The current state and future directions of percolation leaching in the Chinese mining industry: Challenges and opportunities

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Abstract

China is one of the most rapidly growing economies in the world and this growth is underpinned by growing demand for natural resources to meet base and precious metals and energy requirements. Even though China is currently the largest producer of several mined commodities, such as gold and the rare earth elements, meeting the future demands for metal consumption will require China to either develop new mining projects or increase material imports. In terms of nuclear energy requirements the country still depends on uranium imports. To meet this growth in Chinese demand, there has been a strong interest in technologies suited for mining and processing of low grade ore bodies. Percolation leaching methods have been very effective in extracting metals from low grade ores, which could not otherwise be economically extracted. Percolation leaching techniques, such as heap leaching, dump leaching, bio-leaching and in-situ leaching have been extensively employed in the Chinese mining industry in recent decades to primarily extract gold, copper, rare earth elements and uranium. This paper discusses the application of various percolation leaching techniques in the Chinese mining industry and offers a scientific and extensive literature overview on technology developments in commercial percolation leaching operations in China. It also presents the current challenges of percolation leaching and recent technological and research developments and regulatory frameworks pertaining to the application of percolation leaching in China. The future directions of percolation leaching in the Chinese mining industry will also be presented to extract the low grade natural resources both economically and in an environmentally sustainable manner.

Keywords: Chinese mining industry; Heap leaching; In-situ leaching; Low-grade ores; Percolation leaching; Sustainability

1. Introduction

China is the world's largest producer of coal, gold and rare earth elements (REEs) and has more than 10,000 active mines. In addition, being the most populated country and the largest developing country, most mined resources are used by China, such as coal (50% consumption share of world production in 2014), iron ore (56% in 2014) and copper (64% in 2014) (Roberts et al., 2016; World Energy Council, 2016; Ministry of Land and Resources of the P.R. of China, 2017a). China's depleting ore reserves and relatively short life span of mines contribute to shortfalls in local metal production. This will lead to an increase in the country's metal imports (BMI Research, 2017) and prompt additional mineral exploration, mine development and strategies to optimise metal extraction efficiencies. The Chinese National 13th five-year plan (2016-2020) recommends low carbon, clean, safe and modern energy systems (e.g. replace coal power generation with nuclear power) (Xing et al., 2017). In order to develop the Chinese economy and society in a way that contributes to sustainable development and environmental stewardship, metal recovery from natural resources should be increased and optimised through improved recovery efficiencies and minimising waste generation in the primary metal extraction process.

There has been a substantial decline in mined ore grades in China over the past few decades and thus processing of existing low grade reserves is viewed as vital in order to fulfil the country's metal requirements and exports (BMI Research, 2017). Even though several mineral processing techniques are used to extract metals from metallic ores, most increase cost and decrease efficiency as the ore grade decreases (Norgate and Jahanshahi, 2010). Waste rock volumes produced through surface and underground mining activities are typically considered as potential sources of environmental pollution since these can produce leachate enriched in metal ions over time (Amos et al., 2015; Fernando et al., 2018a). This could lead to acid mine drainage (AMD) and subsequent pollution of soil, surface and ground water once metals and dissolved species mobilise. In addition, mine waste rock volumes may contain a significant amount of metal resources and are now targeted as potentially viable resources in the mining industry (Lèbre et al., 2017). Thus, it is important to find effective ways to utilize these secondary resources. Considering all of these aspects, percolation leaching is vital in the development and sustainability of the Chinese mining industry. This technique has mainly been used to produce gold, copper, REEs and uranium.

Percolation leaching can be defined as selective metal extraction using a suitable leaching reagent, which seeps into and flows through ore masses or crushed ore piles that contain the mineral grains (Ghorbani et al., 2016). The percolation leaching technique is typically categorized into heap leaching, dump leaching, in-situ leaching (ISL), vat leaching and agglomerated fines heap leaching (i.e. heap leaching using agglomerated particles). Table 1 summarizes these techniques and their key operational features (John, 2011).

Table 1: Percolation leaching techniques and key operational aspects (adopted from John, 2011). n.a. denotes not applicable.

Leaching Method	Particle size, mm (P_{80})	Crushed	Agglomeration	Liquid addition ($L/m^2.h$)	Lift height (m)	Leach time (years)	Recovery (typical %)
Heap	5-100	Yes	Mostly	2-15	2-10	Cu: 1-4 Ni: 1-5 U: 1-3 Au: 0.1-2	40-97
Dump	30-1000	No	No	2-15	8-75	Cu: >10 Au: 2-6	20-85
ISL	>1000 mm	Can be in-situ blasted	n.a.	Wide and varied	n.a.	Cu: >5 U: 1-3	5-50
Vat	0.5-10	Yes	May be	10-50	1-5	4-30 days	80-97
Agglomerated fines heap	0.25-1	Yes and/or milled	Yes	2-15	1-5	As per heap leach	70-97

Heap leaching is a hydrometallurgical technique that is far less sensitive (economically) to low grade ores compared to other mineral processing techniques (Ilankoon and Neethling, 2016; Petersen, 2016). The crushed (-25 mm particles) and/or agglomerated ore is piled to construct the heap and leaching solution is applied to the top, percolated through the ore and the pregnant solution, enriched with dissolved metal ions, is collected from the bottom of the heap. Heap leaching is typically coupled to solvent extraction and electro-winning (SX-EW) circuits for subsequent metal extraction (Liu et al., 2016a, b). Thus, heap leaching is relatively simple and economical process for extracting metals from low grade ores, waste dumps, tailings and complex ores (Vladimir, 2015). It has also become a major world contributor for the production of gold, silver, copper and uranium (Padilla et al., 2008). Heap leaching has also been considered for nickel (Oxley et al., 2016), zinc (Petersen and Dixon, 2007; Lizama et al., 2012), platinum group metals (Mwase et al., 2012) and electronic waste recycling, such as printed circuit boards (Ilyas et al., 2013). However, the recovery in heap leaching is relatively low and slow compared to other separation techniques, such as froth flotation followed by smelting, while the capital costs of this technique are relatively low, which makes it an attractive option (Bartlett, 1992; Ilankoon and Neethling, 2012, 2013, 2016). Ghorbani et al. (2016)

discussed the current status of heap leaching operations. Heap leaching has also attracted wide attention in the Chinese mining industry in recent decades (e.g. Qiu et al., 2000; Li et al., 2013).

Bio-leaching is similar to conventional heap leaching but bacterial assisted leaching of metals (e.g. copper from secondary sulphides) is key to the technique (Watling, 2006; Brierley, 2010; Lizama et al., 2012; Fagan et al., 2014). When waste dumps of marginal grade run-of-mine (ROM) ore are leached, similar to heap leaching operations, the technique is known as dump leaching. Dump leaching metal recovery values are also very low due to extensive solution channelling or rapid flow paths through ROM ore (Bartlett, 1992; Ulrich et al., 2003; Ilankoon and Neethling, 2016). ISL or flooded leaching (i.e. has saturated liquid flow, but gas phase is typically absent) does not employ a bed of ROM or crushed ore. Leaching reagents are injected from injection wells and flow through adequately permeable ore mass or particles. The metal enriched solution is then extracted from production wells for subsequent metal extractions (Bartlett, 1992). ISL has widely been applied to produce uranium (Mudd, 2001a, 2001b) and notably for heavy rare earth production in Southern China. However, the application of ISL to other commodities has been far more limited.

This paper discusses the current state of percolation leaching techniques in the Chinese mining industry, associated drawbacks and recent changes and developments with respect to the Chinese government’s mining industry priorities. The main metals produced via percolation leaching are also discussed including key industrial operations in China. The article also discusses effective metal extraction from low grade ores, through leaching based techniques, without compromising environmental sustainability.

2.1. Metal production and consumption in China

Considering the main metals that are produced by percolation leaching in the Chinese mining industry, the domestic production and consumption (i.e. the use of each metal or metal containing product by the Chinese manufacturing industry) data of gold, copper, REEs and uranium in the last 10 years is assessed.

2.1. Gold production and consumption

Figure 1 compares gold production and consumption data. A gradual growth in production is seen, where the contributing factors were the increase in substantial demand by the investment sector (e.g. bar and coin demand, physical bar demand) and higher commodity prices through this period. New gold deposits were explored to cater for this demand and the reserves (i.e. economically extractable or producible at the time of determination) thus increased from 1,200 tonnes in 2005 to about 2,000 tonnes in 2017. In 2016, total Chinese mined gold production was about 455 tonnes and China has become the world's largest producer for the last 10 years (Zhang, 2012a, b; Zhang et al., 2015; U.S. Geological Survey, 2017). Gold ores contributed to 87% of the total production in 2016, whereas the rest was attributed as by-products of nonferrous metals. According to BMI Research (2017) estimates, China's gold production will have an annual growth of 0.3% during 2017-2021 and the approximately stagnant gold production during this period will be about 16.5 million ounces or 468 tonnes of gold. However, the currently predicted gold growth rates are significantly lower than the previous five years (i.e. 7.1% per annum during the period of 2012-2016). In comparison, the national gold consumption was 975.4 tonnes in 2016 and China was the world's largest gold consumer for 4 consecutive years (Mosher, 2016; Thomson Reuters, 2016). This implies that substantial gold imports to China are occurring.

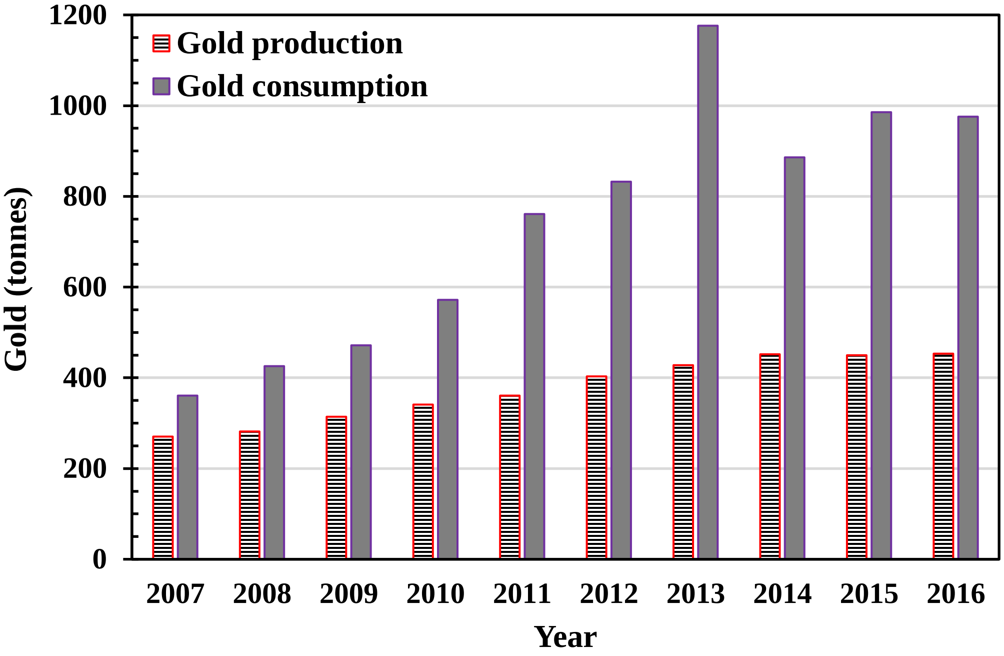

Figure 1: Gold production and consumption in China during last 10 years. Data from China Gold Association (2007-2016) and World Bureau of Metal Statistics (2009-2017).

2.2. Copper production and consumption

Figure 2 illustrates the Chinese total copper production (both primary and secondary) in last 10 years. The primary copper production includes the production of copper concentrates, electro-won (EW) copper cathodes produced from leaching followed by solvent extraction and electro-refined (ER) cathodes (produced from concentrate smelting and electro-refining), whereas recycling and re-used components account for the secondary copper production. The total copper production was 8,436 thousand tonnes in 2016, which indicates 6.1% growth compared to 2015.

Figure 2 also shows mined copper production trends and the latest data indicates 1,400 thousand tonnes in 2016. BMI Research (2017) envisaged that China's copper production will have an average growth of 2.6% per annum during the period of 2017-2021 compared to the average annual growth of 6.6% over the previous five years (i.e. 2012-2016). Thus the estimated mined copper production will be 1,792 thousand tonnes and 1,978 thousand tonnes in 2017 and 2021, respectively. Total production significantly exceeds mined production due to the inclusion of copper sourced from imported concentrates and semi-refined copper (i.e. blister copper or copper mattes), as well as secondary production. However, the copper consumption data generally exceeded the total production with a significant increase in consumption seen over the years, implying the need for importation of refined copper.

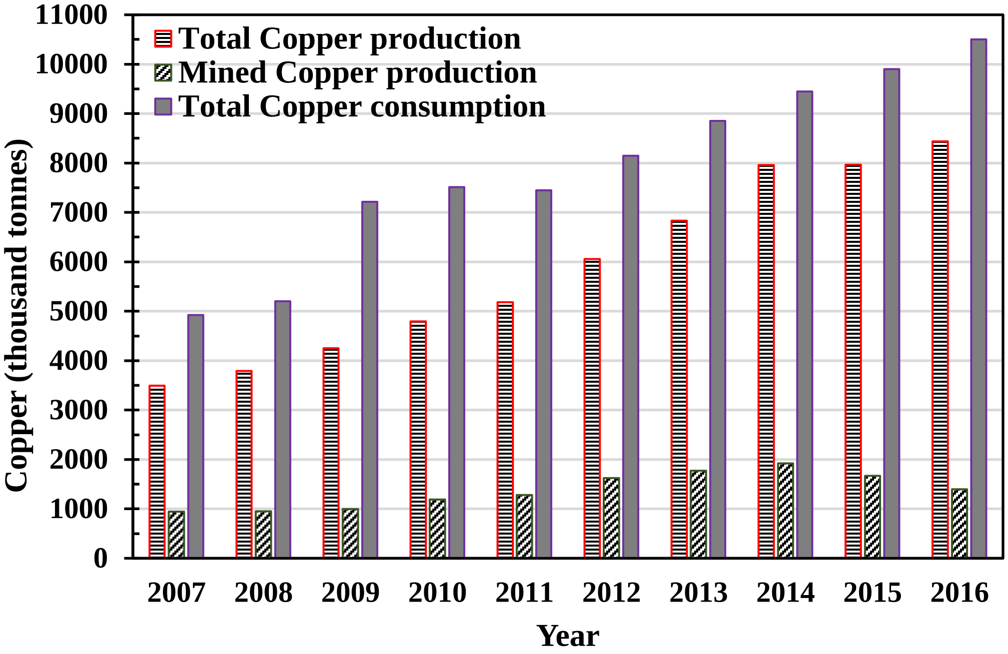

Figure 2: Total copper and mined copper production and total copper consumption in China during last 10 years. Data from International copper study group (2017) and Ministry of Land and Resources of the P.R. of China (2017b).

2.3. REE production and consumption

The REEs constitute a total of 17 elements including the 15 lanthanide elements (from lanthanum - atomic number 57 to lutetium - atomic number 71) (Gschneidner, 1964), and commonly also scandium (atomic number 21) and yttrium (atomic number 39) (Tse, 2011; Packey and Kingsnorth, 2016). These elements are scarce as an economically mineable resource despite their crustal abundance compared to copper, zinc, nickel and lead (Gupta and Krishnamurthy, 2005; Golev et al., 2014). Golev et al. (2014) envisaged that the global data on REEs production is not accurately reported by companies. However, currently China is the dominant producer of REEs globally. Production and consumption data of REEs as rare earth oxides (REOs) in last 10 years in China is shown in Figure 3.

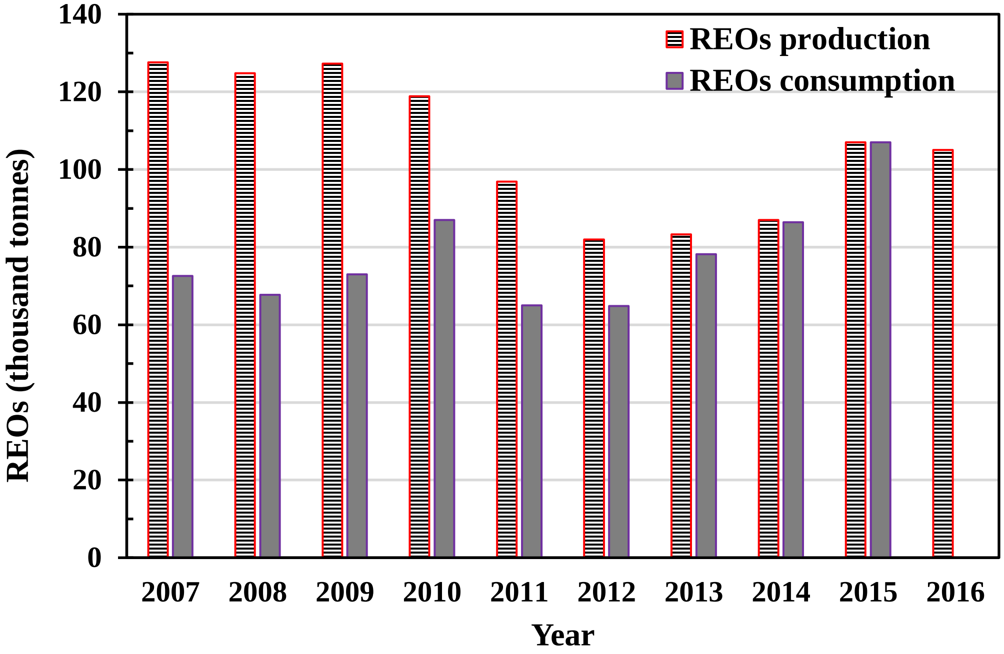

Figure 3: REEs production and consumption in China during last 10 years. Data from the Chinese Society of Rare Earths (2007-2016), China Industry Information Network (2007-2016) and Li and Fang (2016).

China has supplied more than 90% of the total rare earth products in the world in different forms, such as concentrates, REOs, salts and metals, rare earth alloys and chemicals, since 2001 increasing from only 27% in 1990 (Tse, 2011; Li and Yang, 2016). REO production in China in 2000 was 73 thousand tonnes increasing to 133 thousand tonnes in 2006. Since 2006 the average production has been stable at 120 thousand tonnes from 2007 to 2010 (Tse, 2011; Li and Yang, 2016). The majority of rare earth production is sourced from tailings of the Bayan-Obo iron ore mine, where REEs are present in the form of bastnaesite (a rare earth fluoro-carbonate mineral; REE_xCO_3F) and monazite (a rare earth phosphate mineral; REE_xPO4). The only notable non-Chinese production of REEs currently is by Lynas Corporation, which produces a monazite concentrate from the Mt Weld carbonatite deposit in Western Australia that is then shipped to a REE extraction and separation plant in Malaysia. This follows the recent closure of the Mountain Pass rare earth mine in the United States (Tse, 2011).

Even though China's dominance in this sector (production is higher than the consumption), the reported production values indicate a declining trend since 2009, which is in contrast with the drafted Chinese rare earth development plan (2009-2015) that aimed to maintain annual rare earth production at 130-140 thousand tonnes (Tse, 2011). It was mainly caused by government policies and China adopted a cap-control policy for rare earth exploitation in 2006 to protect strategic reserves of REEs (Tse, 2011; Li and Yang, 2016). In addition, the Chinese government imposed an export duty (10-25%) on rare earth products to control exports in 2007 (Tse, 2011). Due to these policies, a dispute against China was lodged at the World Trade Organisation (WTO), instigated by the European Union (EU), Japan, and the United States (Wübbeke, 2013). Following the loss of the WTO dispute, China has adjusted the export policy of REOs and also consolidated REE producing companies (Biedermann, 2014), and it is supposed that the change of policies contributed to the increased production since 2012 (Shen et al., 2017). Wang et al. (2017) predicted that China's REE production would peak in 2038-2045 with a production peak of 265-385 thousand tonnes and these can be used to propose future policy recommendations.

Since 2000 China's rare earth consumption also increased rapidly and the consumption in 2014 (i.e. latest consumption data) was about 450% compared to 2000. The main industries that accounted for this consumption are magnets, metallurgical, chemical and petroleum, ceramics and glass, agriculture and textile, and hydrogen storage (Tse, 2011).

2.4. Uranium production and consumption data

Uranium production in the world was 62,366 tonnes in 2016 and Kazakhstan produced the largest amount of uranium (39.4%) followed by Canada (22.5%) and Australia (10%). China produced 1,616 tonnes of uranium in 2016, which is only 2.6% of the world's production. Uranium contributed to fulfilling 2.4% of China's total electricity demand of 5.5 trillion kWh in 2014 (Zhang et al., 2016). Nuclear power generation was 3% of the total power generation in China in 2015, however it could reach 10% in 2030 according to Chinese Nuclear Energy Association (CNEA) reports in 2015 (Xing et al., 2017). Considering the number of operable nuclear reactors, reactors under construction, reactors planned and proposed, the estimated uranium requirement in China was 8,289 tonnes in 2017 (WNA, 2018). This is predicted to reach 11,000 tonnes by 2020, 18,500 tonnes by 2025 and 20,113-24,000 tonnes by 2030 (WNA, 2017a; Xing et al., 2017). Recent reports from the National Energy Administration of China and China Electricity Council (CEC) expressed concerns over energy demand due to the rapid economic development in China and the Chinese National 13th Five-year plan (2016-2020) highlighted the importance of uranium resource utilisation (Dittmar, 2013; Zhang et al., 2016; Xing et al., 2017).

Production capacity of uranium in China is now relatively low due to poor ore grades leading to a high level of dependency of uranium imports for the country's nuclear industry (Zhou et al., 2011; Wen et al., 2014). Figure 4 explicitly illustrates this behaviour in the last decade. Xing et al. (2017) analysed the supply and demand of uranium in China in detail, as it is considered an important strategic resource for enabling an independent energy supply in the future (e.g. Chinese nuclear long and medium term development planning, 2011-2020, action plan for energy development, 2014-2020). China was the third largest consumer of uranium in 2015, with 12% of global demand (Xing et al., 2017). Due to increasing demand of uranium in

China, uranium-bearing mine tailings have been considered as viable uranium resources. It was reported that there were about 60 million tonnes of uranium-bearing tailings in China in 2010 (Zhang et al., 2010).

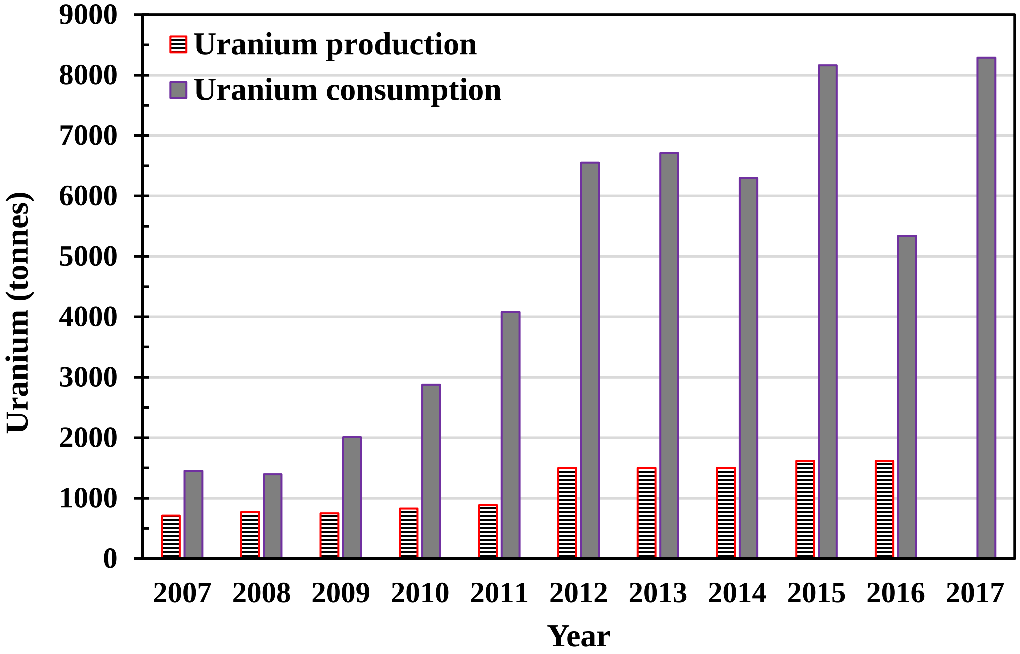

Figure 4: Uranium production and consumption in China during last 10 years. Data from World Nuclear Association, September 2017 and May 2018 updates (WNA, 2017b, 2018). Uranium quantities are expressed in terms of tonnes contained uranium (U) rather than uranium oxide (U_3O_8) [0.848% U= 1% U_3O_8].

3. Percolation leaching in the Chinese mining industry

Percolation leaching techniques (heap and in-situ leaching) are typically employed to produce gold, copper, REEs and uranium in the Chinese mining industry.

3.1. Gold heap leaching

Heap leaching contributed to about 17% of global gold production in 2014 (Vladimir, 2015), having increased from 9.6% (236 tonnes) of global gold production in 2004 (Marsden, 2006). Marsden's (2006) data indicated less than 1% of Chinese production from heap leaching in 2004, although importantly he was unable to account for the extraction method used for 52% of China's total gold production in 2004. This implies the unavailability of exact heap leaching based gold production data for all the key mining operations in China. In a similar other study, Qiu et al. (2000) estimated the contribution of heap leaching as 10% of China's total gold output. Considering current gold heap leaching trends in China, production could reach up to 100 tonnes per annum with overall gold recovery estimated to be 80% (Wu, 1998; Qiu et al., 2000; Hou et al., 2014).

The gold output of Zijin Mining Group, which owns many gold mines in China, was 42.6 tonnes in 2016 and 57% of that was produced in China (Zijin, 2017a). Zijinshan gold mine is one of the largest gold heap leaching operations in China owned by the same group (section 4.1) and the gold production from heap leaching accounts for more than 80% of the total production of the mine (He, 2006; He and Zhang, 2006).

3.2. Copper heap and dump leaching

Heap leaching based copper production in the world was about 16% of total copper production in 2014 with all the major heap leaching facilities located in Chile (Vladimir, 2015).

Yin et al. (2018) recently summarised the main copper ore deposits in China. China's copper deposits and ore geology favour open-pit mining compared to underground mining and the deposits are mainly categorised into porphyry-type (41%), skarn-type (27%), marine volcanic-type (9%), copper-nickel sulphide-type (6%) and others (17%). The copper ore deposits are typically associated with gold (76%) and silver (32.5%). The average copper ore grade is about 0.87% and these low grade copper ore deposits do not favour conventional mineral processing techniques due to ore quantity and quality. In addition, most of the mines are small to medium scale operations (97%) compared to large scale mining operations (3%) (Yin et al., 2018).

Even though copper ores are extensively available in China, the majority of current ores are of low grade and heterogeneous dissemination-type (Yang et al., 2002; Wu et al., 2007; Yin et al., 2018), which promotes the application of heap and dump leaching (both conventional and bio-leaching depending on ore geology). The exact proportion of copper production by heap leaching in China is not accurately reported, but Li (2007) reported the value as about 0.3%. Copper heap bio-leaching has also been very common in China with mines are located in the central and eastern regions (especially the southeast) of the country due to favourable ore geology.

Yin et al. (2018) reviewed the main copper bio-leaching operations in the Chinese mining industry in detail. Many copper bio-leaching studies concentrated on mining operations, such as the Zijinshan mine, Dexing mine, Asele mine (Xinjiang autonomous region) and Yulong mine (Tibet autonomous region). The largest copper heap leaching facility is the Zijinshan copper mine, which is a copper bio-leaching system and it has a daily ore treatment capacity of 20,000 tonnes. 13.9 million tonnes of low grade secondary copper sulphide ores (0.38% Cu) have been treated from 2006 to 2009 and the bio-heap leaching based copper cathode production at Zijinshan copper mine was 37,633 tonnes. The total operating cost was calculated as

US$ 2.4/kg (Ruan et al., 2013). The key aspects of Zijinshan copper bio-heap leaching facility and Dexing bio-dump leaching mine are given in detail in sections 4.2 and 4.3, respectively.

3.3. Percolation leaching of ion-adsorption type REEs

The proportion of REEs production using heap or in-situ leaching has increased to about 10% in China and the technique has been mainly employed in southern China including Jiangxi, Guangdong, Fujian, Guangxi and Hunan provinces (Zhou et al., 2012). China owns the largest reserves of REEs in the world (Li and Yang, 2016). The USGS Mineral Commodity Summaries in 2016 and 2017 estimated global rare earth ore reserves of 120-130 million tonnes, with China's reserves being 44 million tonnes (China owns 37-42% of global reserves) (U.S. Geological Survey, 2016, 2017). Approximately, 95-97% of Chinese rare earth reserves are contained in four deposit types, namely, the Bayan Obo REE-iron-niobium ore deposit (inner Mongolia, 83.7% of China's total REE reserves), the Mianning REO deposit (Sichuan province), the Weishan REO deposit (Shandong province) and ion-adsorption clay type rare earth reserves. The remaining reserves are the southeast China beach deposits, located in the coastal area of west Guangdong and Hainan (Yang et al., 2013; Li and Yang, 2016). Since percolation leaching is applicable to ion-adsorption type rare earth ores, processing of these will only be discussed in this work. Other rare earth minerals, such as bastnaesite and monazite are complex and difficult to process, often require multiple leaching, purification and separation stages that need to be performed in closed systems due to the formation of passivation layers when leaching and thorium and uranium exposure risks (thorium and uranium often substitutes REEs in monazite minerals).

Ion-adsorption type deposits, also known as ion-adsorption clays, account for 2.9% of China's total REE reserves (1 million tonnes of REOs). These ores are the cheapest and most accessible source of heavy rare earths, but have not been discovered anywhere else in the world (Yang et al., 2013; Packey and Kingsnorth, 2016). Ion-adsorption type rare earth ores, which are rich in medium and heavy REEs (e.g. yttrium), are more valuable than light REEs, and consist of more than 80% of word's total heavy rare earth reserves (Yang et al., 2013; Li and Yang, 2016; Packey and Kingsnorth, 2016). These ores are not associated with radioactive elements, such as uranium and thorium (Wübbeke, 2013; Packey and Kingsnorth, 2016). In addition, these have contributed to about 35% of China's total rare earth production in 2009 (Yang et al., 2013). The current annual production of REOs (over 60 wt. %) from ion-adsorption clays is about 10,000 tonnes (Li and Yang, 2016).

These were first discovered in Ganzhou, Jiangxi province, southern China in 1970 (Li and Yang, 2016; Wang et al., 2016a). The reserves can be found in seven provinces of southern China (Yang et al., 2013), Jiangxi, Guangdong, Fujian, Hunan, Guangxi, Yunnan and Zhejiang (Li and Yang, 2016).

The ion-adsorption type deposits (5-30 m deep) are located in small mountains below a humus topsoil layer of 0.3-1 m. The average REO grade of these deposits is 0.03-0.5% and they have relatively low REE concentrations in the range of 10-100 ppm by weight (Yang et al., 2013; Li and Yang, 2016; Wang et al., 2016a), which contrasts with the average grades of 0.63% REO in REE deposits globally (Weng et al., 2016). This ore is soft and has a very fine grain size distribution (Li and Yang, 2016). The ion-adsorption clays were formed by many years of weathering decomposition and dissolution of granite and granite porphyry rocks (Yang et al., 2013; Li and Yang, 2016). The ions were subsequently adsorbed on the surface of clay minerals, such as kaolinite, halloysite and illite (Li and Yang, 2016). Hence, these are also known as weathering crust elution-deposited rare earths (Yang et al., 2013).

Ion-adsorption clays can be extracted by a simple leaching technique with an aqueous electrolyte solution, such as sodium chloride, ammonium sulphate and ammonium chloride via an ion-exchange process (equation 1, Yang et al., 2013). The reason is that the minerals occur in the state of hydrated ions at a simple trivalent cationic state (RE^{3+}, where RE is the rare earth mineral) adsorbed onto clay minerals.

$$2(Kaolin)^{3-}RE^{3+} + 3(NH_4)_2SO_4 \rightarrow 2(Kaolin)^{3-}(NH_4)_3^{+} + RE_2^{3+}(SO_4)_3^{2-} \quad (1)$$

3.4. Uranium percolation leaching

Major uranium minerals include autunite ($Ca(UO_2)_2(PO_4)_2{\bullet}nH_2O$), pitchblende ($U_3O_8$), uraninite ($UO_2$), coffinite ($(USiO_4)_{1-x}(OH)_{4x}$) and uranophane ($Ca(UO_2)2SiO_3(OH)_2{\bullet}5H_2O$) (Blaise, 2002; Wu et al., 2014a). The associated minerals are typically pyrite, pyrrhotite and sphalerite and gangue minerals are quartz, feldspar, micas (e.g. white, black mica, sericite), hematite, chlorites, fluorites, and calcite (Fan et al., 2002; Su et al., 2002a). These uranium minerals are present in various host rock types, namely, granite, volcanic rock, sandstone, breccia, moissanite mudstone, carbonate, andesite, quartzite and uranium-bearing coal (Fan et al., 2002; Zeng et al., 2002a). As of 2012, the distribution of deposits were 35% sandstone type in the north and northwest, 28% granite type in central and southeast China, 21% volcanic type in the southeast, and 10% black shale in the southeast China (WNA, 2017a). China is one of the countries with rich uranium resources and 2 million tonnes of uranium reserves have been estimated in 329 mineralization zones. The uranium deposits in China are generally small in size and low in grade (0.01-0.3% uranium and more than 40% uranium is typically hexavalent). Recoverable (reasonably assured resources plus inferred resources) resources are estimated to be 0.22-0.3 million tonnes of uranium (Fan et al., 2002; Zhang et al., 2012c; Zhang, 2012d; WNA, 2017b; Xing et al., 2017). The China National Nuclear Cooperation (CNNC) engages in all the uranium production operations in China (Zhang, 2012d). There were 24 uranium mining operations in China in 2015 located in 12 provinces (e.g. Guangdong, Jiangxi) (Su and Xu, 2017).

Agitation leaching of milled uranium ore (i.e. conventional chemical leaching) followed by solid/liquid separation and purification was the initial processing route for uranium ores in China and commenced in the 1960s. The technique resulted in higher extraction costs, such as energy and operational costs, and higher water consumption compared to heap leaching (Zhang, 1997; Zeng et al., 2002a). The presence of low grade uranium ores and uranium-bearing tailings thus favours heap leaching and commercial uranium heap leaching started in China in 1990 (Yang, 2014; The Nuclear Energy Agency and the International Atomic Energy Agency, 2016). Even though environmental concerns limit the application of heap leaching with uranium ores, both acid and alkali uranium leaching operations exist (Scheffel, 2002; Petersen, 2016). Heap leaching based uranium production from hard-rock uranium ores accounted for 10.5% of the total uranium output in China in 1990 and it has greatly increased in recent years (Table 2). The main products are ammonium diuranate, ammonium uranyl tricarbonate, uranium peroxide, triuranium octoxide and uranium dioxide (Zeng et al., 2002a).

Low grade uranium ores hosted in hard-rocks in southern China are typically processed using sulphuric acid based heap leaching techniques (acid curing-ferric heap leaching) with the particle size less than 10 mm. The process flow-sheet includes ore crushing, concentrated acid curing, ferric sulphate leaching, tertiary amine solvent extraction followed by uranium precipitation and residue disposal (e.g. as a backfill material in mines) with the process effluent (Zhang, 1997; Zeng et al., 2002a). The typical leaching duration was about 100 days and the uranium concentration in the pregnant solution was 7-9 g/L (Zeng et al., 2002a).

The main chemical reactions occurring during uranium ore heap leaching are as follows (Shakir et al., 1992; IAEA, 1993; Ding et al., 2013):

$$UO_2 + 0.5O_2 + H_2O \rightarrow UO_2^{2+} + 2OH^- \qquad (2)$$

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_20 \qquad (3)$$

$$UO_2 + 2Fe^{3+} \rightarrow UO_2^{2+} + 2Fe^{2+} \qquad (4)$$

$$UO_3 + 2H^+ \rightarrow UO_2^{2+} + H_2O \qquad (5)$$

$$UO_2^{2+} + SO_4^{2-} \rightarrow UO_2SO_4 \qquad (6)$$

$$UO_2SO_4 + SO_4^{2-} \rightarrow UO_2(SO_4)_2^{2-} \qquad (7)$$

$$UO_2(SO_4)_2^{2-} + SO_4^{2-} \rightarrow UO_2(SO_4)_3^{3-} \qquad (8)$$

In sulphuric acid leaching quadrivalent uranium (UO_2) is insoluble, while hexavalent uranium (UO_3) and its compounds are dissolved (Avvaru et al., 2008). Iron present in the ore generates the ferric species that oxidises quadrivalent uranium to hexavalent uranium. Equations 2-4 show the dissolution of quadrivalent uranium and the main parameters that influence the leaching are iron, acid and oxygen. Hexavalent uranium and its compounds are dissolved according to equations 5-8, which show the involvement of sulphuric acid in solubilisation and speciation of uranium (Shakir et al., 1992; Ding et al., 2013).

Uranium ores with high clay content (e.g. Wenyuan uranium mine in Guangdong and ores, such as cracked and clayed granite uranium ore, uranium ore with flake mica, kaolin cementation uranium ore) are difficult to treat by conventional heap leaching due to low permeability. These ores resulted in less than 40% recovery after 200 days leach. Ore agglomeration in alkaline and acidic conditions is carried out with cementing agents and binders in order to increase ore permeability and strength of ore pellets (Zeng et al., 2002b). Agglomeration with concentrated acid curing and ferric salt leaching was found to be give better physical properties. Bonding in pellets were stronger compared to alkaline agglomeration and resulted in faster leaching kinetics (e.g. 92-96% recovery after 60-90 days) (Su et al., 2002a, b; Zeng et al., 2002b).

Bacterial (thiobacillus ferrooxidans) heap leaching of uranium ore (equations 3 and 4) is also performed in China (e.g. Ganzhou uranium mine, CaoTaoBei uranium mine) since it delivers better leaching efficiencies (2-10% more) and greater uranium concentrations in the pregnant liquor (0.5 g/L uranium for first 55 days). In addition, it results in lower leaching periods (shortened by 75 days or 32-50%) and acid consumption (reduced by 0.35-12.5%) compared to conventional acid leaching of uranium ores (Fan et al., 2002; Su et al., 2002a; Zeng et al., 2002a). The accumulation of fluoride and chloride ions inhibit growth of bacteria and thus it should be avoided in the barren solution (Fan et al., 2002).

ISL of uranium ores with cut-off grade of 0.01% uranium and less carbonate content is significant considering its share of the total uranium production (e.g. in Kazakhstan) and its contribution, in terms of total uranium production in the world, was more than 50% in 2014 (48% in 2016). Table 2 also illustrates the ISL based uranium production in China. China's natural uranium strategy prioritises ISL compared to heap leaching. This was demonstrated by a steady increase in expenditures (USD 197 million in 2014 compared to USD 131 million in 2012) and total drilling footage (874,700 m in 2014) for local uranium exploration and most of these development works directed at identifying ISL amenable uranium deposits in northern China (Zeng et al., 2002a; The Nuclear Energy Agency and the International Atomic Energy Agency, 2016). The uneconomical low grade ores could be extracted using ISL and it has been typically employed to treat sandstone type uranium deposits in northern and northwest China (Xinjiang, Yunnan, Shanxi, and Inner Mongolia). The efficiency of uranium leaching in ISL depends on both the uranium content and the uranium activity (i.e. leachable uranium), and the suitability of ISL is assessed based on geological and hydrological conditions of the deposit and surrounding area. Permeability of the uranium sandstone ore is in the range of 0.09-1.6 m per day compared to the permeability of the surrounding clay formations, which is 0.01 m per day (Blaise, 2002; Ma et al., 2017). This method gives better leaching efficiencies (75-85%) and high uranium concentration in the pregnant solution (55-60 mg/L). It is claimed to result in less environmental impacts compared to underground mining (Bakarzhiyev et al., 2002; Blaise, 2002). The other advantages are lower capital costs, shorter start-up time, less labour intensive, greater mining safety considerations and no solid tailing generation. However, low permeability of sandstone uranium deposits has been a challenge. Addition of surfactants at low concentration is suggested to improve uranium extraction with tests mainly reported at lab scale pertaining to ISL of uranium (Cai et al., 2013). Despite these advantages, ground contamination usually occurs and thus ground water restoration, similar to heap decommissioning after heap leaching is mandatory once uranium ISL operations cease (Li et al., 2002) and this is addressed in detail in section 5.6.

Table 2: Uranium (tonnes) extraction methods in China (adopted from The Nuclear Energy Agency and the International Atomic Energy Agency, 2016). ^{e}: estimates only. Uranium quantities are expressed in terms of tonnes contained uranium (U) rather than uranium oxide (U_3O_8) [0.848% U= 1% U_3O_8].

Extraction method	2012	2013	2014	2015^{e}
Conventional	350	350	350	300
Heap leaching	600	650	580	580
ISL	380	430	680	650
Stope/block leaching	120	70	70	70

ISL of low grade uranium ores may not be suitable under certain hydrological and geological conditions, such as small deposits, complex mineralogy and poor permeability and in those cases, stope/block leaching (i.e. the ore body is systematically blasted in underground and subsequently leached.) or in-place leaching is recommended (Zeng et al., 2002a). This technique is also employed to treat low grade uranium ore bodies in the Chinese mining industry. It typically alleviates radioactive contamination since most of the ore is processed underground (Zhang, 1997; Fan et al., 2002; Zeng et al., 2002a).

Uranium ions in the pregnant solution are extracted using ion exchange (for low uranium concentrations), amine solvent extraction (i.e. tri-fatty amine extraction and sodium carbonate back extraction followed by sodium hydrate to precipitate sodium diuranate) and precipitation (Su et al., 2002a, b).

4. Main percolation leaching operations in China

The main mining operations contributing to the production of gold, copper, REEs, and uranium using percolation leaching (conventional heap and bio-leaching, dump and in-situ leaching) in China's mining sector are discussed to highlight the ore types, operational conditions and key metal extraction aspects.

4.1. Zijinshan gold mine

Zijinshan gold mine was started in 1993 by Zijin mining company, which is the most profitable gold producer in the Chinese gold industry. Full scale operations at Zijinshan gold mine was started in 2010. It employed sodium cyanide based heap leaching to extract gold from low grade ores (Table 3) in the Zijin Mountain (Yang, 2011). The deposit is one of the largest porphyritic-type deposits (porphyry related high-sulphidation epithermal copper-gold deposit) in China and discovered in 1980s. It contains oxidised gold ore over a copper ore body and as of December 2016, the proven reserves were about 318 tonnes.

Heap leaching technology is typically prevalent in dry climates (e.g. deserts of western South America) (Ulrich et al., 2003) and heap operations had been rarely employed in southern China before this project. The application of heap leaching for this project was thus not recommended due to high humidity and rainfall around Zijin Mountain. However, Zijin mining has started to treat low grade gold ores through heap leaching operations as the average grade in recent years is less than 0.5 g/t (Table 3) (Tang et al., 2016). The gold recovery was 65-75% prior to 2000 with a relatively long leach cycle (77-92 days) since leaching parameters were not optimized (Wang et al., 2005; Wang and Cao, 2006). Xie (2003) controlled the particle size (50-80 mm), heap construction, heap height and liquid addition to maximise the leaching efficiency. The high oxidation degree of Zijinshan gold ore affected the permeability and Luo (2009) discussed the characteristics of ore oxidation zones and their relationship with mineralisation. High mud content (8-30%) of the ore also reduced the heap permeability and thus for such ores, heap height was kept at 2 m compared to the usual heap height of 8-10 m. An increased leaching recovery (80%) and reduced leach cycles were reported (Luo et al., 2003; Xie, 2003; He, 2006). Thus, it was shown that heap leaching operations were possible under appropriate operating conditions (Yang, 2011). The total gold production in 2016 was about 7.4 tonnes (Zijin, 2017a, b) and the recent production trends made it China's largest gold mine (Yang, 2011).

Table 3: Chemical composition of gold ore at Zijinshan mine by x-ray fluorescence (after Tang et al., 2016). *unit of Au and Ag is g/t. ^{a}Fe, ^{b}S: Total iron and sulphur, respectively.

Elements/compounds	Au*	Ag*	Cu	^{a}Fe	^{b}S	SiO_2	CaO	MgO	Al_2O_3	As	Na_2O	K_2O
Composition (%)	0.34	6.3	0.08	2.14	0.22	92.0	0.14	0.03	3.66	0.03	0.11	0.07

The challenge of this facility has been the handling of waste and control of environmental pollution caused by toxic leakages from heaps (Yang, 2011). Zijin mining invested 2.5 billion Yuan by the end of 2016 as mine rehabilitation expenses in order to restore Zijinshan's soil and water sources (Zijin, 2017b). Despite this, a major toxic spill was reported in 2010 and environmental concerns were expressed (Yang, 2011, section 5.3).

4.2. Zijinshan copper bio-leaching mine

Zijinshan copper mine is located in the southeast of China (Shanghang County, Fujian province) and is now considered the largest chalcocite deposit and secondary sulphide mine in China with total sulphide reserves of 240-400 million tonnes and copper metal of 1.72 million tonnes (Ruan et al., 2006, 2011). It is considered the first and largest heap bio-leaching plant in China (Liu et al., 2010). Zijinshan copper ore contains high pyrite (5.8%) and less acid consuming gangue minerals. The current average copper grade was 0.38%. The daily ore supply through the underground mining system is 10,000 tonnes.

The main copper bearing minerals are, covellite (CuS, 36.6%), digenite ($Cu_{1.8}S$, 47.2%), enargite (refractory copper mineral, Cu_3AsS_4, 15%), kuramite (Cu_3SnS_4, 1.1%), chalcopyrite ($CuFeS_2$) and chalcocite (Cu_2S). The gangue minerals present in ROM ore are quartz (64.2%), alunite (11.67%), which is a hydrated aluminium potassium sulphate mineral, and dickite (15.24%), which is a phyllosilicate clay mineral (Ruan et al., 2006, 2011, 2013; Liu et al., 2016a). The chemical composition of ROM ore is given in Table 4 (Ruan et al., 2011).

A pilot plant consisting of bio-leaching followed by SX-EX was initially built in late 2000 to produce 300 tonnes/year copper cathode. Subsequently, it was scaled up to a capacity of 1,000 tonnes/year copper cathode by June 2002 (Ruan et al., 2006). Ruan et al. (2006) detailed these pilot plants and the initial tests. The commercial copper heap leaching facility was started in late 2005. The heap width was about 44 m and the lift height was 6-8 m for a leach cycle of 30-180 days at 12-16 $L/m^2.h$. The second lift was formed on top of the first lift and another leach cycle was started. The final heap height was maintained at 24 m (i.e. multi-lift heap configuration) and the total estimated heap area was 0.2 million square meters (Ruan et al., 2011, 2013; Liu et al., 2016a). The heap was constructed using crushed ore with coarse particle size distribution (80% smaller than 40 mm) and particle agglomeration was not typically carried out. Unlike other primary copper heap leaching systems that require oxygen, forced air injection was not performed due to the presence of secondary copper sulphides (Ruan et al., 2006, 2011, 2013; Liu et al., 2016a). The annual copper cathode production capacity is 20,000 tonnes since 2010 (Ruan et al., 2011).

Table 4: Chemical composition of ROM ore at Zijinshan copper mine (after Ruan et al., 2011). ^aS: Total sulphur.

Elements/compounds	Cu	^aS	SO_3	Fe	As	CaO	MgO	Al_2O_3	SiO_2	K_2O	Pb	Na_2O
Composition (%)	0.4	5.28	4.18	3.59	0.021	0.032	0.14	12.22	67.19	1.58	0.02	0.11

Zijinshan copper bioleaching mine operates under extreme conditions (elevated temperatures 45-60 ^oC in the leaching solution and more than 60 ^oC inside the heap, low solution pH 0.85-1.1, low redox potential 700-760 mV, low microbial activity) compared to other industrial copper bio-leaching plants. However, high recovery rate of 80% is achieved after 180-200 days without forced air injection (Domic, 2007; Ruan et al., 2011, 2013; Liu et al., 2016a). High heap temperatures are caused by self-heat generation from the oxidation of sulphide minerals (Zou et al., 2015; Liu et al., 2016a) and enhance chalcocite, digenite and covellite leaching (Bolorunduro, 1999; Ruan et al., 2013). The high pyrite fraction also releases heat and sulphuric acid and iron (50 g/L) once it is oxidised (Ruan et al., 2006; Liu et al., 2010; Ruan et al., 2011, 2013; Zou et al., 2015).

Microbial genera present in the Zijinshan copper mine and solution ponds are identified as Acidithiobacillus (such as A. thiooxidans, A. albertensis and A. caldus, these are major sulphur oxidisers), Leptospirillum (ferrous oxidisers), Sulfobacillus, Acidiphilium and Ferrimicrobium. Liu et al. (2010, 2016a) discussed this aspect in detail. Furthermore, these microorganism cultures and their diversity (i.e. more Leptospirillum strain at the outer and lower sites of the heap and in the leaching solution, while greater Acidithiobacillus strain inside the heap and close to the top surface) significantly help in long term incubation of the heap bio-leaching process (Liu et al., 2010; Ruan et al., 2011). They control pyrite and ferrous oxidation, which results in high heap temperatures and ferric ions within the system, resulting in high leaching efficiencies (Zou et al., 2015). In addition, life cycle assessment studies indicated energy saving and improved environmental impact at Zijinshan copper mine compared to conventional flotation followed by smelting (Ruan et al., 2011).

4.3. Dexing copper waste dump

Dexing copper mine is located in Nanchang, Jiangxi Province of China. It currently produces 36 million tonnes of copper ore annually by open pit mining operations. Over the years 500-600 million tonnes of low grade sulphidic over-burden and waste rock (0.1-0.3% copper grade) have accumulated. The dump thus has about 1.2 million tonnes of copper (Yang et al., 2002; Wu et al., 2007, 2009a, 2009b). The dumped waste ore typically contains 0.45% primary copper sulphide (chalcopyrite), 0.028% secondary copper sulphide, 0.0068% free copper oxide and 0.0052% bonded copper oxide. Dump leaching was preferred to extract the copper content due to low capital and energy costs (Wu et al., 2007, 2009b).

The waste dump was built along the upstream valley of the Dawu River with a total area of approximately 7.6 km^2. The height of the dump was about 150 m, which is relatively high compared to conventional dump leaching operations. The steep dump slope, which was about 70^0, poses possible dump failures due to liquefaction and it was not fully addressed (section 5.3).

After the preliminary experiments commencing in 1979, a 1,000 tonnes scale copper dump leach was started in 1984. In 1987, the waste rock copper grade was 0.12% with recovery (copper in chalcopyrite) of about 17% initially achieved. Recovery was improved to 30% after a series of experiments was carried out and commercial production started in 1997 to produce 2,000 tonnes of copper/year (Yang et al., 2002).

Wu et al. (2007) presented the flow-sheet of the dump leaching plant. Since the rock piles are constructed using ROM ore rather than crushed and agglomerated ore, the current recovery is less than 10%. A very broad size distribution ranging from fine particles to boulders was reported (2-1000 mm). These particles get distributed and compacted at the surface during the heap construction, which causes particle segregation and uneven permeability, respectively (Wu et al., 2007; Ilankoon and Neethling, 2016). Subsequently, poor and non-uniform permeability causes preferential flow channels or liquid channelling between the particles and reduces overall copper recovery (section 5.2, Ilankoon and Neethling, 2016; McBride et al., 2017). Microorganisms (Acidithiobacillus) are also required to accelerate the copper leaching process, however the population of Acidithiobacillus within the dump was found to be relatively small (below 10^4 cells/mL) (Wu et al., 2009b). Since bacterial growth is limited and inefficient in leaching primary sulphide minerals, such as chalcopyrite, low copper concentrations are expected. The copper concentration in the leached solution was low, approximately 0.3-0.45 g/L. Thus, the production is less than 800 tonnes/year (i.e. much less than the planned copper production of 2,000 tonnes/year). Liu et al. (2004) recommended pH value of 2 (1.8-2), add nutrients, adopt shorter recycling time of leachate and measures to increase aeration and permeability, but the changes of copper production by implementing these are not reported yet.

4.4. Heap and in-situ leaching of ion-adsorption type rare earth ores in southern China

Considering the small size of ion-adsorption type rare earth deposits and scale of operations, individual mining operations are not identified and the general extraction methodologies used in southern China are discussed instead.

Commercial extraction of REOs using ion-adsorption type deposits was initially performed by tank or heap leaching (Yang et al., 2013). Tank leaching of ion-adsorption clays was carried out in a bath, 10-20 m^3, filled with ore up to about 1.5 m, and the leaching solvent (1-4% ammonium sulphate) was introduced at the top. The metal enriched solution was collected at the bottom and was further processed with oxalic acid to form a rare earth oxalate precipitate. The precipitate is dried and subsequently burned (850 ^{0}C) to obtain a high grade rare earth concentrate, which has 92 wt. % of REOs (Chi and Tian, 2007, 2008; Yu, 2001; Li and Yang, 2016).

Heap leaching was later employed to treat ion-adsorption type rare earth ores since it is cheaper and the heap was built on an impermeable layer. Typical heap heights were in the range of 1.5-5 m and a solid-lixiviant (i.e. ammonium sulphate) ratio of 0.25-1 was maintained. After 100 to 320 hours of leaching time, high rare earth extractions of 90% was obtained (Li and Yang, 2016).

However, both tank and heap leaching based processing of one tonne of ion-adsorbed rare earth ore produces 2,000 tonnes of tailings and 1,000 tonnes of wastewater that contains high concentrations of ammonium sulphate and medium and heavy rare earth metal ions. In addition, 300 m^2 of vegetation and topsoil were typically removed prior to the mineral processing operations (Information Office of the State Council, the People's Republic of China, 2012; Yang et al., 2013). Total of 302 abandoned mines (not specified as formal or unregulated operations) and 191 million tonnes of tailings were found in Ganzhou region and deforestation increased to 153 km^2 in 2010 compared to 23 km^2 in 2000 (Yang et al., 2013). The reclamation cost for these rare earth mines was estimated at US$ 5.8 billion. In addition, the overall environmental degradation effects caused by mining operations were severe soil erosion, increased frequency and magnitude of flooding, air pollution, ecosystem changes, loss of biodiversity and human health problems (Liang et al., 2014; Zhuang et al., 2017). Liang et al. (2014) reviewed the concentrations of REEs in soil, water, air and plants in mining areas and found that the values are significantly higher than the threshold values. The measures to control the environmental contamination were also limited due to the nature of ion-adsorption type rare earth mining activities, which were mostly unregulated (section 5.5). Considering these adverse environmental impacts, the Chinese government enforced a ban on tank/heap leaching of ion-adsorption type REEs and monazite deposits in June 2011 and recommended ISL for this type of ore (Information Office of the State Council, the People's Republic of China, 2012; Li and Yang, 2016).

Surface vegetation clearing, deforestation, soil excavation, and tailing generation on the ground are found to be minimal in ISL and thus it is considered advantageous in terms of tackling environmental effects associated with the ion-adsorption type rare earth mining in China (Li et al., 2010; Yang et al., 2013). During ISL of ion-adsorption type deposits, 0.8 m diameter holes, typically spaced about 2-3 m apart, are drilled into the rare earth ore body up to a depth of 1.5-3 m and REEs are selectively leached by injecting the leaching solution (0.3 M ammonium sulphate) at high pressure. The pregnant liquor is subsequently extracted and processed to obtain REOs. The rare earth extraction is 85-90% and the whole process takes about 150-400 days. The annual average production of REEs using ISL is about 200 tonnes of REOs (Yang et al., 2013; Li and Yang, 2016). However, ISL does not necessarily imply environmental impacts are minimal in ion-adsorption type rare earth mining and this aspect will be discussed in section 5.4 in detail.

Each ISL project requires a detailed geological and geotechnical survey as a prerequisite and necessary parameters are the hydrogeological structure of the potential mining area, permeability of surrounding host rock, ore geology, rare earth ore characteristics, ore grade and composition, and total ore reserves. Otherwise, ISL operations would result in recovery efficiencies as low as 5% (Zhao, 2000; Yang et al., 2013) and high production costs (Zuo, 2012).

4.5. Main uranium percolation leaching operations

Individual uranium operations in China have not been explicitly discussed in the percolation leaching literature and this could be due to the importance of uranium as a strategic resource being extracted by the state owned bodies. Zhang (2012d) identified six uranium production centers in China, namely, Fuzhou and Chongyi (Jiangxi, east China), Lantian (Shaanxi, central China), Benxi (Liaoning, northeast China), Shaoguan (Guangdong, south China) and Yining (Xinjiang, northwest China), where uranium extraction in Fuzhou mine is based on conventional acid leaching. The key percolation leaching operations are summarised in Table 5.

Table 5: Operating uranium mines in China (adopted from Zhang, 2012d, The Nuclear Energy Agency and the International Atomic Energy Agency, 2016, and WNA, 2017b). UG denotes underground and n.a. denotes not available. Uranium quantities are expressed in terms of tonnes contained uranium (U) rather than uranium oxide (U_3O_8) [0.848% U= 1% U_3O_8].

Mine	Province	Ore type	Mining method	Recovery (%)	Nominal capacity (tonnes U/year)	Planned capacity (tonnes U/year)	Started year
Chongyi	Jiangxi	Granite	UG, heap leaching	84	150-200	300	1979
Lantian	Shaanxi	Granite	UG, heap leaching	90	100	n.a.	1993
Yining	Xinjiang	Sandstone	ISL	n.a.	330-480	500-800	1993
Benxi	Liaoning	Granite	UG, block leaching	90	120	n.a.	1996
Qinglong	Liaoning	Volcanic	UG, heap leaching	96	100	200	2007
Shaoguan	Guangdong	Granite	UG, heap leaching	90	200	300	2008

Commercial heap leaching operations of uranium were initially started at the Chongyi mine (Jiangxi) in 1979 and at the Lantian mine (Shaanxi) in 1993 (Dahlkamp, 2009). Stope/block leaching was first applied at the Lantian mine, which had a uranium content of 0.171%. This granite type uranium deposit contains about 2,000 tonnes of uranium. Overall uranium recovery was 80-89% and the residue had 0.014% of uranium (Zhang, 1997; Zhang, 2012d).

The identified in-situ leaching amenable uranium reserves in northern and north-west China are Yili, Tuha and Junggar basin in Xinjiang and Erdos, Erlian and Songliao basins in Inner Mongolia (The Nuclear Energy Agency and the International Atomic Energy Agency, 2016). Uranium ISL operations in China were started in Tengchong (Yunnan) and Yining (Xinjiang) (Zhang, 2012d; WISE Uranium Project, 2015). Xinjiang's Yili and Tuha basin hosts Yining mine and it is contiguous with the Ili uranium province in Kazakhstan, but with different ore geology. These interstratified sandstone type uranium deposits are economically viable and considered as important uranium resources in China (Peng et al., 2016; The Nuclear Energy Agency and the International Atomic Energy Agency, 2016; WNA, 2017b). ISL operations were started in 1993 and acid leaching followed by ion exchange recovers about 330-480 tonnes of uranium per year (Zhang, 2012d; WNA, 2017b). Shihongtan deposit in the Tuha basin of Xinjiang is hosted by flat-lying porous sandstones (Peng et al., 2016) and uranium resources were estimated as 3,000 tonnes of uranium (Dahlkamp, 2009). The average grade and ore body thickness are reported to be 0.03% uranium and 7.2 m, respectively (Su et al., 2002a). Preliminary leaching recoveries of 87-96% and 66-89% were obtained with sulphuric acid and ammonium bicarbonate, respectively. Several challenges were observed in acid leaching tests, such as poor permeability, high acid consumption, high calcite content, existence of clay, lower uranium concentration in the leachate, scaling of the ore bed and corrosion of equipment. Thus acid leaching was not feasible at the Shihongtan deposit and weak acid or alkaline ISL was recommended (Su et al., 2002a, b). Chen et al. (2012) studied the diversity of microbiological communities in the Shihongtan deposit pertaining to bio-leaching of uranium ore. Despite these developments, the current operational state of the deposit is not reported. Pilot tests and feasibility studies are being carried out at the Erdos and Erlian deposits (The Nuclear Energy Agency and the International Atomic Energy Agency, 2016). However, the Erlian sandstone deposit is found to be unsuitable for ISL due to low permeability (WNA, 2017b).

5. Challenges of percolation leaching in the Chinese mining industry

At present, the biggest challenges for China's mineral resources exploitation are declining ore grades, increasing mine depth, complexity of ores, minimising environmental impacts during mining activities and mine rehabilitation. These challenges are associated with higher production costs and create difficulties when selecting and optimizing mining, mineral processing and metallurgical separation and production systems. Percolation leaching is widely used for the treatment of low grade ores with the main factors that affect leaching recovery being ore types, particle size distribution, gangue minerals, heap scale, permeability, leaching time and leaching environment (e.g. ore geology and hydrological factors in ISL). The analysis in this work of gold, copper, REEs and uranium mining based on percolation leaching in the Chinese mining industry implies that the challenges are also specific to different metal processing routes. For example, liquid channelling and less bio-leaching potential of sulphide ores limit recoveries in copper heaps and dumps, while ISL of uranium ores requires that extensive mine site rehabilitation is undertaken once mining operations cease. The main challenges and associated developments of percolation leaching with respect to the Chinese mining industry are highlighted in detail.

5.1. Acid, water and iron balance in heap leaching operations

Secondary copper ores with high pyrite content and low acid consuming minerals result in low pH values of about 0.85 and high ferric ions at the Zijinshan copper bio-leaching plant. This has been a challenge to the heap leaching and subsequent SX-EW operations. Excessive acid and total iron decrease the solvent extraction efficiency and also increase the energy consumption (Ruan et al., 2006; Liu et al., 2010; Ruan et al., 2011). Since pyrite leaching typically contributes to ferric ions, bioaugmentation of microorganisms in the heap can be applied for controlling pyrite leaching (Zhang et al., 2014). Ruan et al. (2011, 2013) indicated that the excessive iron in the solution was removed by jarosite formation, but this is limited at low pH values (Zou et al., 2015). Jarosite formation could also reduce the heap permeability and the contact between the extractant and mineral grains and thus negatively affect the leaching efficiency. However, Ruan et al. (2011) proposed that mineral dissolution would not be affected, since formed jarosite is well crystallised. However, future research studies were recommended to elucidate the detailed mechanisms of jarosite formation (Ruan et al., 2011). Limestone powder was added to the raffinate to balance free acid and ferric ion concentration. In addition, the SX unit was designed as a two-stage process, which achieves iron stripping followed by copper stripping (Ruan et al., 2006).

Since water balance is also a challenge in heap leaching operations, different approaches have been adopted in the Chinese mining industry. For example, the leach solution is recycled in the leaching-SX system at the Zijinshan copper mine, which gets a mean annual rainfall of 1676.6 mm. AMD from heaps rich in copper ions (273 mg/L) is treated separately by membranes in the dry season. The copper rich water (2 g/L) retained by the membranes is directly fed into the SX system. In addition, raffinates from the leaching-SX system and AMD are stored separately in flood collection ponds and subsequently neutralised using lime in the rainy season (Ruan et al., 2011). Water balance challenges at Tuwu copper mine in the Gobi desert are different with the main contributor to water loss being evaporation (Liu et al., 2016b). However, detailed water balance studies (e.g. Bleiwas, 2012) have not been reported pertaining to heap leaching in the Chinese mining industry.

5.2. Unsaturated fluid flow in heaps and liquid channelling

Liquid flow in heaps is not well understood yet compared to the reaction kinetics between mineral grains and chemical reagents in industrial heap leaching to extract base and precious metals (Wu et al., 2009a; Ilankoon, 2012; Yin et al., 2016). The fluid flowing in industrial heaps is unsaturated, consisting of both liquid, which is added at the top during irrigation, and air. The fluid flow between the particles is in the transition region between capillary and gravity dominated flow (length scale of order millimetres), whereas intra-particle flow is capillary dominated (length scales of order tens of microns). Heap fluid flow is complicated not only due to being unsaturated, but because of the different length scale of porosities involved (inter- and intra-particle length scales result in quite different flow mechanisms) (Ilankoon and Neethling, 2016; McBride et al., 2017). Liquid distribution at the top is not uniform in practice and liquid thus flows in preferential flow paths through the particles in the heap. This is known as channelling and is ineffective in transporting reagent and dissolved species to all areas of the heap. It also results in more dilute concentrations of metal ions in the pregnant solution (Bartlett, 1992; Petersen and Dixon, 2007; Yin et al., 2013; Ilankoon and Neethling, 2016).

Heaps are often constructed using dump trucks and this leads to particle segregation since ores have a wide size distribution. The variations of bulk density and permeability (low bulk density means less resistance to flow and hence high permeability) across the heap are thus observed. If the ore has significant quantities of clay, localised low permeability regions also form within the rock mass. The introduced liquid flows preferentially to high permeability inter-particle spaces surrounding these low permeability areas (i.e. short-circuiting of fluid flow) (Yusuf, 1984; Bartlett, 1992). Channelling flow behaviour has been challenging in industrial heaps (e.g. Murr, 1979; Wu et al., 2007, 2009a; Ilankoon and Neethling, 2016; Liu et al., 2016b; Yin et al., 2018) and it appears to be caused by local micro-scale heterogeneities that cannot be eliminated within heap systems by good heap construction alone (Ilankoon and Neethling, 2016; McBride et al., 2017).

In the Chinese heap leaching context, liquid channelling and associated challenges and metal recovery inefficiencies have been reported by several investigators. Wu et al. (2007, 2009a) reported liquid channelling of the Dexing copper dump due to its high clay content, wider particle size distribution and subsequent particle segregation. Very low recovery values were reported (10%) compared with those obtained at the planning stage (30%). Yang et al. (2008) employed computed tomography (CT) based image processing to ascertain permeability variations in column leaching and found reduced permeability at the bottom of the column mainly due to compaction of particles and fine particle migration from top to bottom. Liu et al. (2016b) reported high mud contents of copper oxide ore at the Tuwu copper mine (Xinjiang) and this has been the biggest challenge to heap permeability; otherwise copper oxide ores favour leaching mechanisms. Heap height (2-2.5 m compared to 4 m), percentage of fines (less than 8%) need to be controlled to maintain satisfactory permeability levels and thus minimise liquid channelling (Liu et al., 2016b).

5.3. Accumulation of waste dumps and tailing dams, stability and AMD

Waste dumps that contain low metal content have been a challenge in the Chinese mining industry. The waste dumps occupy a significant land area (e.g. Dexing copper dump) and negatively affect the environment and human health (e.g. AMD). Even though the ores in waste dumps are very low grade, the metal content is significant considering the overall ore volume and thus metal extraction of these ores is encouraged. However, metal extraction is challenging in dump leaching considering the wider particle size distribution and unfavourable heap hydrodynamics (section 5.2). For the Dexing copper operation (section 4.3), dump bio-leaching and hydrodynamics (e.g. loosen the dump, strip the dump surface, minimise liquid channelling, intermittent liquid addition) need to be optimised to improve the copper production (Wu et al., 2009b; Yin et al., 2012; Ilankoon and Neethling, 2016; Yin et al., 2018; Fernando et al., 2018b).

Once waste dumps grow in size, potential for liquefaction also needs to be addressed to ensure dump stability and to avoid catastrophic dump failures. Dump liquefaction is triggered when saturated, loose granular particles contract or collapse under shear strain, which can be initiated by static or dynamic (e.g. a wave caused by dump trucks and blasting) loads (Thiel and Smith, 2004; Wu et al., 2009b; Yin et al., 2012, 2018). Static liquefaction is a far more common triggering mechanism in dump failures. Yin et al. (2012) observed the loss of rock integrity and mechanical strength during leaching conditions due to acid and bacterial attack. Dexing copper waste dump (about 150 m high, dump inclination about 70^0) is constructed over a poorly prepared foundation without any elastic leach pad. Dumps can become locally saturated at high liquid addition rates or during the rainy periods. Once the dump is near saturated, a modest shear strain will trigger local liquefaction, which eventually results in the failure of the whole dump. Thus, increased attention is required to maintain the stability of these waste dumps (Wu et al., 2009b) and/or alternative approaches need to be considered to control the accumulation of tailings (section 6.2).

AMD is associated with waste dumps once sulphide minerals oxidise under oxygen and water in both abiotic and biotic environments. This leads to the unwanted production of sulphuric acid. The acidic streams generate heavy metals, such as zinc, copper, cadmium, lead, cobalt, nickel, arsenic, antimony and selenium and the contaminated water contains species of these metals in addition to high sulphate levels (Falayi and Ntuli, 2014; Fernando et al., 2018a). However, water for human consumption should ideally contain less than 250 ppm of sulphates according to the water quality standards proposed by the World Health Organization (WHO) and US Environmental Protection Agency (EPA) (Balintova et al., 2015; U.S. EPA, 2017). AMD is considered as a major source of surface and ground water contamination associated with waste rock piles (Sáinz et al., 2002; Yin et al., 2012, 2013; Li et al., 2015; Fernando et al., 2018a). This has been identified as a major challenge in the Chinese copper leaching sector with respect to ecology and human health (Yin et al., 2018). Fernando et al. (2018a) discussed the occurrence of AMD due to mining activities in detail, while Wu et al. (2009) and Yin et al. (2012, 2018) presented data on the AMD problem at the Dexing copper waste dump.

Yang (2011) discussed the environmental pollution caused by Zijin mining operations around the Zijin Mountain in Fujian province, eastern China. The nearby Ting River has been contaminated due to toxic spillages and a major leakage of waste water emitted from tailings was reported in 2010. It was reported that the water quality of the river deteriorated and the fish population was significantly affected. The company had used three safety measures to avoid environmental pollution around the mine site. These were employing a leach pad at the bottom of the ore stockpile, maintaining seepage collection wells to collect any leaked water and installing a water quality monitoring station downstream of mine's waste water discharge point. However, the pollution accident in 2010 indicated the simultaneous failure of all the implemented safety measures. Similar environmental impacts associated with tailing dams were reported around the neighbouring Wuping mine (less than 1 km from Zijin Mountain) for which Zijin mining is the largest shareholder followed by Wuping County (Yang, 2011).

5.4. Environmental pollution caused by ISL of ion-adsorption type rare earth ores

The Chinese government supports sustainable utilisation of ion-adsorption type rare earth resources in China and the necessity to recover lean ores and tailings (Information Office of the State Council, the People’s Republic of China, 2012). ISL was adopted to treat ion-adsorption type rare earth ores due to the environmental impacts caused by tank/heap leaching, such as greater surface vegetation clearing (3 times compared to ISL), increased soil excavation and subsequent soil erosion, and disposal of waste water and tailings (section 4.4). The application of ISL in the Chinese rare earth mining does not imply this has led to minimal environmental degradation and negative impacts of the technique have still been reported to occur (Li et al., 2010; Yang et al., 2013).

The main environmental concerns are underground water contamination, mine site remediation, mine collapses and landslides. ISL of ion-adsorbed type rare earth ores generates high volumes of drilling slurry (0.7 million m^3/km^2) and injected ammonium sulphate, which can cause elevated pH, high concentrations of ammonium and sulphate ions and dissolved rare earth species in both surface and ground water (Du, 2001; Liu, 2002; Yang et al., 2013). Mine site rehabilitation, once mine activities cease, is costly compared to heap leaching and the rehabilitation process depends on the mine site characteristics. In addition, mobilisation of injected leaching reagents to the surface topsoil layer makes rehabilitation more difficult since it suppresses surface vegetation and plants (Palmer et al., 2010; Liang et al., 2014). Another related key technical problem is leaching reagent mobilisation around the leaching wells in ISL and this must also be minimised (Li and Yang, 2016). The other adverse effect is the relationship between ISL and triggering of landslides with a number of landslides in Ganzhou region reported to have been caused by ISL (Zuo, 2012; Yang et al., 2013).

Adverse environmental impacts are more likely to be exacerbated by the implementation of ISL without assessing geological, geotechnical, hydrological, financial and environmental factors in detail in potential ion-adsorbed type rare earth mines. However, a ban on heap leaching for these ores by the Chinese government without accounting for mining conditions and their applicability is questionable. Rather it is suggested that the government should facilitate improved tariff and compensation benefits, and regulations to support ISL and get rid of illegal rare earth ore mining activities (section 5.5) (Yang et al., 2013). Li and Yang (2016) identified that ISL must be improved to optimise rare earth extraction efficiencies as well as minimising the adverse environmental impacts.

5.5. Unregulated REEs extraction from ion-adsorption type rare earth ores

Since ion-adsorption type rare earth ores are easier to process, are more valuable and do not contain radioactive elements compared to other rare earth ores (section 3.3), unregulated or illegal extraction of REEs has been a complex challenge in the Chinese mining industry. The ion-adsorption type rare earth ore miners in China are of three types, namely, white, grey and black miners. White miners are fully regulated and adhere to the Chinese government's environmental regulations. However, grey (i.e. sell crude rare earth concentrates for cash transactions) and black miners (i.e. low cost producers) do not follow the government regulations and standards, and are known as unregulated or illegal miners. Even though grey miner operations are unregulated, their role is important in the Chinese economy since they supply essential resources (magnetic rare earths: neodymium, praseodymium and dysprosium) to the down-stream producers, such as the magnet industry (Packey and Kingsnorth, 2016).

It is reported that the local residents dig ion-adsorption clays from mountains behind their homes and process these in their backyards to extract heavy REEs (Yang et al., 2013). The extent of the illegal rare earth ore output is unknown and it is primarily based on the evidence of missing exports. It is estimated to be 20,000-30,000 tonnes per year from 2006 to 2008 (Wübbeke, 2013). The most recent estimates were around 40,000 tonnes (Stanway, 2015). This represents about 40% of the domestic market and 30% of the global rare earth market. The extracted heavy rare earth concentrates (a mix of rare earths) are sold at a cheap price (20,000-30,000 Yuan per tonne) (Packey and Kingsnorth, 2016), which drives down global REO prices and also reduces market stability of external rare earth companies, such as Molycorp in the USA. As a result Molycorp filed for bankruptcy in 2015 (Stanway, 2015).

The economic impacts of illegal ion-adsorption type rare earth ore mining to the local mining industry are well documented. Once the unregulated miners extract the high grade fraction on a large scale, the future resource potential of the area will be significantly reduced. This is due to mining activities without a mine plan whereas in formal mining operations, the mine life can be maximised by mixing high and low grade ores. However, this is typically not the case in illegal mining of ion-adsorption type rare earths. In addition, the environmental impacts are often neglected in illegal mining activities and could cause significant subsequent health problems (Packey and Kingsnorth, 2016).

In order to reduce black miners in the Chinese rare earth industry the government has shutdown several illegal mining sites and processing facilities. In addition, a significant amount of rare earth concentrates have been confiscated. Since the attempted elimination of black miners has resulted in limited success, other approaches have been recommended by the Chinese authorities. The Chinese ministry of industry and information technology (MIIT) and the China ministry of land and resources (MLR) have both set the same rare earth production quota since 2010 in order to limit over-quota production by illegal miners (Tse, 2011). The current policies (e.g. rare earth development plan, 2009-2015) will only approve new ion-adsorption type REE mining and separation projects, which have a minimum capacity of 3,000 tonnes/year (Tse, 2011). These plans and regulatory approaches should minimise illegal REE mining in China.

The downstream production of rare earth products, such as permanent magnets, phosphors, hydrogen storage materials and abrasive polishing materials is also encouraged in China's 12th five year plan. The proposals aim to integrate all rare earth mines and extraction facilities in the country with six state enterprises. This would give the control of about 90% of the world's rare earth supply to the government and establish China's dominance on the local and international rare earth market (Tse, 2011; Wübbeke, 2013; Stanway, 2015; Packey and Kingsnorth, 2016). More detailed discussion of this aspect is outside the scope of this work.

5.6. Ground water restoration and site reclamation in uranium ISL

ISL of uranium could pollute the environment in two main ways, namely, pollution of ground surface due to leakage of pregnant solution and pollution of underground water due to interaction of leaching agents and host rocks (Bakarzhiyev et al., 2002). The US EPA enforced maximum level of uranium in drinking water is 0.03 mg/L (U.S. EPA, 2012; Wu et al., 2014a). Sulphuric acid leaching of uranium ore with oxidants (e.g. H_2O_2) through ISL generates uranium ions and other soluble species, such as arsenic, iron, molybdenum, sulphur and vanadium. The total dissolved solids (TDS) is in the range of 8-12 g/L. Since the dissolved species could mobilise to surrounding ground water during mining activities and after mining has ceased, ground water restoration is carried out once uranium extraction is stopped. Smedley et al. (2006) discussed uranium mobility in groundwater in detail. Ground water restoration is primarily based on the uranium concentration of the production well, which can be below 15-20 mg/L (Blaise, 2002; Li et al., 2002). However, it could be challenging and depends on ionic strength in the mined zone and geological and hydrological conditions.

In uranium ISL operations more solution is typically extracted than the injected volume in order to minimise the mobilisation and dispersion of dissolved species, but this does not necessarily diminish the necessity for mine site reclamation. Test wells are typically employed during the ground water restoration process to determine water quality and assess the pollution level compared to a reference concentration level. The dissolved species need to be removed from the extracted water during the restoration phase and the treated water, which is assessed based on TDS and sulphates, will be re-injected into the aquifer. The main techniques employed to treat contaminated ground water are reverse osmosis, neutralization and precipitation, and electrodialysis. Neutralization and precipitation methods can be considered as pre-treatment methods, which remove free acid, TDS, heavy metals and anions except sulphates. Reverse osmosis would be effective if pre-treatment (i.e. sulphates and total iron removal) is carried out and hence overall treatment costs would be higher (Li et al., 2002). Li et al. (2002) discussed the electrodialysis process in detail and its effectiveness, such as the high water recovery of 83%. Despite that, case studies pertaining to restoration of aquifers after ISL of uranium in China have not been presented. This implies the requirement for future research studies on uranium mine rehabilitation, which has been recognised by the Chinese government (see section 6.4).

6. New developments and research in the Chinese mining industry

There have been new research studies and regulatory frameworks to improve economic and environmental constraints for percolation leaching in the Chinese mining industry.

6.1. Enhance micro-cracks in ore particles

The rate of metal extraction in heap leaching depends on micro-pores, cracks and accessibility of leach solution through those to the mineral grains. High pressure grinding rolls (HPGR) result in formation of increased micro-cracks in the ore compared to other comminution mechanisms (Ghorbani et al., 2012, 2013). Despite the applications of HPGR in mining industry during the past decades (e.g. Apling and Bwalya, 1997; Klymowsky et al., 2002), few examples have been cited with respect to the Chinese heap leaching sector. As increased micro-crack generation enhances the mass transfer mechanisms of leaching reagents and dissolved metal species, Yin et al. (2017) systematically compared the properties of the particles produced by a conventional jaw crusher and HPGR. A higher proportion of effective micro-cracks in coarse particles may be a strategy to enhance heap leaching kinetics (Tang et al., 2016). In addition, Zijin Mining Group introduced HPGR for copper heap leaching in Wuping copper mine and the installation and commissioning of the equipment are being carried out. Yang et al. (2016) employed microwave pre-treatment to enhance micro-cracks of uranium ores pertaining to heap leaching and the increases of specific surface area and porosity were reported.

6.2. Extraction from mine tailings and utilisation of mine tailings in other industries

The mining industry approximately produces 1.2 billion tonnes of tailings per year in China (Chen et al., 2017). Extraction of valuable elements from mine tailings and/or utilisation of that fraction in alternative industries have received greater focus recently. Zhou et al. (2017) studied copper mine tailings that contain low grade refractory gold and assessed the leaching efficiency in column experiments pertaining to dump leaching. The gold extraction was 50-70% (Zhou et al., 2017) indicating that this strategy has merit.

The utilisation of mine tailings as a backfilling aggregate in underground mine workings has also been suggested. Chen et al. (2017) prepared the backfilling aggregate by mixing the mine tailings and construction waste. This could be a potential way to manage tailings produced from heap leaching in the Chinese mining industry in the future.

Since tank/heap leaching of ion-adsorption clay type rare earth ores produce a lot of tailings, which subsequently cause serious environmental concerns (section 4.4), utilisation of these in other industries has also been considered. The rare earth content of the tailings was only 0.04 wt. % and monazite, xenotime, parasite and colloidal rare earths were the main host minerals. It has been proposed that the ion-adsorption clay rare earth tailings could be used to produce raw materials for other industries, but the tailings should be pre-treated (Wang et al., 2016a). Wang et al. (2016a) studied the tailings collected from ion-adsorption clay type rare earth ores in Ganzhou, South China and found that they contain 92% in total of kaolinite and quartz. The remaining iron and titanium containing minerals (1.72 wt. %) were feldspar, biotite, muscovite, titanomagnetite, pyrite, ilmenite and limonite. In order to use these tailings as raw materials for the ceramic industry, initial removal of the Fe_2O_3 content of 2.11 wt. % is suggested, otherwise a brown colour is imparted to the ceramic products (Chinese standard for ceramic industry applications recommends maximum 1.8 wt. % Fe_2O_3). Size separation followed by magnetic separation were performed to remove iron-bearing minerals, such as titanomagnetite and limonite content. The iron content in kaolinite could be further reduced by sodium dithionite ($Na_2S_2O_4$) treatment (Wang et al., 2016a).

6.3. Strategies to improve permeability and leaching rate in percolation leaching

In order to increase the permeability and uranium leaching rate, surfactants were added in uranium column and agitation leaching experiments pertaining to ISL of uranium ore (Cai et al., 2013). Lü et al. (2016) employed surfactants, such as fatty acid methyl ester sulfonate (MES), sodium dodecyl sulfate (SDS) and Tween-80 and it was found that the SDS increases the permeability coefficient and leaching efficiency by about 5 times and 12%, respectively. Cai et al. (2013) tested sodium dodecyl benzene sulfonate (SDBS), cetyltrimethyl ammonium bromide (CTAB), polyoxyethylene octylphenol ether (OP-10), Triton X-100 (TX-100) and FSO (non-ionic fluorocarbon surfactant). Even though all the surfactants reduce the surface tension of the leaching solution by 50%, non-ionic surfactants (e.g. FSO, OP-10, TX-100) were found to be better in terms of uranium extraction compared to cationic and anionic surfactants (e.g. CTAB, SDBS) since the leaching solution contains H^+ ions and the ore surface has weak electronegativity (Cai et al., 2013). The effect of certain surfactants has also been verified in different mines in China (Karavasteva, 2001; Wu et al., 2013, 2014b; Liu et al., 2017).

A device known as a permeator was implemented to improve heap permeability of low grade ores with high clay content without fines agglomeration (Xi et al., 2005). Wang et al. (2016b) recommended the use of novel scale inhibitors to minimise permeability reduction due to the formation of compounds, such as calcium carbonate in alkaline leaching and calcium sulphate in acid leaching. Addition of a chelating agent and polymer organic compound was also considered in acid leaching to reduce iron, aluminium and calcium based scaling compounds (Wang et al., 2016b).

Forced air injection has already been implemented within the heap leaching industry, especially in sulphide minerals leaching, to improve leaching kinetics (Ghorbani et al., 2016). Yu et al. (2017) employed different air flow rates to improve abiotic copper heap leaching at the Yangla copper mine. Intermittent air addition is considered similar to intermittent liquid addition (i.e. reagents) with results indicating that this method improves heap permeability and decreases liquid channelling (Fernando et al., 2018b). The effect of incremental time interval between forced air injections (i.e. rest period between cycles of air addition) on permeability was also studied and it was concluded that the leaching efficiency could be improved by varying aeration cycles (Wu et al., 2015; Yu et al., 2017).

6.4. Proposed regulations and development plans relevant to percolation leaching

The Ministry of Science and Technology of the People's Republic of China commissioned the 13th five-year national science and technology innovation plan in 2016, which promotes geological prospecting and in-situ bio-leaching of copper, gold and uranium ores (Yin et al., 2018). This highlights the significance of ISL in the Chinese mining industry. The 13th five-year plan and one of the five development ideas proposed by the central committee of the communist party strongly supports ecological environment protection. In order to achieve this objective, green uranium mining and metallurgy plans have been proposed. Research and development frameworks and major demonstration projects will be targeted in the future in China to improve mining safety and ensure environmental protection (Su and Xu, 2017). Wang et al. (2017) urged the government to approve the plans for increasing the life cycle of China's REEs resources and improve the extractions of current techniques in order to fulfil future production targets and requirements.

6.5. Developments in percolation leaching of uranium ores

Zhang et al. (2010) presented strategies to minimise the generation of radioactive solid wastes from uranium mining. Also, heap leaching with zero discharge of process water and activated heap leaching methods that improve the ore surface physical properties are being investigated (e.g. Wang et al., 2002). Since sandstone type deposits are comparatively limited in China, new approaches will help to improve heap leaching of hard rock uranium ores. Furthermore, some sandstone deposits that are amenable to ISL will not be extracted using ISL due to complex geological factors (e.g. Dongsheng sandstone deposits in Inner Mongolia, 30,000 tonnes of uranium in a palaeochannel system), poor permeability values (e.g. Erlian sandstone deposit in Inner Mongolia), smaller thickness of the deposit and high content of clay, calcium and carbonates (e.g. Shihongtan deposit, Xinjiang). Alkaline and neutral ISL techniques, however could be employed to process the deposits which have a high content of carbonates. In order to recover dissolved uranium ions from the pregnant solution, new resins have been developed and some (e.g. SLD-225b) were used to effectively adsorb uranium from high chloride bearing solutions. A novel fractional precipitation process, which is simplified and consumes less reagents, was also developed to recover uranium from concentrated leach liquor (Zeng et al., 2002a; Yu et al., 2013; Xing et al., 2017).

7. Future directions of percolation leaching in Chinese mining industry

Novel and sophisticated visualisation techniques have been recently developed primarily for heap and dump leaching. Zhang and Liu (2017) employed aerial image analysis (i.e. a camera installed on a drone) during heap construction to obtain spatial heterogeneity in the particle size distribution from the top to the bottom of the dump. Several non-invasive techniques were also used to visualize the flow in heap leaching systems, such as electrical capacitance tomography or ECT (Ilankoon et al., 2017), MRI (Fagan et al., 2014; Fagan-Endres et al., 2015; Wu et al., 2016), positron emission particle tracking or PEPT (Ilankoon et al., 2013), and X-ray tomography (Lin, 2015). Ilankoon and Neethling (2012, 2013) described the significance of separating inter- and intra-particle flow aspects in heap hydrodynamics and Miao et al. (2017) subsequently simulated heap hydrodynamics as a dual-pore system. McBride et al. (2017) considered the local variations of inter-particle porosities in order to model the fluid flow paths between the particles in heaps. The possibility and characteristics of liquid channelling could thus be assessed based on these recent studies. Implementation of these new techniques, theoretical concepts and simulations (e.g. Petersen and Dixon, 2007; McBride et al., 2014, 2017) will be important in the Chinese heap leaching industry to understand underlying liquid flow characteristics in heap leaching and improve leaching efficiencies.

Internationally, there is increasing research effort and industry focus on reducing the environmental impacts of mining and mineral processing operations. The results of these studies may provide some indication of the potential benefits and detriments of increased use of heap and ISL in the Chinese mining industry. For instance, life cycle assessment based analysis has shown that the ISL of uranium may offer substantial benefits in terms of greenhouse gas emission reductions, when compared to conventional uranium mining (Haque and Norgate, 2014). However, these benefits appear to be less for the ISL of other commodities, such as copper and gold. Other assessments have shown that copper and gold heap leaching processes will have lower direct water consumption per tonne of ore processed than conventional flotation concentrate processing of mined ore (Northey et al., 2014). These types of life cycle assessment studies of the resource burdens and environmental impacts associated with mining and mineral processing are beginning to emerge for various sectors of the Chinese mining industry, for instance for the hydrometallurgical zinc production chain (Qi et al., 2017). The environmental impacts associated with REEs production in China via ISL have been studied using life cycle assessment by several authors (Weng et al., 2015, 2016; Lee and Wen, 2017). However it is difficult to compare the results of studies of REE processing options due to differences in the product obtained from leaching of ion-adsorbed rare earth deposits (heavy REEs dominant) and other REE deposit types (light REEs dominant) (Weng et al., 2013, 2016; Lee and Wen, 2017). Further research in this area is important to enable evaluation of the environmental performance of percolation leaching processes, so that opportunities for process improvement can be identified.

8. Conclusions

This paper reviewed the percolation leaching techniques employed in the Chinese mining industry and that have been typically used to treat low grade gold and copper ores, ion-adsorption type rare earth ores and both hard rock and sandstone type uranium ores. Heap leaching is a well-established hydrometallurgical extraction technique and it has been widely applied to process base metals, such as copper and precious metals, such as gold in the last 50 years. It has been applied in low grade gold and copper ore processing in China including the microorganism assisted leaching (i.e. bioleaching) of secondary sulphide ores. Dump leaching of copper tailings possesses typical challenges in operation, such as uneven permeability due to wide particle size distribution and liquid channelling.

Heap leaching has been adopted to treat low grade hard-rock uranium ores in China. The ISL method has been employed to treat sandstone type uranium ores due to its favourable metal extraction efficiencies and ability to alleviate radioactive contamination. The technique has also attracted wide attention in the Chinese mining industry with its application to ion-adsorption type rare earth ores. Ion-adsorption type rare earth ores were initially processed using tank and heap leaching, which caused severe environmental pollution in southern China. The Chinese government eventually banned tank and heap leaching to process ion-adsorption type rare earth ores in 2011 and ISL was recommended, instead. However, the main on-going concern of ISL is the possible environmental contamination due to the mobilisation of leaching reagents through host rocks and interactions with ground and surface water and soil. Another challenge in ion-adsorption type rare earth mining is the illegal mining activities in China due to relatively easy processing routes of these ores. However, the Chinese government identified the importance of ISL in the future and recommended sustainable ISL based mining methods to exploit low grade uranium ores and ion-adsorption type rare earths.

The environmental implications of percolation leaching methods represent a set of unique challenges in the Chinese mining industry. Gold and copper heap and dump leaching based AMD problems were identified and mitigation strategies need to be extensively adopted to preserve surface and underground water bodies. Even though ISL operations have been recommended to process uranium ores and ion-adsorption type rare earths, effective mine site rehabilitation plans should be developed and adopted rather than imposing legal frameworks, such as the ban on heap leaching to treat ion-adsorption type rare earth ores. The Chinese government's recent proposal to design ISL based green uranium mining facilities highlights the importance of employing percolation techniques in a sustainable manner.

Considering the future directions of percolation leaching in the Chinese mining industry, implementation of novel research and developments to optimise metal extraction efficiencies and life cycle assessment analysis prior to mining activities is recommended. Extensive research studies on the viability of ISL for hard rock ores, low permeability deposits and deeper ore bodies and mine site restoration after ISL activities need to be carried out to enhance recovery efficiencies and extend the application of the ISL technique in the Chinese mining industry.

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