



## Review article

# A systematic review of sustainable gold extraction from raw ores using alternative leaching reagents

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## ABSTRACT

Drawing on recent experimental and commercial developments, this review reappraises potential substitute leach reagents for cyanide in the gold mining sector. In addition to extraction, the application of these reagents in the gold processing, pre-treatment and gold purification stages is explored. The main objective here is to discuss how the gold extraction process can be more sustainable, with a view to developing more greener leaching reagents.

## 1. Introduction

Gold is the most important precious metal in the world, with estimated reserves of 54,000 tons (Garside, 2019). Global gold demand has increased in recent years, projected at 4345 t in 2018. This has influenced its market price, which averaged US\$1269/oz in 2012, more than four times its US\$271/oz figure in 2001 (Garside, 2020). Gold is extracted from aggregated deposits (primary resources) but because these are becoming increasingly scarce, and are often low grade, complex techniques are required to extract it (Oraby, 2009). It has also sparked interest in “mining” recycled gold-bearing materials (secondary resources), including jewellery scrap and electrical components such as printed circuit boards (Fajardo et al., 2016).

In the case of primary production, processing is dictated heavily by geological setting. Gold can occur in primary hydrothermal veins, volcanic or alluvial deposits. Although gold often occurs with quartz, it is more frequently associated with pyrites and to a lesser extent, arsenopyrite, chalcopyrite, antimonite, pyrrhotite, scheelite, tourmaline and sphalerite. In the context of its processing, gold deposits are typically classified, for the purposes of simplification, as: 1) free milling, and 2) refractory ores (including complex and carbonaceous). Based on their mineralogical characteristics and their mineral processing techniques required to liberate them, however, gold ores can be classified further. There are, as Fig. 1 indicates, 11 gold ore types.

Refractory deposits, as well as low-grade and more complex deposits,

are challenging to work. Refractory character is determined by the gold's ultra-fine occlusion inside sulfide minerals, particularly pyrite and arsenopyrite. It is common to distinguish free milling from refractory on the basis of the intensity of cyanide leaching required: it is greater than 90% in the case of the former, and less than 80% for the latter (Marsden and House, 2006). After it is extracted, the raw ore must be processed. This entails, firstly, the gold being liberated by size reduction, using jaw/cone crushers and mills. Valuable components can then be physically separated from tailings, using gravitational processes, flotation, optical sorting, magnetic and electrostatic separation, depending on ore characteristics (Ventura et al., 2018).

Chemical processing, or hydrometallurgy, then takes place. Starting with the leaching stage, an aqueous solution is used to dissolve gold from ores. Cyanide solutions are very efficient but their toxicity makes the development of alternative reagents such as thiosulfate (Birich et al., 2019; Sousa et al., 2016), halides, thiocyanide, thiourea and microbial leaching (Beckman and Thompson, 2004), imperative. If made commercially viable, these alternatives could ensure efficient gold dissolution but without the environmental risks posed by cyanide (Göknelma et al., 2016). Recovery of the dissolved gold from the leaching solution then follows. This can be accomplished using activated carbon, membranes (Andrade et al., 2017; Villalobos et al., 2014), bioadsorbents (Tsuruta, 2004), solvent extraction (Raiguel et al., 2020) and ion-exchange resins (Choi et al., 2020; Gomes et al., 2001). After selectively extracting gold from leaching liquor as adsorbent materials,

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