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Integrated phytomining and ethanol production in the Zambian Copperbelt to minimize mine decontamination costs and environmental and social impacts: a review

by T. Sinkala

Synopsis

The mining industry in the Zambian Copperbelt has polluted the environment with heavy metals, the effects of which are a source of concern to host communities. It is globally known that remediation of polluted mine environments is expensive, and can be as high as US$48 000 or more per hectare, depending on the severity of contamination, using traditional physical and chemical approaches. These methods also often leave significant liabilities for host communities. This paper reviews available opportunities for mining companies in the Zambian Copperbelt to use integrated phytomining and production of ethanol, and its co-products, to minimize the costs for remediating polluted mine environments. The benefits of using this approach are manifold and include additional income streams from extracted metals and ethanol, creation of additional jobs for mine host communities, assured livelihoods for mine host communities even beyond mine closure, reclaimed land for food production and other activities, and improved corporate image for mining companies.

Keywords

phytoremediation, rehabilitation costs, ethanol production.

Introduction

Mining and mineral beneficiation activities in the Zambian Copperbelt have contributed considerable amounts of heavy metals to the environment (Kříbek *et al.*, 2013; Swedish Geological AB *et al.*, 2005). These heavy metal pollutants have affected surrounding land, air, and water quality, which has long been a concern to host communities.

The metal mines in the Copperbelt generally contain variable amounts of sulphide minerals, either in the ore or in the host rocks. When these sulphide ores are mined and processed, heavy metals are leached from tailings under moist conditions owing to the decreased pH resulting from the oxidation of pyrite. This low pH increases the solubility of most heavy metals, which are then dispersed in the surrounding environment. Traditional measures to prevent acid drainage include physically stabilizing the waste by covering the acid-producing material with water, or covering the surface of dry tailings with soil and then revegetating the site to control pyrite oxidation (Renault, Sailerova, and Fedikow, 2000).

Dispersion of heavy metals from mining and milling operations also occurs by wind, where metals are contained in windblown dust. The major source of soil contamination in areas surrounding the mining operations is in fact pollutants spread by wind. Distances of dispersion have been recorded as far as 250 km for manganese and 60 km for copper (Renault, Sailerova, and Fedikow, 2000), making remediation efforts even more difficult and expensive such that mining companies are facing the choice of either paying for a statutory environmental assurance fund or nefariously avoiding paying for the funds (Chifungula, 2014; DMP, 2016; EJA, 2016; LHR, 2017). When traditional physical and chemical remediation approaches are applied, costs for rehabilitation works depend on the topography, the classification of the mine according to the mineral mined, the risk class of the mine, its proximity to built-up or urban areas (DWE, 2015), and the severity and extent of contamination. Following are examples of remediation costs incurred in a few selected countries.

In Zambia, of the projected US$226.65 million that 49 mining companies should have contributed to the environmental rehabilitation assurance fund for the period covering 2009 to 2012, the companies contributed only US$50.40 million (US$10.37 million in cash and the rest in bank guarantees) (Chifungula, 2014). In Western Australia, the total rehabilitation and closure costs for all mines operating under the Mining Act 1978 was estimated in 2010 to be between A$4 billion (US$3.01 billion) and A$6 billion (US$4.51

* *Mining Engineering Department, School of Mines, University of Zambia.*

billion) (DMP, 2016). As of financial year 2015–2016, compliance brought the total principal in the rehabilitation fund to approximately A$60 million or US$45.10 million (DMP, 2016). In Zimbabwe, a study conducted in 2011 by the Zimbabwe Environmental Management Agency (EMA) on four large decommissioned mines revealed a cumulative rehabilitation cost of US$32 million (ZAMI, 2017). In South Africa there are about 6 000 derelict and ownerless mines which have never been rehabilitated; previous owners have simply 'locked the gate' and walked away. As an example of the environmental liability cost, closure of the De Groote Boom mining area in South Africa, with a maximum 5 ha where activities included landscaping a free-draining topography, replacement of soil, revegetation, and general surface rehabilitation of the disturbed area, was estimated at R2.15 million (US$0.24 million), or about US$48 000 per hectare (DWE, 2015).

The above pollution scenario and associated rehabilitation costs indicate that it cannot be left to nature to restore the environment to an acceptable quality. Rather, aggressive efforts based on well-planned commercially viable restoration programmes are required.

The objective of this paper is to look at available opportunities for mining companies in the Zambian Copperbelt to apply phytoremediation to minimize expenses for rehabilitation of polluted mine environments, while also realizing new income streams when suitable hyperaccumulator plants are used to recover valuable metals and also to produce ethanol and associated co-products from the plants.

The discussion starts by explaining phytoremediation and the current international interest in this field, followed by examples of hyperaccumulator plants and their potential use as a source of feedstock for biofuels (biogas, bioethanol, and biodiesel) production. Issues to consider when identifying appropriate heavy-metal remediation plants that can also be used for ethanol production are highlighted, together with the benefits of using hyperaccumulator plants for both remediation and ethanol production.

Phytoremediation

Phytoremediation, the *in situ* use of plants to extract heavy metals from contaminated sites (Anderson *et al*., 2000), is a topic being increasingly investigated for its potential to cost-effectively decontaminate polluted areas (Hunt *et al*., 2014). The research efforts include the identification of metallophyte and pseudometallophyte plant species that can colonize areas that have been highly polluted with heavy metals and metalloids by mining and related industrial activities (Favas *et al*., 2014).

Favas *et al.* (2014) presented six different strategies for phytoremediation techniques that can be applied singly or severally, depending on the chemical nature and properties of the contaminant and the plant characteristics. These comprise:

- **Phytodegradation**/phytotransformation—using plants with specific enzymes to degrade/transform organic contaminants
- **Phytostabilization**/phytoimmobilization—using plants that incorporate the contaminants into the lignin of the cell wall of root cells or into humus
- **Phytovolatilization**—using plants that absorb and volatilize certain metals/metalloids
- **Phytoextraction**/phytoaccumulation/phytoabsorption/phytosequestration—using plants that absorb contaminants through the roots, followed by translocation and accumulation in the aerial parts
- **Phytofiltration**—using plants that absorb, concentrate, and/or precipitate contaminants, particularly heavy metals or radioactive elements, from an aqueous medium through their root system or other submerged organs
- **Rhizodegradation**/phytostimulation—using plants whose growing roots promote the proliferation of contaminant-degrading microorganisms in the rhizosphere that utilize the plant's exudates and metabolites as a source of carbon and energy.

Of interest in this paper are phytoextraction strategies for phytoremediation of metal- and metalloid-contaminated soils because of the potential to extract valuable minerals (Anderson *et al*., 1999; Favas *et al*., 2014; Krisnayanti and Anderson, 2014; van der Ent *et al*., 2015b). An extension of 'phytoextraction' (removal from the soil) is 'phytomining' (accumulating economic metal values in plant biomass) (Chaney and Mahoney, 2014; Chaney and Baklanov, 2017), defined as the use of hyperaccumulating plants to extract metal from soil with recovery of the metal from the biomass to return an economic profit (Lamb, Anderson, and Haverkamp, 2001). The same plants can similarly be used for agromining. According to van der Ent *et al.* (2015a), phytomining takes place on degraded or mined land as part of a rehabilitation strategy, while agromining takes place on low-productivity agricultural soils to generate economic returns to farmers. In this paper, both these activities are regarded as necessary to address environmental and socio-economic concerns in mining areas. There is therefore intensified research into plants which remove metals from soils in significant amounts, after which the valuable metals can be economically recovered from the plants. Over time, land is made available for other socio-economic uses once pollution in the soil has been reduced to acceptable levels.

Hyperaccumulator plants

Hyperaccumulators are plants that have the ability to store high concentrations of specific metals in their aerial parts. Hunt *et al.* (2014) cited van der Ent *et al.* (2013) on the current definition for a hyperaccumulator, which they summarized, for nickel, as a species that when growing in its natural environment accumulates at least 1 000 mg of nickel per kilogram (dry weight) within its leaves. They also report that hyperaccumulator species that concentrate other elements, including zinc (Zn), cadmium (Cd), lead (Pb), cobalt (Co), manganese (Mn), chromium (Cr), and selenium (Se), have been identified, and hyperaccumulation threshold limits have been established for each metal. They give examples of accumulation thresholds of 100 mg/kg for Cd, 1 000 mg/kg for Pb, and 10 000 mg/kg for Mn.

Examples of hyperaccumulators mentioned by Favas *et al.* (2014) include *Elsholtzia splendens, Alyssum bertolonii, Thlaspi caerulescens*, and *Pteris vittata*, which hyperaccumulate copper (Cu), nickel (Ni), Zn/Cd, and arsenic

(As), respectively. Hyperaccumulators include both terrestrial and aquatic plants. Examples of aquatic plants include *Centella asiatica* and *Eichhornia crassipes* (Mokhtar *et al*., 2011). Aquatic plants are reported to be capable of bio-accumulating toxic metals and nutrients in large quantities in comparison to terrestrial plants (Wani *et al*., 2017).

One of the concerns with phytomining is the low yield of metals per unit area in relation to the investment required to extract them (Hunt *et al*., 2014; Mohanty, 2016). The low-grade biomass harvested from the plants may not necessarily be economically treatable by conventional mineral processing approaches.

Hunt *et al.* (2014) clearly stated that any application of phytoextraction requires plants with attributes that include fast growth rates, high biomass composition, deep roots, tolerance to metal uptake, metal specificity, and a high rate of metal transport from roots to shoots. They also stated that, when applied to metal recovery from wastes, phytoextraction can potentially result in environmental clean-up and the recovery of valuable metal products. To make the economics more attractive, however, it is considered that phytoremediation needs to be combined with other technologies, such as biofuel production (Mohanty, 2016).

Bioremediation plants as a source of feedstock for biofuels production

The biomass generated by remediation plants has potential to be a source of feedstock to produce biofuels (Hunt *et al*., 2014; Mohanty, 2016; Warr, Kasonde, and Krishan, 2017), which can be gaseous (*e.g.* methane), liquid (*e.g.* ethanol and biodiesel), or solid (*e.g.* charcoal). For example, in research being conducted at Freiburg University in Germany, plants that accumulate germanium are harvested and fermented to produce biogas, after which the germanium is extracted (Kratochwill, 2015).

Hunt *et al.* (2014) have pointed out that biomass containing Cu (as a catalyst) has proven useful in the improvement of bio-oil quality produced through fast pyrolysis of biomass. The Cu in Cu-enriched biomass effectively catalyses the thermo-decomposition of the biomass and results in an improvement in the yield and heating value of the bio-oil compared with non-Cu containing biomass. Cu did not volatilize during treatment, which prevented metal contamination of the bio-oil. Hunt *et al.* (2014) also reported that research is being carried out into the use of Se-containing plants for applications such as fortified foods, biofuels, or potential bioherbicides and green fertilizers.

For the production of biofuels, care must be taken regarding the suitability of feedstock in relation to the metals being phytomined. In this respect, Gramss and Voigt (2016) studied the gradual accumulation of heavy metals in an industrial wheat crop grown on soil at a former uranium mine in East Germany, and the potential use of the herbage. They gave a caution regarding the use of grains, rather than of straw, with Cd and Cu concentrations above 3 and 12 mg/kg dry weight, respectively, as bioethanol feedstock. They found that Cd and Cu toxicities could lead to productivity losses in the fermentation of alcohol by *S. cerevisiae*, whereas a higher Mn, Ni, Pb, and Zn load could be tolerated by the yeast and be accepted according to forage hygiene guidelines. They observed that if As, Mn, Pb, and uranium (U) contents increased in the straw, the straw could still be used both as a roughage supplement for livestock and as a bioethanol feedstock.

Appropriate heavy-metal remediation plants for ethanol production

Ethanol is commonly produced from biomass feedstocks by a fermentation process. The feedstocks are sugar-based crops (such as sweet sorghum, sugarcane, and sugar beet) and starch-based feedstocks (such as cassava, sweet potatoes, and corn). Recently, technology has been developed to produce ethanol commercially also from cellulose (stringy fibre of a plant) derived from biomass, such as grasses, wood, and bagasse (Verardi *et al*., 2012). Feedstocks for ethanol production via both common and advanced technologies are harvested from large areas and brought to a processing plant where ethanol is distilled from fermented material (or mash) at temperatures below 100°C (usually around 93 to 96°C). The material that remains after distillation is called vinasse. With reference to our subject, heavy metals would therefore be found in vinasse if the fermented material used to produce ethanol contained heavy metals from hyperaccumalator plants.

Suitability of traditional feedstocks for both remediation and ethanol production

The organic material that remains after ethanol disrillation, called vinasse, is where any metals derived from the harvested starch/sugar feedstocks can be found. However, as can be observed in Table I, the heavy metal content in vinasse derived from traditional ethanol feedstocks grown in non-mining environments is generally very low (Gamboa *et al*., 2011; Rodrigues and Hu, 2017; Scull *et al*., 2012).

Izah, Bassey, and Ohimain (2017) assessed the level of some selected heavy metals in cassava mill effluent-contaminated soil from the Ndemili community in the Niger Delta region of Nigeria. Results for both spatial and bimonthly distribution of heavy metals yielded for Cu 1.10–6.83 mg/kg, Zn 14.32–46.15 mg/kg, Mn 18.42–47.49 mg/kg, iron (Fe) 1303.29–4934.04 mg/kg, Pb 1.33–9.42 mg/kg, Cd < 0.001–0.24 mg/kg, Cr 0.19–3.41 mg/kg, Ni 1.57–3.76 mg/kg, and Co < 0.008–9.71 mg/kg. Levels for Fe appear relatively high, but unfortunately the authors did not report the metal elevations in the cassava tubers, which are the source of first-generation ethanol.

Wang *et al.* (2016) investigated the suitability of sugarcane as a crop for phytoremediation in a heavy-metal polluted farmland in Huanjiang County in the Huanjiang River Basin in Guangxi Province, southern China, where sugarcane is widely cultivated as one of the major economic crops. Mining activities in the area have resulted in heavy metals polluting farmland soils. Table II shows the heavy metal concentrations found in agricultural soils and the roots, upper stems, and leaves of sugarcane in the study area. It can be observed that most of the toxic heavy-metals intake by sugarcane accumulated in the roots, while only a small portion was transferred to the stems and leaves. Thus, if sugarcane were to be used for phytomining, harvesting would imply uprooting the entire plant. This indicates that

Table I

Levels of heavy metals in vinasse from the ethanol distillation process using traditional ethanol feedstocks grown in non-mining areas

Metal	Feedstock						
	Sugarcane feedstock[a] (mg/L)	Sugarcane feedstock[b]	Cane molasses[c] (mg/L)	Grapes – wine[c] (mg/L)	Agave – tequila[c] (mg/L)	Sweet sorghum[c] (mg/L)	Beet molasses[c] (mg/L)
Fe	44.9	0.07%	12.8–157.5	0.001–0.077	35.2–45	317	203–226
Mn	4.9						
Zn	1.2	0.04%					
Ba	0.54						
Cd	1.06		0.04–1.36	0.05–0.08	0.01–0.2		<1
Cr	0.15						
Ni	0.26						
Al	72.5						
Cu	0.06	6.60 ppm	0.27–1.71	0.2–3.26	0.36–4	37	2.1–5
Pb		12.90 ppm	0.02–0.48	0.55–1.34	0.065–0.5		<5
Co		6.49 ppm					

a - Rodrigues and Hu (2017)
b - Scull *et al.* (2012)
c - Gamboa *et al.* (2011)

Table II

Heavy metal concentrations in soils and sugarcane in Huanjiang County, China

Metal	Soil (mg/kg)	Sugarcane roots (mg/kg)	Sugarcane upper stems (mg/kg)	Sugarcane leaves (mg/kg)
Cu	33.054	9.3	3.22	3.13
Zn	707.95	197	87.61	42.30
Pb	929.25	161.1	2.95	6.89
Cd	1.15	0.6	0.05	0.029
As	60.89	10.3	0.05	0.12
Cr	47.43	94.5	2.68	4.53
Ni	16.64	4.8	0.44	2.90

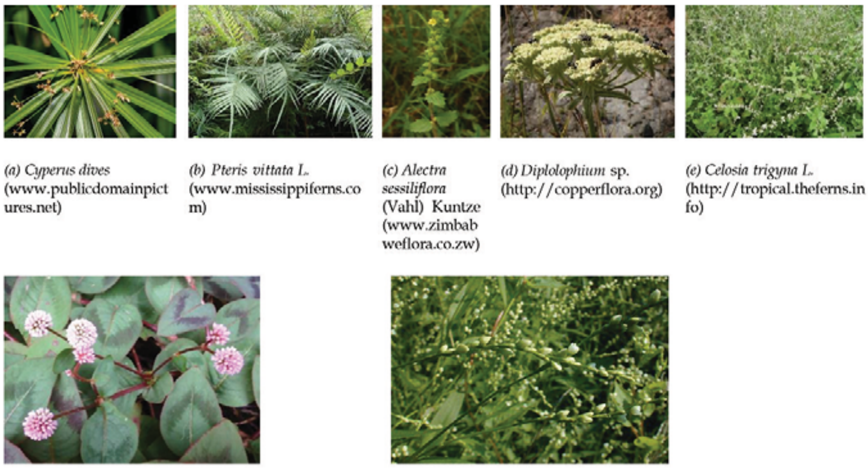
the location of heavy metals in the part (roots, stems, leaves) of the plant, or in general the biomass distribution in the plant, determines how the plant will be managed and consequently the commercial viability of phytomining using such a plant.

There is therefore a need to look at plants that can extract and accumulate significant amounts of valuable metals to make phytomining economically viable. The use of phytoaccumator plants that can also be applied to produce biofuels will create another income stream which can contribute to the reduction of remediation costs, because of the revenues from biofuels, even if the recoverable valuable metals from the plants are not in economically viable amounts. Furthermore, land will be made available for general agricultural use as the heavy metals in the soils are progressively reduced to acceptable levels (van der Ent. *et al*, 2015a).

Growing periods for sugar- and starch-based crops differ. For example, the period is 9–18 months for sugarcane, 4–4.3 months for sweet sorghum, 10–16 months for cassava, and about 6 months for sweet potatoes (Sinkala, Timilsina and Ekanayake, 2013), during which time the crops accumulate metals according to their respective abilities. Sugarcane and sweet sorghum, following the first harvest, are thereafter harvested from ratoons (Sinkala, Timilsina, and Ekanayake, 2013; Verheye, 2017). Harvesting from ratoons can be after 7–9 months from the virgin crop harvest (Verheye, 2017). Furthermore, the cost range for replanting sugarcane is about US$1 135–US$2 530 per hectare, whereas for managing a ratoon (or stubble) crop it is much cheaper at US$321–US$633 per hectare (PECEGE and CNA, 2016; Deliberto and Salassi, 2015). Thus, uprooting a sugarcane crop would be a relatively expensive operation as sugarcane would have to be replanted every year or after every harvest, as opposed to harvesting from cheaper ratoon/stubble crop.

Hyperaccumulator terrestrial plants

A study by van der Ent *et al.* (2015c) revealed that there are more than 30 Cu-Co hyperaccumulator plants (see examples in Figure 1) in the copper-cobalt belt of the Democratic Republic of Congo and Zambia that accumulate extraordinarily high concentrations of Cu and Co metal in their living tissues. They pointed out that such plants can be grown and harvested to remove Cu-Co from (polluted) soils, thus serving to remediate contaminated soils, for example around smelters (phytoextraction), or to create a 'metal-



(a) *Cyperus dives* (www.publicdomainpictures.net)
(b) *Pteris vittata* L. (www.mississippiferns.com)
(c) *Alectra sessiliflora* (Vahl) Kuntze (www.zimbabweflora.co.zw)
(d) *Diplolophium* sp. (http://copperflora.org)
(e) *Celosia trigyna* L. (http://tropical.theferns.info)
(f) *Persicaria capitata* (https://keyserver.lucidcentral.org)
(g) *Persicaria puncata*. http://www.illinoiswildflowers.info)

Figure 1—Some Cu-Co hyperaccumulator plants found in the copper-cobalt belt of the Democratic Republic of Congo and Zambia

Table III

Highest detected metal contents from preliminary XRF analysis of plant material from the Zambian Copperbelt, (mg/kg)

Family	Name	Se	As	Zn	Cu	Co
Cyperaceae	Cyperus dives	128				
Pteridaceae	Pteris vittata L.		259			
Orobanchaceae	Alectra sessiliflora (Vahl) Kuntze			918		
Apiceae	cf. Diplolophium sp.				3 038	
Amaranthaceae	Celosia trigyna L.					1 060

Compiled from van der Ent *et al*., 2015c

Table IV

Highest detected metal contents from preliminary soil analysis by DTPA extraction (indicative of plant-available metal concentrations), mg/kg

Type	Location/species	Co	Cu	Fe	Mn	Ni	Zn
Rhizosphere	Persicaria capitata	307	958	30		3.6	
Topsoil	Tailings (at Luanshya)				14		
Rhizosphere	Persicaria puncata						18

Compiled from van der Ent *et al*., 2015c

enriched crop' (phytomining). The project aimed to elucidate metal speciation and elemental distribution in selected Cu-Co hyperaccumulators with high potential for phytoextraction, for which 200 plant specimens, 25 soil samples, and 10 mineral samples were collected for chemical analysis.

Table III indicates the highest detected metal contents from preliminary X-ray fluorescence (XRF) analysis of plant material from the Zambian Copperbelt, while Table IV indicates the highest detected metal contents from soils collected in the same area and extracted with diethylene triamine pentaacetic acid (DTPA). It can be observed that the levels of metal in both plants and soil are significantly higher than those reported in Table II for the mining area in China. However, using these plants to produce ethanol may require advanced biofuels technologies.

Křibek *et al*. (2013) studied the content of metals and As in the leaves and tubers of cassava (*Manihot esculenta*) and sweet potatoes (*Ipomoea batatas*) growing on uncontaminated and contaminated soils of the Zambian Copperbelt. They found that the order in which metal concentration increased in different plant organs was tuber, root, stem, leaf stalk, and leaf. The contents of Cu in cassava and sweet potato leaves growing on contaminated soils were as high as 612 mg/kg total dry weight (dw) and 377 mg/kg dw, respectively. The contents of Cu in leaves of both plants growing on uncontaminated soils were much lower (up to 252 and 198 mg/kg dw, respectively). The contents of Co, As, and Zn in leaves of cassava and sweet potatoes growing on contaminated soils were higher than in uncontaminated areas, while the contents of Pb did not differ significantly.

The highest detected copper content of 612 mg/kg in cassava leaves growing in Copperbelt soils (Křibek *et al*. 2013) translates to 0.0612% grade (or 0.612 kg/t), while the highest copper content of 958 mg/kg detected in Persicaria capitata (van der Ent *et al*. 2015b) translates to 0.0958% grade (or 0.958 kg/t). The highest Cu content of 3 038 mg/kg detected by van der Ent *et al*. (2015b) in Apiceae cf. *Diplolophium* sp, and the 1 060 mg/kg Co in Amaranthaceae *Celosia trigyna L*., translate to 0.3058% grade (or 3.058 kg/t) Cu and 0.1068% grade (or 1.068 kg/t) Co, respectively. Compare these to prevailing prices of US$7 100 per ton for Cu and US$75 500 per ton for Co (LME, 2018), and to published copper ore grades for surface mines in Zambia of 0.46% for Barrick's Lumwana mine (Barrick, 2014) and 0.5% for First Quantum's Kansanshi mine (FQML, 2017). Furthermore, for Zambia there are reasonable margins between production costs of ethanol and the pump price of petrol (gasoline). Ethanol is the equivalent of petrol and can be used either 100% or in any ethanol/petrol proportion in a flexible fuel engine, or can be blended with petrol in appropriate petrol engines (Barros, 2010). Production costs of ethanol range from about US$0.4 to US$0.7 per litre (PECEGE and CNA, 2016; Sinkala, Timilsina and Ekanayake, 2013), depending on the feedstock and refinery technology used, while the petrol price at the pump in Zambia is currently US$1.375 per litre. Clearly, the above metal grades concentrated by plants, and the ethanol production margins, appear to be sufficiently attractive to warrant feasibility studies on the possible implementation of integrated agro/phytomining with bioethanol production in viable areas.

Hyperaccumulator aquatic plants

There is also interest in appropriate aquatic hyperaccumulator plants that are technically and economically viable for both phytoremediation and ethanol production. Among the plants of interest that can be used to accumulate heavy metals and also to produce first-generation ethanol are cattails, or *Typha latifolia* L (see Figure 2). Cattails are herbaceous, rhizomatous perennial plants with long, slender green stalks topped with brown, fluffy, sausage-shaped flowering heads that are often found in marshlands where they extract dissolved nutrients out of water, leaving the marsh relatively clean (Acres USA, 2008). The plants are about 1.5–3.0 m tall, and are fairly high in starch content, usually about 30–46% (USDA, 2006). Cattails grown under marsh conditions using sewage yield 7 500 gallons of alcohol per acre (70 155 litres of alcohol per hectare) (Acres USA, 2008). The average yield of cattails from constructed wetlands is reported to be 16.1 t/ha, with a maximum of 42.7 t/ha (Suda, Shahbazi and Li, 2007).

The cattail core can be ground into flour (see Figure 2c), with one acre of the plants yielding about 6475 pounds (16 t) of flour per hectare (USDA, 2006). Projectgaia (2015) has quoted ethanol yields of 10 051 L/ha for wild cattail, 23 375 L/ha when produced from cattail starch only, and 93 500 L/ha for cellulose from cattails grown in sewage. Indicative levels of heavy metals accumulating in this plant can be seen in Table V.

(a) Cattail (Typha latifolia L.) aquatic plant (www.publicdomainpictures.net). *(b) Cattail (Typha latifolia L.) roots (https://i.pinimg.com).* *(c) Cattail (Typha latifolia L.) flour and fibre (https://www.tapatalk.com).*

Figure 2—Examples of aquatic hyperaccumulator plants

Table V

Heavy metal accumulation in various parts of cattail (*Typha latifolia L*) (mg/kg)

Data source and plant location	Cu	Co	Fe	Zn	Ni	Cr	Pb	Sn	As	Mn
Substrate[a]	1 156.7			1 231.7	296.7					
Root[a]	93.3			391.7	55.0					
Stem/leaves[a]	15.0			60.8	27.5					
Tissue[b]	48.0	7.7	341.0	1 412.0	524.0	15.0	27.0	138.0	157.0	3 161.0
Sediment[c]	3 738.0			30 09.0	9 372.0	92.1	5 686.0			
Root[c]	50.0			946.0	55.0	44.0	1 108.0			
Leaf[c]	30.0			215.0	40.0	21.0	40.0			

a – Manios *et al*.. (2003)
b - Hussain *et al*.. (2014)
c – Beisner *et al*.. (2014)

For every ton of combined roots and shoots (stems and leaves) of cattails harvested in ratios of about 86.15:14.85 respectively, the 108.3 (93.3 + 15) mg/kg of Cu obtained by Manios *et al.* (2003) would yield 0.1083 kg of Cu. At the time of writing this paper, literature quoting heavy metal tolerance levels for cattail could not be found. Such levels would have helped to determine the maximum amount of metals that can be extracted from this plant.

Benefits of using hyperaccumulator plants for both remediation and ethanol production

The above review of the literature shows that there are plants that can be used both to remediate mine environments polluted with heavy metals and to produce biofuels. Terrestrial plants such as Apiceae cf. *Diplolophium* sp identified in the Zambian Copperbelt and aquatic plants such as *Typha latifolia* L. (or cattail) that are found in the country (Catarino and Martins, 2010) are very promising. Below are examples of conceptual major socio-economic benefits that can be realized from a combined phytomining and biofuels/ethanol production approach:

- Unlike other methods, where money is spent to remediate contaminated mining areas, the use of appropriate plants for phytoremediation would instead generate income streams through reclaimed valuable heavy metals and production of ethanol and associated co-products from the harvested plants.
- Mining communities can be engaged in the agromining and ethanol production value chains, thus creating jobs for the communities.
- After mine closure and remediation of mine areas, ethanol production and its value chain activities can continue to provide livelihoods for host communities, thus diverting the communities from engaging in resource-degrading activities for livelihoods.
- The remediated land can be used for the production of food crops and other socio-economic activities, in addition to continued ethanol production.
- Mining companies would overall improve their corporate social responsibility image.

Countries engage in development of biofuels industries for a variety of reasons. Reasons often reported include energy security, job creation, rural industrialization, retention of wealth created from national resources, enhancing food security, and minimizing impacts of climate change (Filho, 2017; Hodur and Leistritz, 2009; Silalertruksa *et al.* 2012; Sinkala, Timilsina, and Ekanayake, 2013; IRENA, 2018).

Below are a some examples from a few countries, illustrating the benefits that would accrue to the Zambian Copperbelt due to the biofuels industry alone, if successfully implemented:

Economic contribution

In **Brazil**, the sugarcane sector contributes about US$43.8 billion to country's gross domestic product (GDP) – equivalent to almost 2% of the entire Brazilian economy. When various suppliers and stakeholders who depend on Brazil's sugarcane industry are added, the entire sugarcane agro-industrial system generates gross revenues totaling more than US$87 billion annually, to which ethanol contributes about US$12.42 billion (Filho, 2017; Neves *et al.*, 2008).

In a projection to the year 2022, in **Thailand**, the biofuels sector's contribution to the GDP is around US$150 million, with savings in imported goods worth US$2.547 billion compared to petroleum fuels (Silalertruksa *et al.*, 2012).

Sweden, which currently produces 55 ML of ethanol and 403 ML of biodiesel per annum (Ekbom, 2018), has made foreign exchange savings of more than US$600 million. Of the biodiesel, 100 ML per year are produced from wood pulp.

In the **USA**, a study by Hodur and Leistritz (2009) on the economic impacts of biofuel development revealed that an investment of US$176.5 million into the production of 190 ML of ethanol per year in North Dakota resulted in an annual operating expenditure of US$74.6 million. Of this, US$53 million constituted payments to North Dakota entities, of which the largest expenditure item by far (US$36million, or 68%) went to feedstock purchases and related supply logistics. In the Zambian context, feedstocks are expected to be produced largely by smallholder farmers, who would thus be among the major beneficiaries.

In 2017, the ethanol industry contributed more than US$24 billion to the US economy. The most significant impact of the ethanol industry is increased income to farmers who benefit from the demand for feedstock, which leads to both increased production and increased prices as well as earnings from locally-owned ethanol plants (Urbanchuk, 2018). This, again, illustrates the likely benefits that would accrue to smallholder farmers engaged in feedstock production.

In 2013, production of 6.4 billion litres of biodiesel contributed US$16.8 billion to the US economy (NBB, 2018). Use of 4.3 billion litres of biodiesel was estimated to lower greenhouse gas emissions by nearly 10 million metric tons of CO_2 equivalent.

Job creation

In **Brazil**, the sugarcane industry employs 1.09 million workers, according to 2011 data from the Ministry of Labor and Employment's Annual Report of Social Information (Filho, 2017). Salaries for sugarcane industry workers are among the highest in Brazil's agricultural sector, second only to wages in the soybean industry. For example, in 2008, sugarcane workers employed in Brazil's South-Central region (the country's main cane-producing zone) earned an average monthly income of R$1 062.55 (US$487.41), while in the North-Northeast region the average was R$666.20 (US$305.60). For context, the national average monthly salary amounted to R$942.02 (US$432.12) that year, and the minimum was R$415.00 (US$190.37). This is indicative of the reasonable incomes for the labour force that would be engaged in the biofuels sector in the Copperbelt.

In **Thailand**, a study by Silalertruksa *et al.* (2012) showed that producing ethanol and biodiesel requires about 17–20 more workers than gasoline, and 10 times the number for diesel, as per equivalent energy content, and that direct employment in agriculture contributes to more than 90% of total employment. In a projection to the year 2022, the estimated employment generation was found to be between around 238 700 and 382 400 person-years. Thus, the

Zambian Copperbelt Province, which has the largest percentage (29%) of youth unemployment, would benefit from the large labour requirements in the biofuels industry (CSO, 2016).

In **Sweden**, a study in 1998 found that each extra TWh of bioenergy use resulted in 300 extra jobs in the whole supply chain. The study did not include employment in construction, *e.g.* of heat plants. It was also found that one big advantage with bioenergy was that the employment was spread over the whole country, which is of great significance to the smaller communities and to rural development (Anderson, 2015). This scenario is in support of expectations from the success of the concept presented in this paper.

In the **USA**, when the direct, indirect, and induced jobs supported by ethanol production, construction activity, agriculture, exports, and R&D are included, the ethanol industry contributed nearly 360 000 jobs in 2017 (Urbanchuk, 2018). In 2012, the total employment in the biodiesel industry in the USA stood at nearly 47 000 jobs, with more than US$2.6 billion in wages paid (LMC International, 2013). Employment has since risen to 64 000 jobs in 2018 (NBB, 2018).

Clearly, there are demonstrable benefits of a biofuels industry if well implemented. Phytomining, on the other hand, is yet to be commercially implemented. To deploy the concept presented here, van der Ent *et al.* (2015a) proposed 'agromining' (a variant of phytomining). This is a type of agriculture to be carried out on degraded lands, where farming would not be for food crops but for valuable metals. They also presented a demonstration of how this can be carried out, as shown in Figure 3. The production sequence proposed in this paper is that processing of metals would be done after bioethanol has been produced from fermented material (Peters and Stojcheva, 2017; Verardi *et al.*, 2012).

Conclusions

It is globally recognized that traditional physical and chemical approaches to remediation of polluted mine environments are expensive, and often leave significant liabilities for host communities. These include permanently altered soil properties, destruction of host soil and microflora, and the creation of additional pollution problems, such as the generation of large volumes of chemical waste (Ayangbenro and Babalola, 2017). The abandoned, degraded land becomes a loss for future generations. Where communities continue to use the polluted land, their health is adversely affected, and so is that of wildlife.

Agro/phytomining, which involve planting and subsequent harvesting of appropriate vegetation that selectively concentrates specific metals from the environment into the plant tissues and recovery of valuable metals from the plants, offer hope of finding win-win methods of remediating contaminated mine environments. This is because in addition to cheaply remediating the environment, the valuable accumulated heavy metals in plants can be commercially exploited to add to normal mining revenues.

Some hyperaccumulator plants can also be used to produce biofuels, such as ethanol, on a commercial basis, which would also add to income streams for mining companies. The participatory nature of biofuel production would significantly benefit mining host communities, both during and beyond mine life.

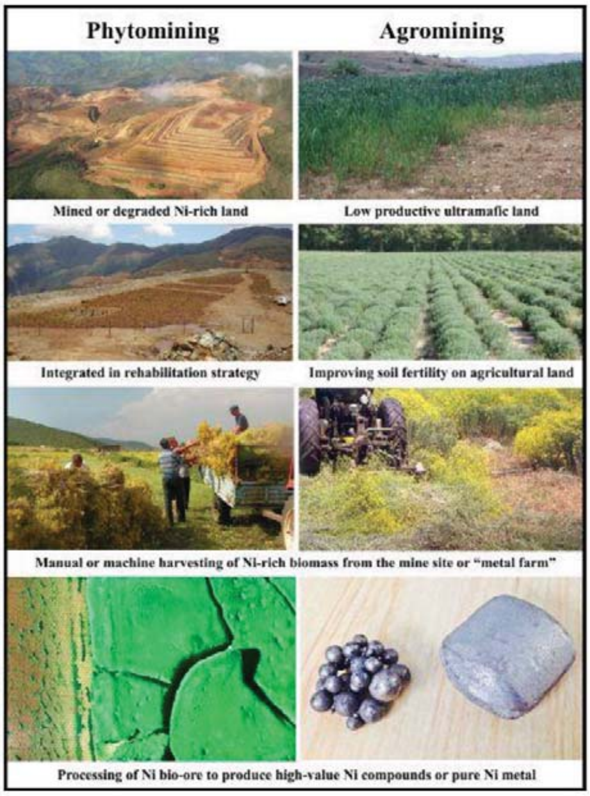


Figure 3—Phytomining/agromining operations with harvesting of biomass and processing of bio-ore (van der Ent *et al.*, 2015a)

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