Potential pre-treatment and processing routes for recovery of gold from complex (refractory) gold ores. A review

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Abstract

The depletion of high grade and easily extractable gold ores has inspired development of innovative approaches for sustainable beneficiation of complex (refractory) gold ores. A complex gold ore is generally defined as an ore that is difficult to treat by using the conventional metallurgical unit operations. This difficulty is mainly due to their complex mineralogy that is associated with a low degree of liberation. Mineralogical characterisation strongly assists in defining the amenability of the complex ore to conventional treatment processes. This paper reviews the currently available pre-treatment and processing routes in order to determine future research in the treatment and processing of complex gold ores. The overall goal is to inspire knowledge improvement for the development of a commercially effective technique.

Keywords
Complex gold ore, Sustainable beneficiation, processing, conventional treatment

1. Introduction
Gold is a noble metal with excellent physical and chemical properties and is therefore found in nature in its pure metallic form (Adams, 2016). However, the rapid depletion of amenable gold ores has alert researchers to come up with effective techniques in extracting gold from the refractory/ complex ores.

Complex ores are defined as the ores that are difficult to treat by using the conventional metallurgical unit operations largely due to their complex mineralogy. Complex ores can be conveniently classified as cyanide consuming, oxygen consuming or preg-robbing (Ilyas & Lee, 2018). Cyanide consuming ores are not economical and environmentally friendly as they require high concentrations of cyanide for leaching. This is mainly due to the presence of other minerals species such as silver and copper minerals that complex with cyanide. Cyanide consuming ores have low recoveries and often require a pre-treatment step to remove the metals that compete with gold for cyanide. Carbonaceous material such as wood and organic carbon adsorb dissolved gold from solution during leaching and act like activated carbon hence the name 'preg-robbing'. This results in reduced gold extractions during leaching to less than 80% (Marsden & House, 2009). Carbonaceous gold ores require pre-treatment before cyanidation and methods such as chemical oxidation, bioleaching, roasting and others can be employed (Afenya, 1991). Complex ores can also be termed refractory as they often give very poor recoveries.

Refractory gold ores can be defined as those ores that give less than 80% gold recovery with simple cyanidation when ground to a conventional size of 80%-75µm (Yannopoulos, 1991). The major causes of refractoriness are physically locked, chemically locked gold and passivation of gold (Asamoah, 2014).

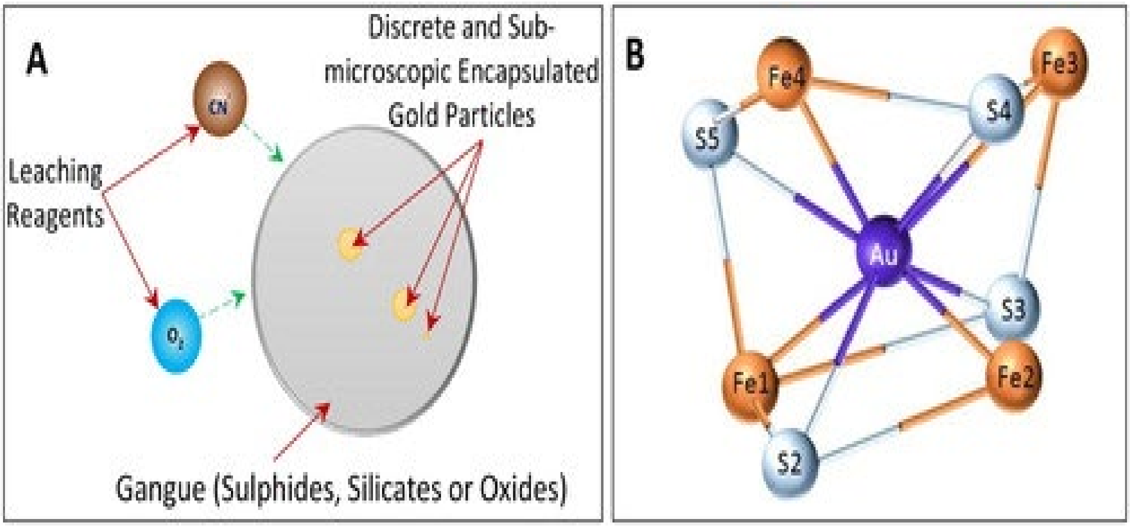

Figure 1. Schematic diagram of: (A) physically locked gold in gangue mineral; (B) chemically locked gold in pyrite interstitial lattice site (Asamoah et al. 2014; Chen et al. 2014).

Refractory ores also require pre-treatment as they commonly contain organic carbon or/and sulphide minerals. Some of the pre-treatment processes applied in industry are going to be reviewed in this paper. Refractory gold ores can be classified according to the proportion of gold recovered as shown in Table1.

Table 1: Classification of Refractory Gold Ores based the proportion of gold recovered

Classification	**Gold recovery**
Free milling	More than 95%
Mildly refractory	80-95%
Moderately refractory	50- 80%
Highly refractory	Less than 50%

The insusceptibility of gold ores to conventional treatment processes is defined by the mineralogical characterisation of the ore (Yannopoulos 1991). Consequently, complexities of ore mineralogy pose a lot of mineral processing challenges (Feng and Deventer, 2010). Gold can be found in complex sulfide minerals in particular, pyrite and arsenopyrite (Asamoah et al, 2018). In refractory gold ores, the gold is highly encapsulated in the sulfide matrix and pre-treatment is an important process to recover gold from the sulfide minerals. The sulfide minerals interfere with recovery of gold thus it is imperative to remove the sulfide minerals prior to leaching. The most employed pre-treatment methods are flotation and roasting. In order to leach valuable metals from sulfide minerals, there is need for surface oxidation of pyrite The gold present in sulfide minerals can be divided into visible gold and invisible gold where visible gold can be observed with an optical microscope and invisible gold is very difficult to observe with these microscopes. Formation of a passive layer on the mineral surface hinders gold recovery from complex sulfide minerals (Cho et al, 2020).

Gold can also be found in Arsenic-bearing refractory gold ores. The ores have stones where gold is locked up in matrix and are extremely difficult to deal with. In the stones, gold leaching rate by conventional gold extraction processes is very low. The gold in such ores is very fine and is wrapped with arsenic making it difficult for the leach reagents to reach it in conventional leaching process. The gold ores that contain As must be crushed in order to expose the gold for leaching with an appropriate gold leaching agent (Yanget al, (2008); Zhou et al, 2009)

In order to maintain the sustainable use of gold resources, effective pre- treatment and processing of complex gold ores is urgently required. This project aims to review on the techniques currently being employed in order to determine research gaps for sustainable processing of refractory gold ores.

2. Pre-treatment of Refractory Gold Ores

Improvements in mineral processing technology would lead to a lot of benefits that include but not limited to improved energy efficiency, reduced emissions to the environment, improved worker health and safety in processing activities and increased productivity. It is therefore imperative that future research must address these issues. Microwave technology is one such technology which satisfies most of the benefits outlined (Appleton et al, 2005)

2.1 Microwave pre- treatment of refractory gold ores

Most of refractory gold occurs within sulphide minerals such as FeS_2 and FeAsS and are treated by roasting, pressure leaching or bacterial leaching to render the gold amenable to recovery by subsequent treatment techniques (Haque, 1987). The microwave process has been reported as an alternative for the roasting process in the processing of gold ores. The process has many advantages, such as selectivity to specific substances, rapid and uniform heat transfer, no direct contact between the heating source and the heated material , reduced equipment size and the opportunity for the production of less waste thus economical and environmentally friendly (Jones et al, 2002). Exposure of refractory gold ores to microwave energy will result in the oxidation of the pyrites hence their decomposition. This will also result in considerable reduction of the refractoriness of the ore and reduce the amount of sulfides in the ore thereby increasing the ore's amenability to conventional treatment techniques (Haque, 1987). Although the use of microwave technology is attractive, it will only be beneficial under certain conditions whereby the key benefits of microwave heating over conventional heating methods are utilised.

2.2 Roasting Oxidation Pre- treatment

The principle employed in roasting oxidation pre- treatment is to destroy the ores tissue and expose the gold by the means of roasting. This results in improved gold cyanide leaching rate. Some of the advantages of the roasting process are mature and reliable technology, adaptability and simple operation. However during roasting it is easy to form secondary wrapping that reduces leaching rate of gold in the roasting process, and also releases gases such as SO_2 and As_2O_3 that are serious environmental pollutants. Also, roasting treatment involves the production of sulphuric acid in ores with a high sulphide content and in ores with low sulphide content it requires gas purification equipment. In some instances, roasting pre-oxidation can result in very low metal recovery. There is need therefore to research on ways of improving and developing the roasting process (Liu, 2005). The sulphide and carbon roasting can be respectively represented as:

$$2MS + 3O_2 \rightarrow 2MO + 2SO_2 \qquad [1]$$

$$C + O_2 \rightarrow CO_2 \qquad [2]$$

(Ilyas & Lee, 2018)

2.3 Chemical pre- treatment

Chemical treatment is another pre- treatment method and has advantages such as the absence of secondary leaching issues caused by under burning and over-burning, well-adapted and a wide selection of reagents according to different ores. However, its limitations include cost of reagents, cost of materials of construction and environmental concerns. Chemical pre- treatment can be divided into alkaline and acid leaching pre-treatments. It can be further divided into atmospheric pressure and high pressure pre-treatments depending on the reaction conditions. Acid treatment has low expense compared with roasting pre-treatment and pressure oxidation however, this method has not yet been used in industrial applications because of some technology and equipment problems (Nie, 1997)

2.4 Wet Chlorination

In wet chlorination chlorine (or chlorine oxidant) is used in the treatment of Arsenic-bearing refract-tory gold ore. The water chlorination is employed to leach the gold and gold leaching rate can reach as high as 91.48%. However high cost of chlorides and corrosion of equipment are the main disadvantages in the application of wet chlorination. (Meng et al, 2002)

2.5 HNO3 Catalyzing Oxidation Decomposition Method

Nitric acid is employed as the most efficient oxidant for pyrite, arsenopyrite and nonferrous metal sulfide. In this method, nitric acid acts as a catalyst and oxidant of spyrite and arsenical pyrite under low temperatures and pressure. Trial experiments have been conducted using the HNO3 oxidation pre-treatment technology and results showed that time needed for oxidation pre-treatment was short. It is however temperature and pressure controlled and the problem of nitric acid regeneration is yet to be solved (Wang and Liu, 2000; Li, 2003)

2.6 Pressure Oxidation

This is a more mature pre- treatment process. It exposes the gold by oxidizing and decomposing gold bearing sulfide under conditions of high temperature and pressure. High temperature and pressure are employed to avoid the generation of sulphur which is bad for cyanidation leaching. . The process can be carried out in both acidic and alkaline medium. The process can also be applied to raw ores and concentrates. The advantages of pressure oxidation include: soluble product of oxidation, complete decomposition reaction, environmentally friendly and can be employed on a large scale. However, its drawbacks include the need for high cost equipment and materials, security risks and expensive to maintain. Also, when not carefully monitored, it produces sulfur that reduces the recovery of gold and method not suitable for refractory gold ore bearing organic carbon (Fraser et al, 1991). The main oxidation reactions in the high pressure vessels can be expressed as:

$2FeS_2 + O_2 + 4H^+ \rightarrow 2Fe^{2+} + 4S + 2H_2O$ [3]

$2Fe_7S_8 + 7O_2 + 28H^+ \rightarrow 14Fe^{2+} + 16S + 14H_2O$ [4]

$4FeAsS + 5O_2 + 8H^+ \rightarrow 4Fe^{2+} + 4HAsO_2 + 4S + 2H_2O$ [5]

$4CuFeS_2 + 3O_2 + 12H^+ \rightarrow 4Cu^+ + 4Fe^{2+} + 8S + 6H_2O$ [6] (Ilyas & Lee, 2018)

2.7 Bacterial Pre-oxidation

The method is employed to pre-treat refractory gold ores by oxidation. After oxidation, the arsenic is then removed from solution. The process is showed in Figure 2.

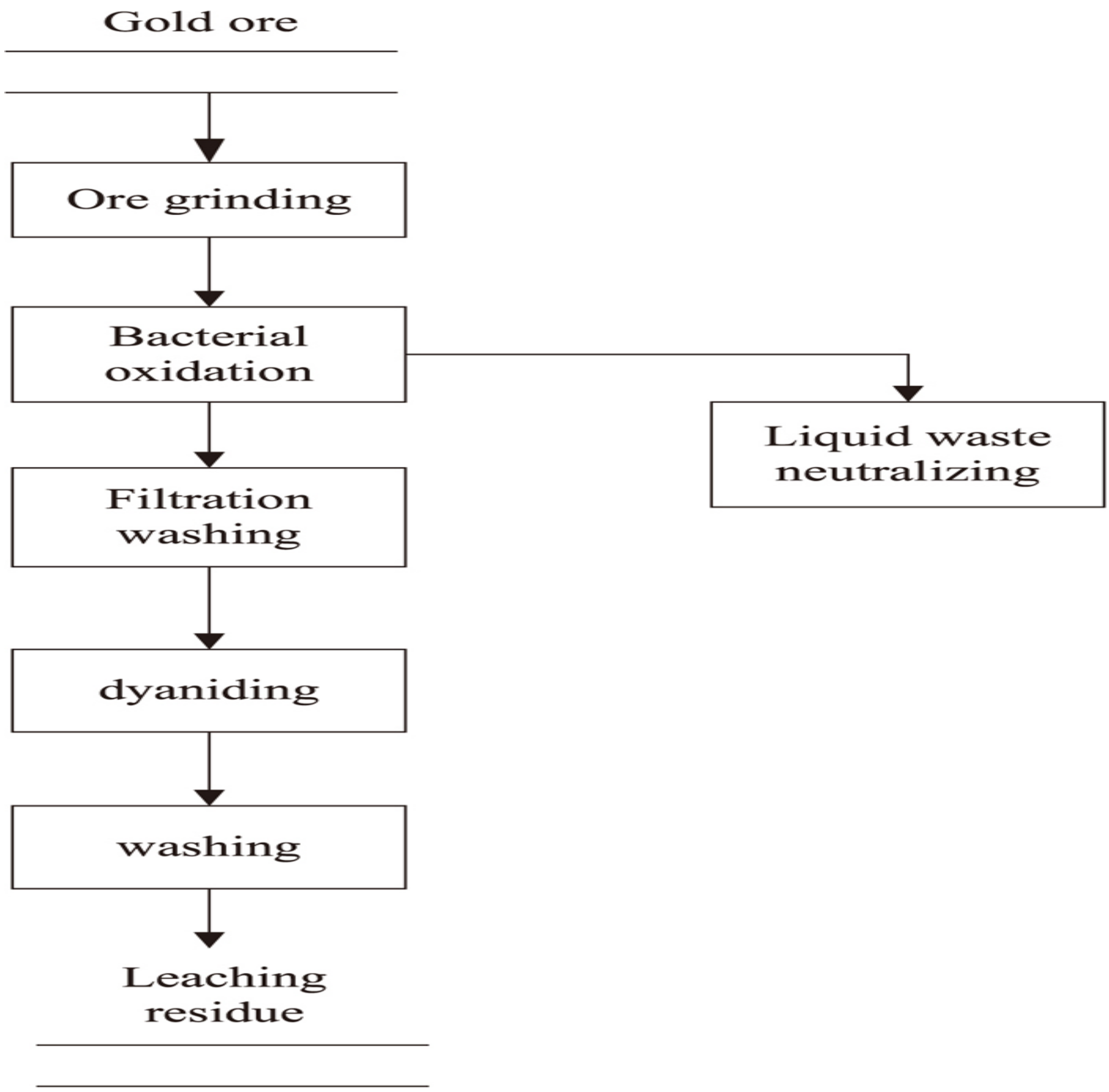

Figure 2. Block diagram for Bacterial Pre-oxidation process (Nan et al, 2014)

Bacterial oxidation for pyrite and arsenopyrite can be represented as:

$FeS_2 + 3.5O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4$ [7]

$FeS_2 + H_2SO_4 + 0.5O_2 \rightarrow FeSO_4 + H_2O + S_2$ [8]

$FeAsS + 5.5O_2 + 3H_2O \rightarrow 2FeSO_4 + 2H_3AsO_3$ [9]

$2FeSO_4 + 0.5O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O$ [10]

$H_3AsO_3 + 0.5O_2 \rightarrow H_3AsO_4$ [11]

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \quad [12]$$

(Yannopoulos, 1991)

Temperature, particle size, pulp density, pH and ore mineralogy are the main factors affecting the rate of biological oxidation and these need to be optimised. It is a recommended process because it requires small investment, low cost, it is a simple method, easy to operate and environmentally friendly. It can also be employed in low grade ore bearing arsenic where it improves the heap leaching rate. However, low pulp density, corrosion of iron, high temperature sensitivity and low processing speed are encountered during Bacterial pre-oxidation (Bailey and Handford, 1994).

3. Processing of refractory gold ores

3.1 Pyro-metallurgical gold recovery processes

Pyro-metallurgical processing involves the smelting of gold ore in a furnace at high temperature for a certain period of time. The pyro metallurgical recovery process is cost, energy and time inefficient, and also releases toxic gases, such as sulphur dioxide (Syed, 2012).

3.2 Hydrometallurgical gold recovery processes

The mostly practiced beneficiation process of refractory gold is the leaching with cyanide (Brooy et al, 1994; Vaughan and Kyin, 2004; Moses and Peterson, 2000). The dissolution of gold in cyanide is best described by heterogeneous reactions which occur at the solid-liquid interfaces. This can be outlined as follows:

- Oxygen absorption in solution
- Oxygen and dissolved cyanide transportation to the solid-liquid interface
- Adsorption via the Nernst boundary layer of CN^- and O_2 onto the solid surface
- Electrochemical reaction
- Desorption of products from the surface of the solid
- Reaction products transportation to the bulk solution (Ilyas & Lee, 2018)

Figure 3 further expresses these steps.

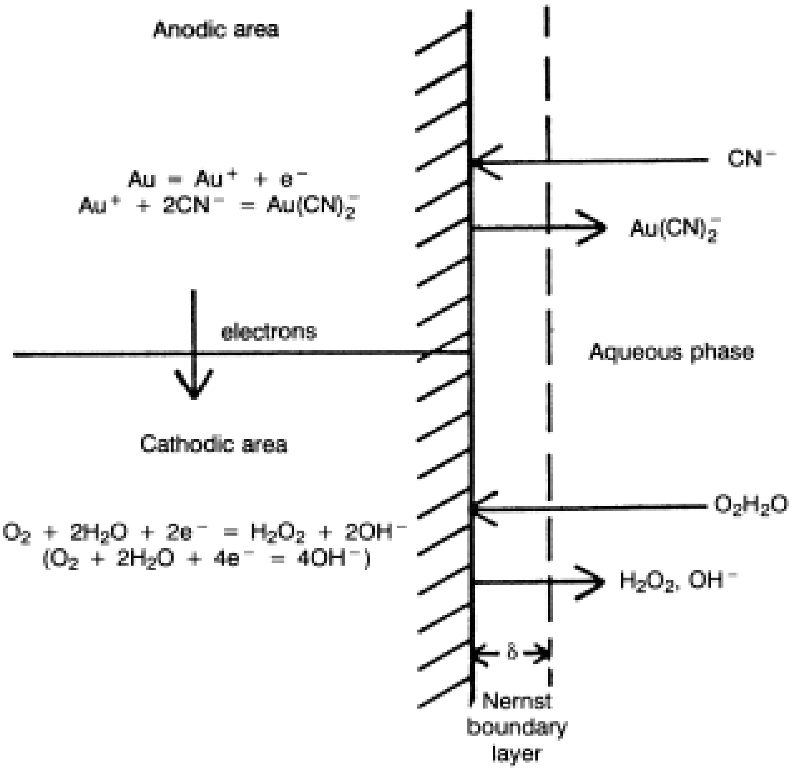

Figure 3. Illustration of gold dissolution mechanism in cyanide (Yannopoulos, 1991)

Although leaching is easily controlled and highly predictable, it is costly and uses toxic chemicals such as cyanide and is environmentally unfriendly. Froth flotation has thus been employed to preconcentrate gold ore before leaching as it is much more cost-effective and environment friendly.

3.3 Coal-oil gold agglomeration process

Coal-oil gold agglomeration (CGA) utilizes the natural hydrophobicity of coal and gold (Sen et al, 2005). In this process intensive agitation causes the coal – oil agglomerates to form in a coal slurry and oil. Under intensive agitation the pre-formed agglomerates are added into gold-bearing ore slurry where the gold particles then contact, collide and attach with the coal-oil agglomerates, and eventually penetrate into the agglomerates (Akcil et al, 2009).
Generally this process is more environmentally friendly compared to the conventional methods as the tailings produced in CGA process only contain small amounts of harmless contaminants, such as coal fines, oil, collectors and possibly lime. Also, concentrations of these pollutants will be far below threshold levels in environmental regulations. However, there is need for further research on cost effectiveness of this process (Akcil et al, 2009).

4. Conclusion

The pre-treatment and processing of complex/ refractory gold ore is becoming more and more pronounced and is an inevitable trend to gold development due to the rapid depletion of high grade ores. Significant progress has been recorded in recent years as scientists continue to explore ways of pre-treating and processing refractory gold ores sustainably. A process for gold recovery will only be deemed successful if the cost of implementing the process is much less than the value of the precious metal itself. In addition, environmental issues should be valued in the selection of a process.

A review of the potential pre-treatment and processing technologies has shown that the main problems that need urgent attention in the gold industry are the need to improve on recovery, cost and environmental issues. A highly cost efficient and environment friendly technology to improve gold recovery from complex ores is therefore needed in future. In summary, as the proportion of low grade ores is becoming larger and larger, it is imperative to develop technologies for lower cost and higher gold recovery rates to ensure sustainability in the gold industry.

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Biography

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