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Greening Chilean copper mining operations through industrial ecology strategies

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A B S T R A C T

Sawdust was used as cheap sorbent for the remediation of a diesel and oil fuel-contaminated mining soil whereas biosolids were evaluated as collectors and frothers in froth flotation of copper sulphide ores. The use of these waste materials in copper sulphide ore mining and mineral processing may have a positive impact on the cleaner production of copper from its natural raw sources and may decrease the deleterious effect that mining operations have on the environment. Mixtures of oil fuel contaminated mining soil and sawdust were treated in an aerobic reactor at 50.0% humidity for several days. A significant decrease (over 60.0%) of Volatile Organic Compounds (VOCs) content in these mixtures was obtained after one-month of treatment. Rougher flotation of copper sulphide ores using biosolids – from wastewater treatment plants – and humic acids – a component of biosolids – as collector and frother yielded a copper sulphide concentrate with a copper grade and copper recovery of 0.8% and 26.0%, and 3.5% and 29.7%, respectively. Biosolids and humic acids have shown to be potential candidates to partially substitute traditional organic chemicals used in industrial flotation of copper sulphide ores. This possibility opens up an alternative for greening copper sulphide ore flotation by using more environment-friendly flotation reagents. Based on these results, a conceptual model based on industrial ecology and cleaner production principles is proposed for greening the overall copper sulphide ore processing.

1. Introduction

Chile is highly vulnerable to impacts of climate changes due to the great diversity of scenarios where economic activities –intensively based on natural resources exploitation– take place (ECLAC, 2010). These anthropogenic impacts are attributed to continued exploitation of natural resources as raw materials for the agriculture, aquiculture and mining industries, the latter being related to ore extraction, mainly copper ores (Schmidt-Hebbel, 2012).

The environmental impacts caused by continual exploitation of natural resources as well as pollution generated by industrial activities are affecting the quality of life of populations inhabiting surrounding areas and creating wealth inequalities (Subramanian and Kawachi, 2004).

A good example of controversial tradeoffs between economic growth and environmental pollution is the Chilean copper mining sector, where the relationship between the mining industry and society has historically been complex (Oyarzún and Oyarzún, 2011).

The aim of this paper is to provide a conceptual model based on concepts from industrial ecology and cleaner production through the use of environment friendly waste products for greening the mining and mineral processing steps during copper production. These concepts could be a complement to technological innovation, which plays a fundamental role in the long-term development of cleaner production improving the sustainability and performance of mineral processing operations by reducing impacts on the environment.

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In Chilean copper mining operations, copper sulphide ores predominate over copper oxide ores (Bulatovic, 2007). According to statistics from the Chilean Copper Commission (Cochilco, 2013a), in the year 2012 domestic copper mining operations had an annual handling capacity to concentrate 450 million tonnes of copper sulphide ore by froth flotation, yielding 3.7 million tonnes of fine copper. It is projected that for the year 2021, the installed capacity to process copper sulphide ores will increase to around 1200 million tonnes whereas fine copper production will reach 6.8 million tonnes.

Over the period 2001–2011, the total energy consumption of the Chilean copper mining operations increased 59.6%, from 86.2 to 137.6 PJ. During this period, fuel consumption (i.e., diesel, natural gas, coal, etc.) rose from 39.0 to 65.7 PJ, whereas electrical energy consumption increased from 47.2 to 71.9 PJ. Areas with a more intensive use of energy in 2011 were mining exploitation (40%), concentrating plants (25%) and treatment of oxide ores (21%). It is projected that for the year 2020, Chilean copper mining operations will consume 141.8 PJ in electricity. Concentrating plants will consume 56% of the total energy employed in mining, whereas desalination plants and drive systems are projected to consume 14% (Cochilco, 2013c).

In the year 2011 the Chilean copper mining operations consumed 12.6 m^3/s of fresh water (about 400×10^6 m^3). Out of this total water consumption, pyrometallurgical production of copper accounted for 71%, whereas hydrometallurgical production of copper represented 14%. Mine water, drinking water and other services accounted for the remaining 15%. Water consumption per tonne of ore treated in the concentrating plant and hydrometallurgical processing is 0.65 m^3 and 0.12 m^3, respectively. It is expected that demand for fresh water in 2020 will be 17.1 m^3/s (about 540×10^6 m^3) (Cochilco, 2013c).

The copper pyrometallurgical process (Fig. 1) includes five basic stages: 1) comminution, aimed at reducing ore particle size; 2) froth flotation, for obtaining copper minerals concentrate; 3) smelting, to separate the metal from its minerals; 4) converting, aimed at obtaining blister copper, and 5) electrorefining, to purify resulting final products (Biswas and Davenport, 2002; Memary et al., 2012). Every stage requires raw materials, chemical reagents as well as water (Gunson et al., 2012) and energy consumption (Northey et al., 2013), which translates into high levels of environmental impacts due to dust and gaseous emissions (CO_2, SO_2), wastewater discharges containing persistent chemicals, and solid wastes (slags and tailings) disposal.

In general, all steps shown in Fig. 1 are highly energy-intensive and generate hazardous waste materials (Memary et al., 2012; McLellan and Corder, 2012; Moors et al., 2005); however copper smelting and matte converting are autogenous processes requiring less energy.

Other environmental impacts of the mining industry are the production of hazardous wastes by discharges and drainage resulting from daily operation of heavy machinery, where repetitive spills of fuel oil have occurred during their repair and maintenance as well as casual accidents. In many cases soils and sawdust have been used as cheap and readily available adsorbent materials to help the cleanup which must be contained in Hazardous Wastes Landfills (HWL). Current Chilean legislation contemplates bioremediation technologies, such as composting (Antizar-Ladislao et al., 2004), as a valid alternative practice to environmental decontamination (Minsal, 2004), although this green technology needs to be experimentally tested, as argued by Godoy-Faúndez et al. (2008). The composting process applied on soil to remove organic pollutants can be a useful treatment to transform hazardous wastes into inert wastes to be disposed of in a landfill to avoid environmental and human risks.

Froth flotation uses chemical reagents (collectors, frothers and modifiers) to control the wettability of solid surfaces, the electrochemistry of the solution, the dispersion and aggregation of solid particles, and the generation of foam (Herrera-Urbina, 2003). In this way, it is possible to recover mineral species of interest and to prevent the flotation of unwanted gangue minerals.

Because average copper grades of copper sulphide ores in Chile have decreased from 1.18% to 0.90% over the period 2003–2012 (Cochilco, 2012), greater consumption of water, energy and chemical reagents is required to efficiently process low-grade copper sulphide ores. In particular, the consumption of collectors, frothers and modifiers in froth flotation is increasing because higher amounts of low-copper grade ore are processed. For example, the average concentration of collectors and frothers being used in 2012 was 50 g/t ore and 30 g/t ore, respectively. These concentrations correspond to 26,243 tonnes of collectors and 15,745 tonnes of frothers per year. Both of these chemicals represent expensive reagents that pose environmental risks due to their properties such as flashpoint, high vaporization rates and residual chemical properties, which produce an unpleasant odor in warmer climates (classified as hazardous materials for potential health effects) (Chockalingam et al., 2003; Ralston, 2002; Tan et al., 2005).

The copper sulphide minerals industry of Chile may be able to find new environment-friendly reagents for froth flotation through new strategies and concepts from industrial ecology, cleaner production, green chemistry, life cycle assessment and sustainable engineering (Basu and van Zyl, 2006; McLellan et al., 2009; Laurence, 2011) as well as new uses for inert materials after bioremediation processes by composting.

2. Biosolids generation and disposal

Chile will achieve at least 98% of household wastewater treatment by 2013, according to statistics and forecasting from *Superintendencia de Servicios Sanitarios* (Superintendency of Sanitary Services, SISS). Activated sludge has been the main technology deployed at national level, accounting for 51% of total production (SISS, 2010). The accomplishment of this national goal has translated into large organic waste volumes (called sludge or biosolids) that need to be disposed of according to national legislation based on international standards. Biosolids generators are mainly located

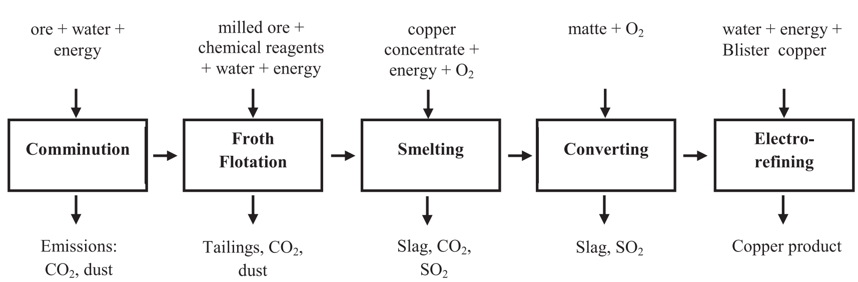

Fig. 1. Flowchart of copper production in a pyrometallurgy operation showing the inputs and outputs at each process step.

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