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An Alternative Procedure for a Win-win African-Swiss Cooperation in Gold Production in Africa

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In memory of my grandfather Dr. Mohammad Ali Hedayati, a Swiss-educated J.D.

Abstract: The growth of Africa as a major gold (Au) exporter can not only strengthen economic ties with other parts of the world, but also lead to solutions to global industrial challenges, and the only way to stop gold smuggling out of gold-producing African countries seems to be having multiple refineries in Africa, for which developing gold-producing African countries might need technological assistance provided by a more developed country, especially Switzerland. In this Note, the chemistry of gold mining was discussed, and the idea is conveyed that if *aqua regia* is used as a main reagent in both gold mining and the electrolytic refinement of gold, then the two systems of gold mining and gold refining can be coupled industrially and geographically, and such a coupling can facilitate the growth of home-grown gold refineries in gold-producing African countries. It is also discussed that with Swiss companies finding it economical to properly use *aqua regia* in Africa as described, a win-win African-Swiss cooperation will be established that will benefit both the Swiss companies and gold-producing African countries. Further, it is concluded that the addressed cooperation will be accompanied by four of the seventeen goals called 'Sustainable Development Goals' by the United Nations.

Keywords: *Aqua regia* · Gold · Mining · Refineries

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1. Introduction

The most desired element, as well as an element of low abundance of only 0.004 grams per metric ton of the Earth's crust, is gold (Au).[1] Africa is one of the three largest gold- producing continents in the world.[2] With the gold reserves becoming scarcer in mature gold-mining countries, mining in those countries requires deeper digging and becomes more costly.[3] As of December 31, 2022, Ghana, Mali, Burkina Faso, South Africa, and Sudan are the top five gold-producing African countries, with Ghana, producing 127.0 metric tons in 2022, being the sixth of the top ten gold-producing countries in the world (Table 1).[4] The growth of Africa as a major gold exporter can not only strengthen economic ties with other parts of the world, but also lead to solutions to global industrial challenges. Further, shown to reduce poverty directly, gold mining in Africa helps create jobs for local communities.[2]

The gold that is mined in an African country is not necessarily refined there. Except for South Africa, which has an already large gold refining industry, there were only a handful of gold refineries in sub-Saharan Africa until 2012; however, their number has been increasing since then. The refineries offer the countries a way to benefit from their own mineral wealth more than exporting raw gold. Furthermore, the governments of the gold-producing countries in Africa are concerned that the gold in their rocks is produced illegally and smuggled out extensively, and it has been stated by the African Union that the only way to stop the smuggling is to have multiple refineries in Africa.[5] The obvious conclusion is the fact that the refineries often win high-level political backing.[5]

Can developing gold-producing African countries be technologically assisted with the development of the refineries by a more developed country? International gold-mining companies are already potentially interested in investing in gold-mining projects in West Africa,[3] for instance. However, the legal frameworks in gold-producing African countries have not been found equally positive as to their governments permitting foreign companies to explore and operate gold mines.[3] The perception that some foreign companies might ignore the harmful effects that the gold-mining toxic waste has on locals is one possible reason, which might be deepened by the

Table 1. African countries producing more than 50 metric tons of gold in 2022.[4]

African Country	Gold Produced in 2022 (metric ton)	Gold Production Worldwide Rank in 2022
Ghana	127.0	6th
Mali	101.7	11th
Burkina Faso	96.2	12th
South Africa	92.6	13th
Sudan	80.1	16th
Guinea	63.5	17th
Tanzania	50.9	20th

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engravement of colonization by several European countries in the African nations' memories. For the African countries to interact with a foreign gold-producing company that can be held as accountable as possible in the matter of sustainability, natural resource management by the United Nations Environment Programme (UNEP) can be helpful, and Switzerland is the most well-known country in the world for gold refineries, which also has a colonization-free history. Still, any Swiss company that gets involved to help Africa overcome its gold-refining challenge needs to have not only the technological capability, but also the economic desire. The availability of alternative mining procedures may lead to such a desire. This Note is focused on an alternative gold-mining procedure to facilitate the growth of home-grown gold refineries based on African-Swiss cooperation in gold-producing African countries.

2. Traditional Gold Mining

Found in nature mainly in the elemental form, each metric ton of gold ore contains around 4 grams of the element. The majority of the current gold production originates from microscopic grains of the metal, some encapsulated by sulfide minerals containing arsenic (As) or copper (Cu). The normal method for gold mining is cyanidation. The procedure includes treating the crushed and ground gold ore with a solution of sodium cyanide (NaCN) adjusted to a pH value of 10 by the addition of sodium hydroxide (NaOH) (Fig. 1). Under ambient oxidative conditions, the oxidation-reduction (redox) reaction described by the two half-reactions shown by Equations 1 to 3 takes place.[1]

$$4Au(s) + 8CN^-(aq) \rightarrow 4[Au(CN)_2]^-(aq) + 4e^- \quad (1)$$

$$O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq) \quad (2)$$

$$4Au(s) + 8CN^-(aq) + O_2(g) + 2H_2O(l) \rightarrow 4[Au(CN)_2]^-(aq) + 4OH^-(aq) \quad (3)$$

The gold in the complex ion $[Au(CN)_2]^-$ is then removed from the solution by reduction to produce elemental gold.[6] Cyanidation was not used in the gold industry before around 1887, when the process was patented.[1] The other traditional method for gold mining, which has been used for centuries and is still in practice today, is processing gold with elemental mercury (Hg), called amalgamation. In this method, mercury is added to the crushed and ground gold ore, and an easily identifiable gold-mercury amalgam is formed. When the amalgam is heated enough, the mercury is vaporized, and the gold is separated.[6] Many miners in many countries use mercury in artisanal and small-scale gold mining.[7] In both the cyanidation method and the amalgamation method, the finally formed gold ingots need to be refined electrolytically to give gold of 99.99% purity, which is sold as bullion.[1]

Neither the cyanidation method nor the amalgamation method is toxicologically friendly. Although the pH value of 10 in the cyanidation process is high enough to prevent the production of volatile hydrogen cyanide (HCN), which is extremely poisonous,[1] cyanidation is potentially hazardous, and the toxic waste, dumped into tailings dams, is very concerning as to the health of aquatic organisms, animals, and human beings.[6] All the forms of mercury are also variously toxic to aquatic biota and humans.[8] It is estimated that the mercury emission caused by artisanal and small-scale gold mining averages out to 1000 metric tons of mercury per year, and many of the millions of the people who work as gold miners or live in small-scale gold mining areas are exposed to mercury contamination (Fig. 2).[6] In Ghana alone, the estimated number of small-scale gold miners, who commonly use mercury to process gold, is one million.[9]

3. Using *Aqua Regia* as an Alternative

Gökelma *et al.*[10] review a set of alternatives to cyanidation. They mention chlorination and using iodine and thiourea as promising; however, they acknowledge that those methods are young and less developed than cyanidation as to understanding the process design and procedure.[10] Still, they refer to using *aqua regia* as using an 'efficient reagent' with the advantage of a high dissolution rate (as an alternative to cyanidation).[10] *Aqua regia* literally means 'royal water' and has been known for such a long time that it was named so by alchemists, due to its ability to dissolve 'the king of metals' (gold). It is a solution of 3:1 by volume mixture of concentrated hydrochloric acid (HCl) and concentrated nitric acid (HNO_3) and dissolves 'unreactive' metals through the elemental metal oxidation by HNO_3 and the cation complexation by chloride (Cl^-).[11] In light of the discussion presented by Mousavi,[12] the process of gold dissolution in *aqua regia* may be shown by Equation 4, where nitrogen monoxide (NO) is produced; however, it is worth noting that since the dissolution is in *aqua regia*, where HNO_3 is concentrated, nitrogen dioxide (NO_2) will be the dominant nitrogen oxide produced and NO will be a by-product, according to the reaction shown by Equation 5.[12]

Aqua regia is commonly used in the electrolytic refinement of gold.[10] Can gold dissolution in *aqua regia* be useful as an alternative gold-mining procedure to facilitate hosting home-grown gold refineries in gold-producing African countries?

A part of a well-established industrial procedure to extract palladium (Pd) and platinum (Pt) can serve as a model to extract gold. Greenwood and Earnshaw[13] show that the first step in the extraction of palladium and platinum from platinum metal concentrates is dissolution in *aqua regia* to separate residues of ruthenium (Ru), rhodium (Rh), iridium (Ir), and silver chloride (AgCl) and to prepare a solution of $H[AuCl_4]$, $H_2[PdCl_4]$, and $H_2[PtCl_6]$. With

Fig. 1. A sign placed next to the cyanidation facility (cyanidation ponds) at a small-scale gold mining site in Zimbabwe (Kadoma region), where miners use cyanide to extract the remaining gold from the tailings. Credits to Malgorzata Stylo, UNEP. Permission obtained on January 9, 2024.

Fig. 2. Using mercury to form a gold-mercury amalgam in Burkina Faso. The image is owned and copywritten by the Artisanal Gold Council (https://artisanalgold.org). Permission obtained on October 10, 2023.

$$Au(s) + NO_3^-(aq) + 4H^+(aq) + 4Cl^-(aq) \rightarrow [AuCl_4]^-(aq) + NO(g) + 2H_2O(l) \quad (4)$$

$$NO(g) + 2HNO_3(l) \rightarrow 3NO_2(g) + H_2O(l) \quad (5)$$

the addition of iron(II) chloride ($FeCl_2$), which is the second step in the process, gold will precipitate, and a solution of $H_2[PdCl_4]$ and $H_2[PtCl_6]$ will remain to be processed further.[13] On the basis of this standard industrial procedure, gold can be extracted from its ores according to the following two-step process:

1. Dissolving gold ores in *aqua regia* to prepare a solution of $H[AuCl_4]$, according to the reaction shown by Equation 4.
2. Adding $FeCl_2$ to the $H[AuCl_4]$ solution to extract gold, according to the two half-reactions shown by Equations 6 and 7 and the reaction shown by Equation 8.

$$3Fe^{2+}(aq) \rightarrow 3Fe^{3+}(aq) + 3e^- \quad (6)$$

$$[AuCl_4]^-(aq) + 3e^- \rightarrow Au(s) + 4Cl^-(aq) \quad (7)$$

$$3Fe^{2+}(aq) + [AuCl_4]^-(aq) \rightarrow 3Fe^{3+}(aq) + Au(s) + 4Cl^-(aq) \quad (8)$$

The two-step process described here also allows isolating and saving any silver (Ag) contained in the gold ores in the form of a residue of AgCl, since dissolving the gold ores in *aqua regia* yields aqueous $[AuCl_4]^-$ and solid AgCl (the same compound of silver from which silver is separated in the extraction of palladium and platinum).[13]

4. Coupling the Mining and Refining Systems

If *aqua regia* is used as a main reagent in both gold mining and the electrolytic refinement of gold, then the two systems of gold mining and gold refining can be coupled industrially and geographically, and such a coupling can facilitate the growth of home-grown gold refineries in gold-producing African countries. It is noteworthy that a concern that some might have about gold mining using *aqua regia* instead of cyanidation and amalgamation is its toxicity;[10] however, as discussed above, the latter two are also very concerning from environmental and toxicological viewpoints. Although the set of nitrogen oxides (NO_x), including both NO and NO_2, in the atmosphere lead to the development of photochemical smogs, which contain a wide variety of harmful organic compounds, photochemical smogs develop in inner cities where the NO_x concentration is high (at least 1 ppm, due to the burning of fossil fuels in automobile engines and in furnaces), while the global concentration of NO_x is much lower (for example, 0.003 ppm, as of 1998).[14] Gold mines are in rural areas, and using *aqua regia* instead of cyanidation and amalgamation is not expected to exacerbate the environmental problems of those areas in general.

The fact that *aqua regia* is a fundamentally used reagent in the extraction of palladium and platinum from platinum metal concentrates makes a standard operating procedure for *aqua regia* readily available to the Swiss companies that refine precious metals. This availability is to the extent that even the precious metal storage company Swiss Gold Safe, with 'The world's gold is melted in Switzerland' as a motto, mentions using *aqua regia* in the process of extracting gold in refineries,[15] which means that those Swiss companies can bear the costs and sourcing of *aqua regia* with no difficulty. With those companies finding it economical to properly use *aqua regia* as a main reagent in both gold mining and the electrolytic refinement of gold in Africa, a win-win African-Swiss cooperation will be established that will benefit both the Swiss companies and gold-producing African countries.

5. Conclusions

The use of *aqua regia* as a main reagent in both gold mining, as discussed, and the electrolytic refinement of gold in gold-producing African countries and coupling the mining and refining systems in such countries are directed toward a subset of the set of goals called 'Sustainable Development Goals' by the United Nations.[16] It is especially directed toward Goal 9, entitled 'Industry, Innovation and Infrastructure', which tells us to 'build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation'. With Goal 9 met, Goal 8, entitled 'Decent Work and Economic Growth', is met. Goal 8 tells us to 'promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all'. Therefore, Goal 1, entitled 'No Poverty', is also met. Goal 1 tells us to 'end poverty in all its forms everywhere'. Further, Goal 17 (the last goal), entitled 'Partnerships for the Goals' is present in the African-Swiss cooperation suggested in this Note: 'Strengthen the means of implementation and revitalize the global partnership for sustainable development'.

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