route.

The three published articles on applied mineralogical studies formed strong foundational
and knowledge based tool for this study. Process mineralogy was concluded to be a useful
tool for choosing suitable flowsheet, improving hydrometallurgical recovery of sulphide
ores, and for optimizing and improving plant performance. The underlying principle for
understanding the recovery processes and interpreting bioleaching results is understood
from the detailed mineralogical characterization study. The knowledge of
mineralogical/chemical composition, size, morphology and association with other
minerals obtained from the characterization of the ore, provides insights and information
on the characteristics, type, nature and amount of minerals and elements present within
the ore at different locations. This knowledge thus, permit an assessment and
determination of the optimal processing route for its constituent minerals/metals. This
becomes an important factor in overcoming wrong assumptions during process design as
it gives a sound background of the ore and in the understanding of the behavior of the ore
during bioleaching processes.

The applied mineralogical study revealed that the response of the constituent minerals of the ore to breaking is largely determined by their mineralogical properties, as there were variations in elemental and mineralogical distributions within the different particle size fractions. The prediction made for optimal hydrometallurgical selection, design and recovery of the constituent’s metals using mineralogical differences amongst the constituent minerals of the size fractions could, therefore, be used in the plant for choosing suitable grinding circuit. This could thus, assist in reducing energy cost, reducing grinding times, and optimizing grinding circuit to obtain particle sizes that will give optimum leaching in the leaching circuits. Variable choices that a mineral processor can make in deciding suitable comminution process for obtaining a particular amount of size(s) can easily be made, while relative percentages of metal that could be recovered at a given particle size can also easily be determined. Since there is variation in the amounts of each element within the particle sizes, estimation of percentage metal recovered would be a quotient of the percentage of such metal within a particular particle size. At a glance, the effects of associated metal(s) within a particular particle size on the recovery of metal are easily predicted. For instance, the bioleaching of copper and zinc would be highest where the amount of iron is widely distributed, while the presence of silica would affect the dissolution process, as it will cause a shift in iron mobilization.

4.2.2 Interaction of Ore Mineralogy and Bioleaching Process

Three published articles dealing with the subject of ore mineralogy and its effects on bioleaching process of low grade complex sulphide comprise articles 4 to 6. **Article 4** provided an understanding of the influence of particle size and ore mineralogy on the microbial dissolution behaviour of the ore by utilizing mineralogical data on the variations in mineral and elemental distribution within particle size fractions of -53, 53, 75 and 106 µm reported in **Article 3**. A further understanding of the effects of particle size on bioleaching of the low-grade complex sulphide ore initially reported in **Article 4** is provided in **Article 5** by studying the interplay of ore mineralogy, particle size, and
mineral phase distribution within varying particle sizes on bioleaching behaviour through bioleaching experiments, electrochemical techniques and scanning electron microscopy methods. Based on the results obtained from Article 4 and 5, the role that ore mineralogy plays in understanding and optimizing the conditions favouring the bioleaching of complex sulphide ore was reported in Article 6 by studying bioleaching behaviours at various influencing process parameters including particle size, stirring speed, volume of inoculum, pulp density, and pH.

Article 4 contributed and added a new dimension to the numerous reported investigations aimed at explaining the effects of particle size on bioleaching of sulphide minerals. Particle size remained a critical and a major controlling factor while making a choice of bioleaching process (Pradha et al., 2008), but a thorough understanding of its effects during leaching is not fully known. Both larger and smaller particle size fractions have been reported to have inhibitory effects on both bacterial activity and ferrous oxidation, and several arguments have thus been put forward to justify higher recoveries at either larger or smaller particle sizes (Torma et al., 1972; Pinches et al., 1976; Nikolov et al., 1988; Shrihari et al., 1991; Shrihari et al., 1995; Gonzalez et al., 1999; Mazuelos et al., 2001; Makita et al., 2004; Deveci, 2004; Hossain et al., 2004; Gonzalez et al., 2004; Shi and Fang, 2005; Shi et al., 2005; Mousavi et al., 2006; Munoz et al., 2007; Olson and Clark, 2008). As there is yet to be a conclusion on the interrelationship between particle size and bioleaching microbes and the effects of particle size on the overall bioleaching behaviour, this article gave clarifications on the interplay of ore mineralogy and particle size on bioleaching.

The understanding of the bioleaching process amongst the varying particle sizes was concluded in this article to be dependent on mineralogical differences and elemental distributions within the various particle sizes. The differences in the chemical and mineralogical compositions affected dissolution at these size fractions chiefly because mineral reactivity depended on the chemical compositions of the ore. As a result of the differences in the mineralogical compositions at different particle sizes, there existed variation in the microbial-mineral interaction phenomena. This possibly resulted from the
differences in the electrochemical galvanic interactions within the varying particle sizes, as galvanic interactions depend on the mineralogical association between the phases present. Although dissolution studies on galvanic interactions in bioleaching systems have been studied and reported by some authors (Mehta and Murr, 1982; Valix et al., 2001; da Silva et al., 2003), it is however observed that no studies have taken into account, and have been reported on galvanic interactions at varying particle sizes resulting from the difference in the mineralogical compositions. The differences in dissolution behaviour resulting from galvanic interactions at different particle sizes reported in this article is therefore a substantial contribution to knowledge on the effects of particle size on bioleaching.

An insight to solving the controversial issue on the interrelationship between particle size and bioleaching which before now remained unanswered, but was partly dealt within article 4, is given in Article 5. Numerous studies aimed at explaining particle size effects on bioleaching (Nemati et al., 2000; Shi and Fang, 2005; Shi et al., 2005; Mousavi et al., 2006; Munoz et al., 2007; Olson and Clark, 2008; Pradhan et al., 2008) have all been centered on the physico-chemical factors relating to particle size. The overall effect of these factors in obtaining optimum particle size and in understanding the interrelationship between microbial attack on minerals and oxidation behaviour is yet to be fully known and predicted. Although an understanding on the effects of particle size have been provided in article 4 from a mineralogical perspective, a better understanding of mineralogical influence on bioleaching is given in this article from an electrochemical viewpoint. As galvanic interactions depend on the mineralogical association between the phases present (Cruz et al., 2005), there existed variations in the electrochemical galvanic interactions at varying particle size fractions due to mineralogical and elemental compositions at different particle sizes.

This Article reported a major discrepancy but consistent and clarifying bioleaching and electrochemical behaviour. Similar to results obtained in article 4, bioleaching studies revealed highest recoveries at a particle size fraction of 75 µm. Electrochemical investigations on the other hand, revealed highest dissolution at a particle size of 106 µm.
Electrochemical and scanning electron microscopy studies however, showed similar results of highest bioleaching and bacterial attack at sphalerite-rich phase but least at the galena-rich complex phase. The discrepancies and similarity in the bioleaching and electrochemical behaviour within particle sizes fractions is therefore very novel in the field of bioleaching and thus it is a major and significant contribution to knowledge.

**Article 6** revealed fundamental information that could aid and allow biohydrometallurgical process optimization and guide decisions on bioleaching parameters. As a result of the comparative higher operating cost, solution evaporation and possible environmental problems associated with thermophiles bioleaching, attention has been focussed on investigating parameters that could increase the dissolution rates of the mesophiles through the use of mixed mesophilic cultures (Rodriguez *et al.*, 2003a, 2003b, 2003c; Sampson, *et al.*, 2005; Akcil *et al.*, 2007). Despite the knowledge of physical bioleaching parameters (particle size, stirring speed, leaching time, pulp density, and volume of inoculum), a lack of mineralogical oriented understanding on bioleaching process still exist. It was concluded from this article that ore mineralogy played a major role in understanding the influence of the process parameters on the bioleaching rates. The information on mineralogical effects and bioleaching as well as electrochemical influences reported in **Articles 4 and 5**, brought together and applied for optimizing conditions favouring bioleaching at varying bioleaching process parameters and as reported in **Article 6** is therefore a substantial contribution to existing knowledge on optimizing bioleaching parameters.

The published articles on the interaction between ore mineralogy and bioleaching process corroborate the applied mineralogical studies and the predictions made on optimal recovery of the constituent’s metals using mineralogical differences amongst the constituent minerals of the size fractions. It was concluded that particle size distribution alone did not provide relevant information for understanding bioleaching behaviour. Mineralogical information on the mineralogical and elemental distribution within the various particle sizes did not only affect the mineral–microbe interaction and the galvanic
interaction, but also precipitate formation on the surfaces. This in turn plays vital role on the bioleaching process.

Higher galena content at lower particle sizes led to a higher pH during bioleaching, while higher silica contents also hindered bacterial activities and iron mobility. Higher siderite, galena and silica contents at lower particle size fractions resulted in increased amounts of precipitates (especially jarosite, anglesite and sulphur). Since the interaction between microbes and minerals within an aqueous solvent involves a redox process, the oxidation product goes into aqueous solution while the reduced products at the cathode form an insoluble precipitates. These insoluble precipitates therefore, hindered bacterial growth and access to the metal contents of the ore. In addition to physical parameters favouring the highest recovery at particle sizes of 75 µm, a reduction in galena and silica contents coupled with the amount of iron within the sphalerite matrix, enhanced dissolution of the zinc and copper from the ore. These observations were confirmed by both the electrochemical and SEM studies. Electrochemical investigations as well as SEM studies showed that sphalerite rich phase had the highest bioleaching rate and bacterial attack while galena-rich complex phase had the least.

Owing to the observation that the types and amounts of mineral present determines the reactivity and ascertains the relative recovery of specified metal, mineralogical variations within the size fractions therefore becomes a useful tool that would govern the overall bioleaching design process. Coupled with the information on the detailed mineralogical characterization studies, where very good mineral liberation was attained at 75 µm, the optimal bioleaching obtained at 75 µm suggested that grinding the ore finer than 75 µm may not necessarily lead to higher recovery, but to a mere over grinding. While lower particle size fractions resulted in decreased bioleaching, using particle sizes fraction lower than 75 µm will not only lead to poor recoveries, but also an increased production costs that would be incurred from time and energy spent on over milling.
4.2.3 Interplay of Mineralogy, Microwave Heating and Dissolution

Two published articles relating to the subject of ore mineralogy and microwave processing, and their corresponding effects on ore dissolution comprise of articles 7 and 8. Article 7 provided an understanding from a mineralogical viewpoint on the means by which microwave treatment enhances comminution and improves hydrometallurgical recovery of complex sulphide ore. A further clarification on the influence of microwave heating on the processing and dissolution behaviour reported in Article 7 is provided in Article 8. Mineralogical information on the mechanisms by which microwave pretreatment improve the bioleaching behaviour of low grade complex sulphide ore was provided in this article, while an interpretation of the interrelationship between mineralogy, microwave processing, and bioleaching process was made.

As the mechanisms by which microwaves interact with chemical systems have been a matter of controversy over the years (Joret et al., 1997; Al-Harahsheh et al.; 2005) and there is still no strong agreement on the mechanism of the interaction of microwaves with hydrometallurgical systems (Al-Harahsheh and Kingman, 2004), coupled with insufficient research information for which industrial systems of microwave application in sulphide ore recovery could be understood, thus providing basis for its industrial acceptability, Article 7 and 8 provided useful information for optimizing the operation of microwave processing, minimum energy consumption and improving dissolution effectiveness. Article 7 provided an understanding of the interaction between ore mineralogy and microwave irradiation, their resultant effects on heating behaviour, size reduction, size and elemental distribution amongst particle size fractions, and ore dissolution behaviour. Investigations on the interplay of mineralogy and microwave irradiation, their duo effects on ore dissolution behaviour initiated and partly dealt with in article 4 is culminated in Article 8 on the bioleaching behaviour of the microwaved heated ore.

These Articles revealed that the application of microwave heating has a beneficial effect on the processing behaviour complex sulphide ore and its hydrometallurgical recovery. Ore mineralogy and microwave irradiation had dual influences on the heating
characteristics, size reduction, and the effectiveness of microwave treatment in improving dissolution. The complexities in the mineralogical associations of complex sulphide ores resulted in different responses to microwave heating, thereby building-up internal stresses within the ore and thus result in induced cracks within the matrices of the ore. Although microwave irradiation did not cause any significant mineral phase change, the peak intensities of some of the sulphide mineral content (sphalerite and pyrite) of the ore were altered. Phase change promoted galvanic interaction within the system and thus improved electrochemical behaviour; while the decrease in the amounts of sulphur contents in the microwave treated samples reduced the inhibitory effects of sulphur on the ore dissolution process. Crack propagation increased electrochemical active sites and the preferential sites for microbial activities, which increased the initiation and acceleration of microbial dissolution process.

From the industrial view point, information obtained from these articles is significantly important during flow sheet design. Optimized microwave heating process parameters investigated in these studies revealed that heating at optimal microwave power of 1100W for 11 minutes aided comminution but also resulted in larger amounts of fine particles. Based on information obtained from the bioleaching studies reported in article 4 and 6 it was concluded that adopting a microwave processing parameters having too much fines of less than 38 µm would not be industrially economical and practically effective for bioleaching process. The need to carefully select a route that could result in optimal processing and recovery therefore prompted the consideration and the adoption of the most economical heating route for optimum process selection and design. This information guided the consideration and selection of microwave heating at 1100W for 5 minutes as the most suitable microwave processing operation where optimal size distribution with lower amounts of fines and higher amounts of particle size fraction of 75 µm was obtained at lower energy cost. Thus, for optimum and technical microwave pretreatment at least processing cost, optimum microwave processing parameters should not be only based on microwave assisted comminution, but also microwave assisted optimum size and elemental distribution amongst the size fractions.
4.3 Conclusions

A number of investigations were carried out in this study to provide a problem-solving mineralogical approach for understanding the role that ore mineralogy plays in the biohydrometallurgical processing of low-grade complex sulphide ores, and means by which microwave processing improves microbial recovery, using a low grade ore from Nigeria as a case study. The study carefully considered all the research questions and the set aim and objectives. Based on the results obtained from the present study, the following conclusions could be drawn:

Although arrays of available characterization techniques co-exist for process mineralogical studies, it is very necessary that a combination of relevant techniques suitable for improving and optimising hydrometallurgical processing of complex sulphide ore be selected and adopted. The combination of characterization techniques used in this study is therefore very useful in providing relevant information needed for understanding the biohydrometallurgical recovery of the Nigerian low-grade complex sulphide ore that was used as a case study for this research.

Applied mineralogical study played a major role in determining an optimal hydrometallurgical recovery process for base metals from complex sulphide ores. It also showed that the choice of a grinding process is largely determined by the mineralogical properties of the ore.

Particle size distribution solely could not provide relevant mineralogical information for understanding bioleaching behaviour. Mineralogical information on elemental and minerals phases’ distribution within varying particle sizes influenced microbe-mineral’s reactivity at various size ranges. The differences in metal dissipations obtained at various particle size fractions is attributed to the variation in the galvanic behaviour within varying particle size fractions resulting from the differences in their mineralogical compositions. Therefore, to obtain optimum results during base metals recovery from complex sulphide ore, processing must start from a completely detailed mineralogical study.
The discrepancies in the dissolutions within particle sizes obtained from bioleaching experiments and electrochemical studies were consistent with and attributed both to the physical and mineralogical influences. The combined effects of mineralogical variation, precipitation phenomenon as well as the physico-chemical effect of particle size, controlled bioleaching behaviour, while galvanic interaction resulting from variations in mineralogical distribution within particle size fractions controlled the electrochemical behaviour of the ore.

The application of microwave irradiation improves the processing behaviour of complex sulphide ore and thus hold potential for improving biohydrometallurgical process efficiency. Ore mineralogy and microwave heating have shown to have dual influences on the heating characteristics, size reduction, and the effectiveness of microwave treatment in improving dissolution. An increase in dissolution of the microwaved treated samples was attributed to phase changes in the ore which promoted galvanic interaction within the system, decrease in the amounts of sulphur contents, and an increase in electrochemical and microbial growth sites resulting from an increase in the number of cracks induced by microwave heating.

Conclusively, this study showed that applied mineralogy provided useful information about the Nigerian complex sulphide ore that aided the understanding, explanation and optimization of its bioleaching process. Differences in the mineralogical property of the constituent minerals resulted in varying response of the ore to milling that lead to variations in the deportments of the constituent minerals amongst the varying particle size fractions. The differences in the mineral phases amongst the particle size fractions thus lead to variations in the bioleaching and precipitate formation behaviour at these size fractions due to variations in their galvanic interactions. In addition, mineralogical differences within the ore affected microwave pretreatment while microwave irradiation also slightly modified the mineralogy of the ore. Mineralogical differences caused an uneven heating within the ore that resulted into stress built-up which lead to micro-crack formation while microwave interaction cause relative increase in pyrite phase and partial oxidation and a decrease in the sulphur contents, thus improving bioleaching.
4.4 Recommendations

1. Although the combination of characterization techniques used in this study was very useful in providing relevant information needed for understanding recovery processes, the results showed that the characterization techniques are semi-quantitative in nature. Therefore, in order to effectively avoid and overcome faulty assumptions during the recovery process, it is recommended that a further detailed and absolute quantitative analysis of the ore deposit using alternative methods (e.g. image analysis, MLA, QEMSCAN) be carried out. This should also be used in characterizing the various particle sizes and the bulk mineral phases before and after microbial attack.

2. Since ore deposits are heterogeneous in nature, it is recommended that further characterization should be done and constantly repeated, in order to ascertain the ore’s constituents and changes in mineralogy within the deposit, at other locations and as it undergoes successive exploitation.

3. When critical decisions are being made on biohydrometallurgical recovery processes, attention should not be exclusively based on particle sizes, but more on the distribution of the constituent minerals and elements within the particle size fractions.

4. For optimum and technical microwave pretreatment at least processing cost, optimum microwave processing parameters should not be only based on microwave assisted comminution, but also microwave assisted optimum size and elemental distribution amongst the size fractions.

5. Further studies on other accelerating parameters of oxygen and carbon dioxide favouring the bioleaching efficiencies of a mixed culture of mesophiles on zinc and copper should be carried out. Growths and attachments of the mixed culture of mesophiles to the sulphide ore at varying particle sizes and the varying bulk minerals phases should be carried out to further understand reactivity and the mechanism(s) involved in the bioleaching processes.