Gold Phytoextraction by *Alocasia macrorrhizos* (Giant Taro): Implications in Phytomining

[1]A. K. Saim, [1]R. Ntiri-Bekoh, [2]H. Orleans-Boham and [1]R. K. Amankwah
[1]Minerals Engineering Department, University of Mines and Technology, Tarkwa, Ghana
[2]Egypt-Japan Unversity of Science and Technology

Saim, A. K., Ntiri-Bekoh, R., Orleans-Boham, H. and Amankwah, R. K. (2020), "Gold Phytoextraction by *Alocasia macrorrhizos*: Implications in Phytomining", *Proceedings of 6th UMaT Biennial International Mining and Mineral Conference*, Tarkwa, Ghana, pp. 272-280.

Abstract

Gold phytoextraction has over the years drawn much attention from various researchers as an alternative to conventional extraction methods to recover metals from low-grade ores or mineralised soils. Although various plants species have been employed to recover gold from mineralised soils, the literature is silent about the use of giant taro. Therefore, to examine the feasibility of gold phytoextraction from gold ore, laboratory scale experiments were carried out using *Alocasia macrorrhizos* (giant taro) without chemical inducement of the ore. Bioaccumulation (BAF) and Translocation Factors (TF) as well as gold accumulation by the plant in the roots, stem and leaf tissues were evaluated. BAF and TF were 13.65 and 1.46 respectively. This work has shown that *Alocasia macrorrhizos* demonstrates high ability to uptake and accumulate gold and it is efficient in translocation of gold to its above-ground tissues. Averagely, 14 mg/kg, 220 mg/kg and 10.7 mg/kg of gold were accumulated in the roots, stem and leaves respectively. In addition, dissolved gold across the setups after weeks 3 and 4 were 0.384 mg/L and 1.097 mg/L respectively. The results demonstrate that giant taro can solubilize and sorb gold and is a potential candidate for recovering gold from the tailings environment, low-grade stockpiles and heaps as well as mineralised soils in an eco-friendly and cost-effective approach.

Keywords: Phytoextraction, Alocasia macrorrhizos, Gold, Bioaccumulation, Translocation

1 Introduction

Gold is one of the valuable minerals that has stayed in the spotlight for years. This is due to its multipurpose nature and thus its high demand with technology advancement. Due to its unique chemical and physical properties (Marsden and House, 1992), gold has become vital indiverse fields such as dentistry, photography, medicine, electronics, and nanotechnology. Unfortunately, the current processes used for gold recovery are not only expensive, but also harmful to the environment, due to the use of toxic compounds containing cyanide (Korte et al., 2000). These processes disturb the soil where mine tailings are deposited, thus destroying ecosystems and forever altering the environment (Aucamp and van Schalkwyk, 2003). Thus, the need for less toxic leaching reagents continues to receive attention.

1.1 Hyperaccumulation

In the phytoextraction process, living plants accumulate high amounts of metals in the aboveground plant parts. Ideally, plants suitable for phytoextraction should be hyperaccumulators and must have high metal tolerances. Hyperaccumulation refers to the capacity of a plant to take up and keep a contaminant in its tissue, while tolerance refers to the plant's ability to survive in soils that have a high concentration of contaminants. Hyperaccumulators have found their widest application in phytoextraction, which is one of the phytoremediation strategies (Van Nevel *et al.*, 2007). Ideal plant species to be used in this process should have: (i) high biomass production, fast growth and easy harvesting (short time needed for effective reduction of element concentration in phytoremediated soils; McGrath and Zhao (2003); and (ii) ability to exist outside of their aboriginal area (Bhargava *et al*., 2012). Natural hyperaccumulators have the ability to solubilize metals from the soil matrix, efficiently absorb them into the root, translocate to the shoot and store in a nonphytotoxic form in the aerial portions. Root surfaces of natural hyperaccumulating plants are specifically developed for uptake of elemental nutrients from the soil and have a very large surface area covering several miles.

The potential for hyperaccumulation depends on the interaction between soils, metals, and plants. In soil, metals exist as a variety of chemical species in a dynamic equilibrium governed by soil, physical, chemical, and biological properties. For most metals, uptake into roots takes place from aqueous phase. Strong binding to soil particles or precipitation renders a significant soil metal fraction insoluble and largely unavailable for plant uptake. Some metals such as lead and gold, are largely immobile in soil and their extraction rate is limited by solubility and diffusion to root surface. Mobility of such metals in soil is enhanced by chemical treatments (induced hyperaccumulation).

Induced hyperaccumulation is suggested for high biomass plant species (Zea *mays*, Brassica *juncea*, V. *zizanoides*, and Helianthus *annus*), even for nonhyperaccumulators, as most natural hyperaccumulators accumulate a high concentration of metal, but have low biomass (Thlaspi *rotundifolium*, Thlaspi *caerulescens*, Alyssum *lesbiacum*). Chemicals for this purpose include various acidifying agents, fertilizer salts, and chelating agents such as CA, EDTA, NTA, oxalate, malate, tartarate, and succinate (Huang *et al*., 1997a). These chemicals increase the amount of bioavailable metal in the soil solution and hence uptake by plant increases.

1.2 Phytomining

Phytomining has been applied in the recovery of metals with commercial value, such as gold, silver, nickel, platinum, and palladium (Gardea-Torresdey *et al*., 2002; Anderson *et al*., 1999; Nedelkoska and Doran, 2000). Gomez (2002), reported that alfalfa seedlings accumulate more than 263 mg Au kg^{-1} DWM in the aerial parts when cultivated in agar enriched with 320 mg Au L^{-1}. Rodriquez *et al*., 2007, reported 179 mg/kg dry weight mass of desert willow. Lamb *et al*., 2001, also reported the accumulation of gold in Brassica juncea, Berkheya codii and Chicory. Species of Haumaniastrum and Aeollanthus are known for accumulating high levels of both Cu and Co in mineralized soils of Zaire (Brooks, 1997, 1998b; Brooks *et al*., 1987). An analogous approach used by Anderson *et al*. (1998) described induced hyperaccumulation of Au for phytomining using Brassica juncea. In addition, the formation of gold nanoparticles inside living alfalfa plants was for the first time reported (Gardea-Torresdey *et al*., 2002; Gomez, 2002). Li *et al*. (2003) described phytomining as an environmentally friendly technique that successfully recovers valuable metals from low-grade ores, which would otherwise remain unused for metal extraction. Brooks *et al*. (1998) asserted that an uptake of 1.8 mg Au kg^{-1} DWM or 131 mg Ag kg^{-1} DWM is required in order to provide a \$500 ha^{-1} return, with a crop that produces 25 t ha^{-1} of biomass.

Phytomining could be used to extract Au from tailings areas that contain concentrations of Au at a level uneconomic for conventional extraction techniques. In the initial stages of a revegetation programme, phytomining could also be used to extract Au from low-grade ore that many mining companies stockpile against expected increases in the gold price. In 2009 (Wilson-Corral *et al*., 2011), a field trial was conducted to establish the potential of the species H. *annuus* to recover gold from mine tailings. A plot of 50 m^2 was constructed. The average gold concentrations for leaves, stems, and roots, were 16 mg/kg, 21 mg/kg, and 15 mg/kg of dry matter, respectively after cyanide treatment of the mature biomass.

1.3 Alocasia *macrorrhizos* (Giant taro)

Giant taro (Figure 1) is a plant that produces a large amount of biomass with high water consumption. *Alocasia macrorrhizos*, commonly called giant taro, native to Asia, is a fast-growing herbaceous plant, growing up to 5 m in height, which has been intentionally introduced in many tropical and subtropical regions to be used as an ornamental crop and animal feed (Leon, 1987; Manner, 2011). It is a large, succulent perennial herb with a large, elongated stem. The stem, which is above ground, can be up to 1 m long and 20 cm in diameter. The genus Alocasia comprises approximately 70 species, which most commonly inhabit wet disturbed sites, areas of regrowth, large canopy gaps, and roadside ditches, but are also forest undergrowth species.

The present study was performed to determine the capability of giant taro (Alocasia *macrorrhizos*) to uptake gold from a gold-enriched ore. In earlier studies, the plant was found to degrade cyanide (Saim *et al*., 2018) and also sorb Cd, Pb and Ni (Armah, 2017). Despite several considerations about the use of plants as hyperaccumulator for precious metals, the literature is silent about the use of giant taro as hyperaccumulator for precious metals such as gold. This investigation considered the capabilities of giant taro to dissolve, uptake and concentrate gold in its above ground tissues. Also studied was the uptake performance of the plants by translocation of metal to the stem and leaf.

Figure 1 Giant Taro (Alocasia *macrorrhizos*)

2 Materials and Methods Used

2.1 Materials

The plants used for the study were obtained from the same field along a stream flowing through the University of Mines and Technology. Three (3) plants of relatively equal width and height were uprooted for the study. Deionized water and all other relevant materials were obtained from the Minerals Engineering Laboratory of University of Mines and Technology. The gold ore used for the experiment was refractory sulphidic ore from the Birimian System of Ghana.

2.2 Gold Ore Preparation

The gold ore used for the experiment contained about 2.3±0.1 g/t. The ore was crushed, milled and sized to about 50% passing 1 mm screen size. The ore was uniformly blended and 2 kg of the ore was weighed into each of the three containers (Setup 1, 2, 3) as shown in the experimental setup, Figure 2. No chemical or chelating agent such as cyanide, thiosulphate was added to the ore.

2.3 Experimental Setup

Three (3) setups were made for the 4 weeks experiment. Each setup contained one giant taro planted in 2 kg gold ore (Figure 2) with 1.5 L deionized (DI) water. The mixture of the ore and the DI water was uniformly mixed in the container. Thereafter, each plant was placed gently in the container. The setups were left for 4 weeks in an open environment. The plant was allowed to grow and solution samples were analyzed after the 3rd and 4th week. After the 4th week, the plants were harvested, dried, acid digested and analyzed for gold in the root and in the above-ground tissues.

2.3.1 Control Experiment

Control experiments were carried out to investigate the natural hyperacumulation of giant taro. An additional plant was also digested and analyzed for gold in the various compartments of the plant along with the experimental plants used for the experiment. Another setup was made containing the mixture of the gold ore and DI water only and solution gold was determined after the 3rd and 4th week.

2.4 Plant Digestion

After the experiment, the plants were harvested and thoroughly washed with DI water to clean the surface to prevent contamination. The plant was cut into the various parts; root, stem and leaf and was oven-dried at 80 ℃ for 24 hrs. One gram of each compartment of the plant was weighed and digested in aqua regia containing 75 mL HCl and 25 mL HNO_3 in a 250 mL volumetric flask. The mixture was heated on a hotplate for 30 minutes after which they were allowed to cool. The solutions were then diluted to 100 mL with DI water and taken for gold analysis in the root, stem and leaf.

Figure 2 Experimental Setups

2.5 Gold Analysis

Gold analysis was determined in plant digest and tails using a Varian AF 220 Fast Sequential Atomic Absorption Spectrophotometer (AAS). The detection limit for gold was 0.01 mg/L. Reagent blanks were below the detection limits in the solutions (<0.01). The gold concentration in each sample was determined in triplicate, and the average values are reported.

3 Results and Discussions

3.1 Gold Uptake

The results in Table 1 indicate that a significant amount of gold was present in the various compartments of giant taro after the experiment. The highest gold concentrations were recorded in the stem of the plant in setups 1 and 2 and were three to four times higher than that in the root of the same plants. This observation may indicate that giant taro hyperaccumulated most (about 89%) of the gold in its stem, which constitutes about 70-80% of the plant biomass. On the average, gold concentration recorded in the leaf across the setups were low compared to the various compartments of the plant. In setup 3, about 65.9% (Figure 3), of the gold was found in the leaf which demonstrates that giant taro can accumulate an appreciable amount of gold in the leaves.

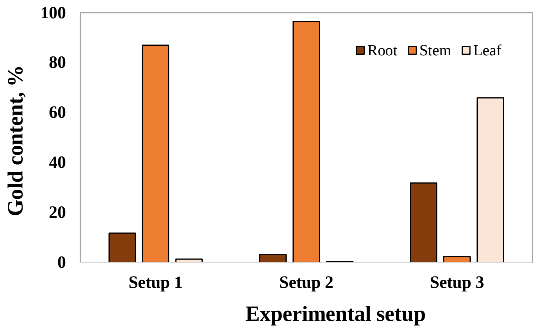

Figure 3 Percent Gold Accumulation in Root, Stem and Leaf across the Setups.

These results are consistent with those reported by Gomez et al., (2002), Rodriquez et al., (2007) and Anderson et al., (1998). Wilson-Corral et al., (2011), reported an average gold concentration of 16 mg/kg, 21 mg/kg, and 15 mg/kg of dry H. *annuus* for leaves, stems and roots respectively. It was also observed that the concentration of gold recorded in the control plant was very low. The threshold for gold accumulation in the plant has been established at 1 mg gold/kg dry weight biomass to be considered as a gold accumulator (Anderson et al., 1998).

Table 1 Gold concentrations in giant taro

Gold Uptake(mg/kg) dry weight				TF	BAF
Setups	Root	Stem	Leaf		
Setup 1	9.00	67.00	1.00	7.55	1.70
Setup 2	19.00	592.00	2.00	31.26	2.37
Setup 3	14.00	1.00	29.00	2.14	0.30
Control (mg/L)	0.02	0.01	0.01		
Average	14.00	220.00	10.70	13.65	1.46

TF = Translocation Factor BAF=Bioaccumulation Factor

3.2 Bioaccumulation and Translocation of Gold

The Bioaccumulation Factor (BAF) and Translocation Factor (TF) were calculated according to Equations 1 and 2, respectively. The calculated BAF across the three setups indicate that giant taro can be a potential hyperaccumulator of gold. Plants with a BAF >1 are considered as accumulators or hyperaccumulators (Wang *et al.*, 2012), and giant taro has demonstrated its hyperaccumulative property with a high BAF of 1.46, Table 1.

$$\text{BAF} = \frac{\text{Au Concentration in Shoot}}{\text{Au Concentration in Ore}} \quad (1)$$

$$\text{TF} = \frac{\text{Au Concentration in Shoot}}{\text{Au Concentration in Root}} \quad (2)$$

Higher Translocation Factor (TF) as shown in Table 1 indicates that a significant amount of gold was translocated to the shoot. The higher the TF, the better the ability to transport metals from roots to shoots (Wang *et al*., 2017).

3.3 Gold Dissolution

The chemistry of gold indicates that the metal remains in the native state in an aqueous environment without a chelating or complexing agent such as cyanide and thiosulphate. It was observed in week 3 and 4 as shown in Table 2, that significant amounts of gold dissolved and was present in solution. This may be as a result of gold dissolving in the presence of giant taro. The control experiment recorded an insignificant amount (0.1 mg/L) of gold in the absence of the plant after week 4. This indicates that through the process of gold uptake, giant taro was able to dissolve appreciable amounts of gold and after dissolution the roots passively accumulated the gold in its above-ground tissues through transpiration.

Table 2 Gold in solution

	Gold in solution(mg/L)			
	Setup 1	Setup 2	Setup 3	Control
Week 3	0.34	0.39	0.41	0.09
week 4	1.04	1.01	1.24	0.10

The actual mechanism of gold dissolution is yet to be understood but relevant explanations suggest that some of the natural metal-accumulating plants secrete metal-chelating compounds (phytosiderophores) to the rhizosphere, such as mugineic and avenic acids, in response to nutrient metal ion deficiencies, and some secrete organic acids, such as citric, malic, malonic, and oxalic acid, which act as metal chelators and decrease the rhizosphere pH and thus increase the bioavailability of metals that are tightly bound to the soil and help to carry them into plant tissues (Eapen *et al*., 2005, Ma *et al*., 2001). From Table 2, gold concentration in the 4th week increased remarkably about two to three times the concentration of the 3rd week which could indicate faster dissolution kinetics. Another reason could also be that the sorption capacity of the plant biomass was at its maximum and therefore limited sorption occurred after the 3rd week. This phenomenon could also cause an increase in the concentration of gold in solution.

3.4 pH and Cyanide Studies

To study the variations in pH during the experiment, the pH of solution samples was analyzed before and after. Table 3 shows the initial and final pH recorded. The final pH values across the setups were high than the initial. The increase in pH may be due to secretion of certain alkaline compounds from the plant into the solution. Cyanide investigations were also carried out to determine potential secretion of cyanide or cyanogenic compound by giant taro. No cyanide was recorded in solution containing only the plant species. It was thus concluded that giant taro was not secreting cyanide into solution during the experiment. Potential cyanide in the ore samples was also investigated to confirm the observations but no cyanide was in solution when the ore was contacted with DI water for 4 weeks. These findings suggest that gold dissolution may be as a result of secretions of certain chemicals by giant taro into solution or through the process of rhizofiltration.

Table 3 Solution pH

	pH	
	Initial	After
Setup 1	7.5	8.2
Setup 2	7.2	7.9

Setup 3	7.6	8.6

3.5 Potential of Giant Taro in Phytomining

Phytomining of gold is a very fascinating technique that could be applied to extract gold from tailings environment, mineralized soils and low-grade heaps which are subeconomic for conventional mining methods. Natural accumulation is preferred to induce accumulation which employs chelators to enhance the bioavailability of the mineral of interest to the plant root. The results show that giant taro can be a potential candidate to be used in phytomining of gold from mineralized soils and tailings impoundments. Reports indicate that a considerable amount of gold accumulates in the tailings environment suggesting that hyperaccumulators can be employed to recover gold in an ecofriendly approach.

Plants grown at the tailings environment should naturally be able to withstand toxic chemicals such as cyanide. Earlier works suggests that giant taro can strongly withstand the toxicity of cyanide, (Saim *et al*., 2018). A considerable amount of cyanide present at the tailings impoundment can also act as a chelating agent that could increase the bioavailability of gold to the rhizosphere of giant taro. In phytomining, plants with high biomass yield per hectare of land are mostly preferred and giant taro is no exception. The annual production of taro is estimated at 170,000 tonnes from an area of 31,000 ha (FAO, 2001). Phytoextraction of gold using giant taro looks promising in the future as a result of higher Bioaccumulation (BAF > 1) and Translocation Factor (TF).

4 Conclusions and Recommendations

This investigation demonstrates that giant taro can uptake and accumulate gold in its above-ground tissues without any significant adverse effect on giant taro. On average, 14 mg/kg, 220 mg/kg and 10.7 mg/kg of gold was accumulated in the root, stem and leaf respectively.

About 89% of the gold was accumulated in the stem. Key indicators of gold uptake and accumulation such as the Translocation and Bioaccumulation Factors were estimated to be 1.46 and 13.65 respectively. The secretion of certain chemicals or rhizofiltration processes by giant taro to dissolve gold may have caused a slight increase in pH from about 7.4 to 8.2 on the average.

Phytomining is a promising technique and giant taro is a potential candidate to be used to recover gold from tailings environment, low-grade stockpiles and heaps as well as mineralized soils.

Most local and international mining companies intentionally cultivate grass and other plant species on old tailing impoundments as cover crops to minimize dust generation. These mines can employ giant taro to recover an appreciable amount of gold from the tailings area, but at a level uneconomic for conventional extraction techniques. Giant taro could also be used to extract gold from low-grade ore that many mining companies stockpile in expectation of favorable fluctuations in the value of the metal.

Further works could be done to establish the actual mechanism of gold dissolution and uptake by giant taro. Field studies can also exploit adequate parameters and strategies to utilize giant taro in gold phytomining.

References

Anderson, C., Brooks, R.R., Stewart, R.B. (2000), "Phytomining: a new method of mining", *Chem. N.Z.*, Vol. 81, pp. 16 – 22.

Anderson, C., Brooks, R.R., Stewart, R.B., Simcock, R. (1998), "Harvesting a crop of gold in plants", *Nature*, Vol. 395, pp. 553 – 554.

Anderson, C.W.N., Brooks, R.R., Chiarucci, A., LaCoste, C.J., Leblanc, M., Robinson, B.H., Simcock, R., and Stewart, R.B. (1999), "Phytomining for nickel, thallium and gold", *J. Geochem. Explor*., Vol. 67, pp. 407 – 415.

Anderson, C.W.N., Brooks, R.R., Stewart, R.B., Simcock, R. (1999b) "Gold uptake by plants", *Gold Bull*. Vol. 32, 48 – 51

Anderson, C.W.N., Moreno, F., Meech, J., (2005), "A field demonstration of gold phytoextraction technology", *Minerals Engineering*, Vol. 18, pp. 385 – 392.

Anderson, C.W.N., Stewart, R.B., Moreno, F.N., Wreesmann, C.T., GardeaTorresdey, J.L., Robinson, B., Meech, J.A. (2003), "Gold phytomining. Novel developments in a plant-based mining system", *In: Gold 2003 Conference. World Gold Council*, Vancouver, pp. 35 – 45.

Armah, K. A. A. (2017), "Investigations into the heavy metal biosorption capabilities of Seapurslane (Sesuvium portulacastrum) and giant taro (Alocasia macrorrhizos)", *MPhil Thesis*, UMaT.

Aucamp, P. and van Schalkwyk, A. (2003), "Trace element pollution of soils by abandoned gold mine tailings, near potchefstroom, South Africa", *Bull. Eng. Geol. Environ*., Vol. 62, pp. 123–134.

Bhargava, A. Carmona, F. F., Bhargava, M. and Srivastava, S. (2012), "Approaches for enhancing phytoextraction of heavy metals", *Journal of Environmental Management*, Vol. 105, pp. 103 – 120.

Brooks, R.R., Chambers, M.F., Nicks, L.J., and Robinson, B. H. (1998), "Phytomining", *Trends in Plant and Science*, Vol. 3, No. 9, pp. 359–362.

Eapen, S., and D'Souza, S.F. (2005), "Prospects of genetic engineering of plants for phytoremediation of toxic metals", *Biotechnol. Advan.*, Vol. 23, pp. 97 – 114.

Garbisu, C. and Alkorta, I. (2001), "Phytoextraction: A cost-effective plant-based technology for the removal of metals from the environment", *Bioresour. Technol*., Vol. 77, pp. 229 – 236.

Gardea-Torresday, J.L., Parson, J.G., Gomez, E., Peralta-Videa, J., Troiani, H.E., Santiago, P., and Yacaman, M. J. (2002), "Formation and growth of Au nanoparticles inside live alfalfa plants", *Nano Lett*., Vol. 2(4), pp. 397 – 401.

Gardea-Torresdey, J. L., Rodriguez, E., Parson, J. G., Peralta-Videa, J.R., Meitzner, G., and CruzJimenez, G. (2005), "Use of ICP and XAS to determine the enhancement of gold phytoextraction by Chilopsis linearis using thiocyanate as a complexing agent", *Anal. Bioanal. Chem*., Vol. 382, pp. 347 – 352.

Gardea-Torresdey, J. L., Tiemann, K. J., Gamez, G., Dokken, K., Cano-Aguilera, I., Furenlid, L.R., and Renner, M. W. (2000), "Reduction and accumulation of gold (III) by Medicago sativa alfalfa biomass: X-ray absorption spectroscopy, pH, and temperature dependence", *Env. Sci. Tech*., Vol. 34, pp. 4392 – 4396.

Girling, C. A. and Peterson, P. J. (1978), "Uptake, transport and localization of gold in plants", *Trace Subst. Environ. Health*, Vol. 12, pp. 105 – 118.

Gomez, E. (2002), "The nanoparticle formation and uptake of precious metals by living alfalfa plants", Master of Science Thesis, University of Texas at El Paso.

Huang, J. W., Chen, J., Berti, W.R. and Cunningham, S.D. (1997), "Phytoremediation of lead-contaminated soils: role of synthetic chelates in lead phytoextraction", *Environmental science and Technology*, Vol. 31, No. 3, pp. 800 – 805.

Korte, F., Spiteller, M., and Coulston, F. (2000), "The cyanide leaching gold recovery process is a nonsustainable technology with unacceptable impacts on ecosystems and humans: The disaster in Romania", *Ecotoxic. Environ. Saf*., Vol. 46, pp. 241–245.

Lamb, A. E., Anderson, C. W. N., and Haverkamp, R. G. (2001), "The induced accumulation of gold in the plants Brassica juncea, Berkheya codii and Chicory", Chem. in New Zealand, pp. 34 – 36.

Li, Y., Chaney, R., Brewer, E., Roseberg, R., Scott, J.A., Baker, A., Reeves, R., and Nelkin, J. (2003), "Development of a technology for commercial phytoextraction of nickel: Economic and technical considerations", *Plant Soil*, Vol. 249, pp. 107 – 115.

Ma, J. F., Ryan, P. R., and Delhaize, E. (2001), "Aluminium tolerance in plants and the complexing role of organic acids", *Trends Plant Sci*., Vol. 6, 273 – 278.

Marsden, J. and House, I. (1992), "The Chemistry of Gold Extraction", *New York, Ellis Horwood*.

Mcgrath, S. P., and Zhao F. J. (2003), "Phytoextraction of metals and metalloids from contaminated soils", *Current opinion in biotechnology*, Vol. 14, No. 3, pp. 277 – 282.

Nedelkoska, T.V. and Doran, P.M. (2000), "Characteristics of heavy metal uptake by plant species with potential for phytoremediation and phytomining", *Minerals Engineering*, Vol. 13, No. 5, pp. 549 – 561.

Rodriguez, E., Parsons, J. G., Peralta-Videa, J. R., Cruz-Jimenez, G., RomeroGonzalez, J., Sanchez-Salcido, B. E., Saupe, G. B., Duarte-Gardea, M., GardeaTorresdey, J. L., (2007b), "Potential of Chilopsis linearis for gold phytomining: using XAS to determine gold reduction and nanoparticle formation within plant tissues", *Int. J. Phytoremediat*, Vol. 9, pp. 133 – 147.

Rodriguez, E., Sanchez-Salcido, B., Peralta-Videa, J. R., Parsons, J. G., Romero, J., GardeaTorresdey, J. L., (2007), "Improving gold phytoextraction in desert willow (Chilopsis linearis) using thiourea: a spectroscopic investigation", *Environ. Chem*. Vol. 4, pp. 98-108.

Rodriguez, E., Sanchez-Salcido, B., Peralta-Videa, J. R., Romero, J., Cruz-Jimenez, G., Gardea-Torresdey, J. L., (2006), "Phytomining gold: soil trials", *In: 231st American Chemical Society National Meeting, Division of Environmental Chemistry*, Atlanta, GA, pp. 384 – 389.

Rodriguez-Lopez, M., Wilson-Corral, V., Anderson, C., Lopez-Perez, J. (2009), "Chemically assisted gold phytoextraction in Sorghum halepense", *In: The 5th International Conference on Gold Science, Technology and Its Applications, World Gold Council*, Heidelberg, p. 353.

Saim, A. K., Ntiri-Bekoh, R., Orleans-Boham, H., Amankwah, R. K. (2018), "Phytoremediation of cyanide by Alocasia macrorrhizos (giant taro)", *Proceedings of the 5th UMaT Biennial International Mining and Mineral Conference, University of Mines and Technology, Tarkwa, Ghana*, pp. ES105-109.

Shacklette, H. T., Lakin, H. W., Hubert, A. E., Curtin, G.C., (1970), "Absorption of gold by plants", *U.S. Geol. Surv. Bull*., 1314-B, pp. 1 – 23.

Sheoran, V., Sheoran, A. S., Poonia, P. (2009), "Phytomining: a review", *Minerals Engineering*, Vol. 22, pp. 1007 – 1019.

Van Nevel, L., Mertens, J., Oorts, K. and Verheyen, K., (2007), "Phytoextraction of metals from soils: how far from practice?", *Environmental Pollution*, Vol. 150, No. 1, pp. 34 – 40.

Wang, L., Ji, B., Hu, Y., Liu, R. and Sun, W., (2017), "A review on in situ phytoremediation of mine tailings", Chemosphere, Vol. 184, pp. 594 – 600.

Wilson-Corral, V., Anderson, C., Rodriguez-Lopez, M., Arenas-Vargas, M., Lopez Perez, J. (2011), "Phytoextraction of gold and copper from mine tailings with Helianthus annuus L. and Kalanchoe serrata L", *Minerals Engineering*, Vol. 24, pp. 1488 – 1494.

Wilson-Corral, V., Lopez-Perez, J., Arenas-Vargas, M., Anderson, C., (2006), "Gold concentrations in mine tailings. Potential application of phytomining" *In: Ecology in an Era of Globalization: Challenges and Opportunities for Environmental Scientist in the Americas, Ecological Society of America (ESA)*, Merida, pp. 156 – 157.

Authors

Alex Kwasi Saim holds a BSc in Minerals Engineering at the University of Mines and Technology, Tarkwa, Ghana (2019). He is currently a Teaching/Research Assistant at the Minerals Engineering Department of the University of Mines and Technology. His research interests include biotechnological applications in Minerals Engineering, water and wastewater management, phytoremediation, agromining, phyto-nanotechnology and hydrometallurgy He is a graduate member of the West African Institute of Mining, Metallurgy and Petroleum (WAIMM),

Rabboni Ntiri-Bekoh holds a BSc in Minerals Engineering from the University of Mines and Technology, Tarkwa, Ghana. He is currently a Research Assistant at the University of Mines and Technology. His current research is into mineral processing and extractive metallurgy (Geometallurgy) and phytoremediation.

Hamdiya Orleans-Boham received a BSc in Minerals Engineering from the University of Mines and Technology, Ghana in 2017 and was a teaching/research assistant for a year in the same institution. She is currently pursuing MSc in Egypt-Japan Unversity of Science and Technology. Her current research work is on the development and fabrication of Nano-adsorbent for the sequestration of heavy metals in water. She has had industrial experiences from the mining firms. She is also a graduate researcher in Process Innovations, a Mining consultancy Company. Hamdiya is a Team Lead and a Jnr Coordinator for Women in Mining (WiMGh) Ghana Organisation Social Team and Artisanal and Small Scale Mining respectively.

Richard K. Amankwah is a professor of minerals Engineering from the University of Mines and Technology (UMaT), Tarkwa, Ghana. He holds a PhD degree in Mining Engineering from Queen's University, Canada, and MPhil and BSc in Metallurgical Engineering, both from the Kwame Nkrumah University of Science and Technology, KNUST, Kumasi, Ghana. His research interests include gold beneficiation, water quality management, microwave processing of minerals, small-scale mining, medical geology, microbial mineral recovery and environmental biotechnology. He is a Fellow of the West African Institute of Mining, Metallurgy and Petroleum (WAIMM), a member of the Ghana Institute of Engineers (GhIE) and Society for Mining and Exploration Engineers.