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Review

Phytoremediation and phytoextraction in Sub-Saharan Africa: Addressing economic and social challenges

Jordy Lee [a,*], Rennie B. Kaunda [b], Thomson Sinkala [c], Caleb F. Workman [a], Morgan D. Bazilian [a], Greg Clough [a]

[a] The Payne Institute for Public Policy, Colorado School of Mines, 816 15th St., Golden, CO, USA
[b] Department of Mining Engineering, Colorado School of Mines, 816 15th St., Golden, CO, USA
[c] Department of Mining Engineering, University of Zambia, Great East Road Campus, Lusaka, Zambia

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ABSTRACT

Mining and mineral processing continues to be a source of lasting environmental problems in many developing economies. Phytoremediation has proven to be a viable strategy to remediate contaminated lands and limit environmental damage, but it has not been widely implemented partially due to social and economic challenges. However, by encouraging phytoremediation with a focus on phytoextraction, it may be possible to rehabilitate contaminated lands while simultaneously providing economic support to local communities. This can be achieved by the sale of phytoextracted metals to fund large-scale phytoremediation, particularly in Sub-Saharan Africa. To this end, this paper provides a conceptual approach for phytoremediation-based mineral recovery and explores the social and economic challenges related to large-scale deployment. The viability of the approach is explored and future work on phytoremediation implementation is defined with the goal of advancing research and collaboration.

1. Introduction

Phytoremediation, a bioremediation process that uses plants to remove pollutants from an environment, has proven to be a viable, low-cost strategy for rehabilitating mining-active regions (Elbehiry et al., 2020; Favas et al., 2014; Festin et al., 2019; Gerhardt et al., 2009; Sarwar et al., 2017; Sinkala, 2018; Wiszniewska et al., 2016). The process, which involves extracting pollutants from soils using plant roots, has been efficiently tested and implemented in former mining communities around the world, including in Africa and South America (Elbehiry et al., 2020; Gerhardt et al., 2009, 2017; Marrugo-Madrid et al., 2021; Odoh et al., 2019). It is widely accepted as a potentially cost-effective, environmentally friendly alternative to engineered solutions, as it does not require invasive remediation processes such as soil excavation or chemical use (Gerhardt et al., 2017; Yan et al., 2020).

Over the last decade, research into phytoremediation has further advanced its viability as a remediation technique. Continuous studies on the effects that different chemical additives have on phytoremediation, the viability of genetically engineered plants, the uptake mechanisms of different plants, and general enhancements of phytoremediation processes, have increased phytoremediation's efficiency (Ali et al., 2013; Bauddh and Singh, 2012; Eapen and D'Souza, 2005; Elbehiry et al., 2020; Etim, 2012; Glick, 2010; Muthusaravanan et al., 2018; Tauqeer, Fatima et al., 2021; Tauqeer, Karczewska et al., 2021). However, despite these advances, and the increased viability of phytoremediation, it has not become a widely adopted strategy. This is partially because of the scale of remediation that is often required to clean up existing pollution sites (meaning lots of plants and maintenance), but also because many of the communities that would benefit from phytoremediation have other socioeconomic concerns. These concerns make large-scale remediation projects difficult and unappealing, especially in mining active regions where resource governance is weak and many people are heavily impoverished (Gerhardt et al., 2017; Odoh et al., 2019; Salt et al., 2003; Sarwar et al., 2017).

With increasing mineral demand, there is now the possibility to use phytoextraction — the use of pollutant-accumulating plants to directly recover metals from soils — to create a more economic phytoremediation approach (Bloomberg, 2019; Church and Crawford, 2018; Giurco et al., 2019; Graedel et al., 2015; IRENA, 2019; Muthusaravanan et al., 2018; Raymond et al., 2011; World Bank, 2017; Lee et al., 2020).

* Correspondence to: Payne Institute for Public Policy, Colorado School of Mines, 816 15th St., Golden, CO, USA.
E-mail address: jorlee@mines.edu (J. Lee).

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To demonstrate the increased feasibility of phytoremediation, and to address the social limitations of phytoremediation adoption, this paper provides a conceptual outline for a phytoremediation-based mineral recovery and remediation in Sub-Saharan Africa. The social and potential economic benefits of phytoextraction and phytoremediation are outlined, as are the social limitations to current studies and how this research can be leveraged to advance adoption. Section 2 reviews the existing impacts of mining activities in Sub-Saharan Africa. Section 3 explains the advanced remediation approach and its usefulness in solving presented issues. Section 4 provides conclusions and recommends for the next steps to be taken by subsequent researchers.

2. The challenges and impacts of mining in underdeveloped regions

In many parts of Sub-Saharan Africa, the need for phytoremediation is shown through the numerous mining activities that have altered the natural landscape and are the source of many environmental hazards (Festin et al., 2019; Sikaundi, 2008; Sinkala, 2009). Many regions also lack the proper governance to clean up pollution or ensure that environmental issues do not worsen.

2.1. Mining as a source of pollution

Areas where large-scale, industrial mine sites were poorly managed have resulted in the pollution of great tracts of land, the effects of which can potentially be limited by phytoremediation (Festin et al., 2019; Sinkala, 2009, 2018). Metalliferous mine environments are usually polluted with toxic heavy metals, such as lead, arsenic, cadmium, zinc, nickel, copper, and mercury (Bortey-Sam et al., 2015; Tchounwou et al., 2012). These heavy metals can be ingested by local populations through a variety of channels, leading to serious health hazards in human beings, plants, and animals. As the metals are non-biodegradable, their impacts can be long-lasting and multi-generational (Fig. 1), especially in Sub-Saharan Africa (Sovacool et al., 2020; Tembo et al., 2006).

In the Democratic Republic of Congo (DRC), investigations into working conditions have found an estimated 255,000 artisanal miners, 35,000 of whom are children, working in “exceedingly harsh, hazardous, and toxic conditions” (Kara, 2018; The United Nations, 2001; Togoh, 2019; Walt and Meyer, 2018). Due to these conditions and a lack of preventative strategies, such as drilling with water and proper ventilation, many miners have extremely high levels of toxic metals in their bodies and are at risk of developing respiratory illnesses, heart diseases, and cancer (Sovacool et al., 2020).

People living in nearby regions within the Katanga Copperbelt (covering Zambia and the DRC) have also exhibited high concentrations of metals within their systems relative to nearby control areas (Banza Lubaba Nkulu et al., 2018). These differences were most pronounced among children, where there was evidence of exposure-related oxidative DNA damage that could lead to lifelong health problems (Banza Lubaba Nkulu et al., 2018). Even without new and developing mining projects, the area is already part of one of the ten most polluted places on Earth due to its role in industrial extraction and processing, as illustrated in Fig. 1 (Dominish et al., 2019).

Studies undertaken on the Zambian Copperbelt Province also indicate that mining pollutants often disperse to much wider areas (50 km by 150 km) than the permitted mining and processing zones from where they emanated (Fig. 2) (Kříbek et al., 2013). Heavy metals in food crops growing on contaminated soils, such as cassava and sweet potatoes, have exhibited much higher levels of lead, zinc, nickel, and copper — with lead being a particularly prominent health risk (Bortey-Sam et al., 2015; Kříbek et al., 2013; The World Bank, 2016; Uchida et al., 2017). For many Sub-Saharan countries, such as Zambia, cassava is the main food-security crop after maize, and its pollution or non-availability can exacerbate existing food security and malnutrition issues (Alamu et al., 2019; Kříbek et al., 2013).

2.2. Governance shortcomings

While it is clear that mining and processing of minerals and metals have created long-lasting environmental problems, environmental governance is also lacking. This makes it difficult to correct environmental problems or ensure that they don’t happen again. Both of these shortcomings support the deployment of phytoremediation as a self-sufficient strategy.

For a mining company, environmental impacts are often assessed in separate processes and by separate institutions from financial revenues, often making them secondary considerations (Woodroffe and Grice, 2019). Because of this, many mitigation efforts rely heavily on civil society groups, the private sector, and governments acting as “watchdogs” to hold mining entities accountable or create actionable plans (Lee et al., 2020). This is inefficient because the direct impact of mining

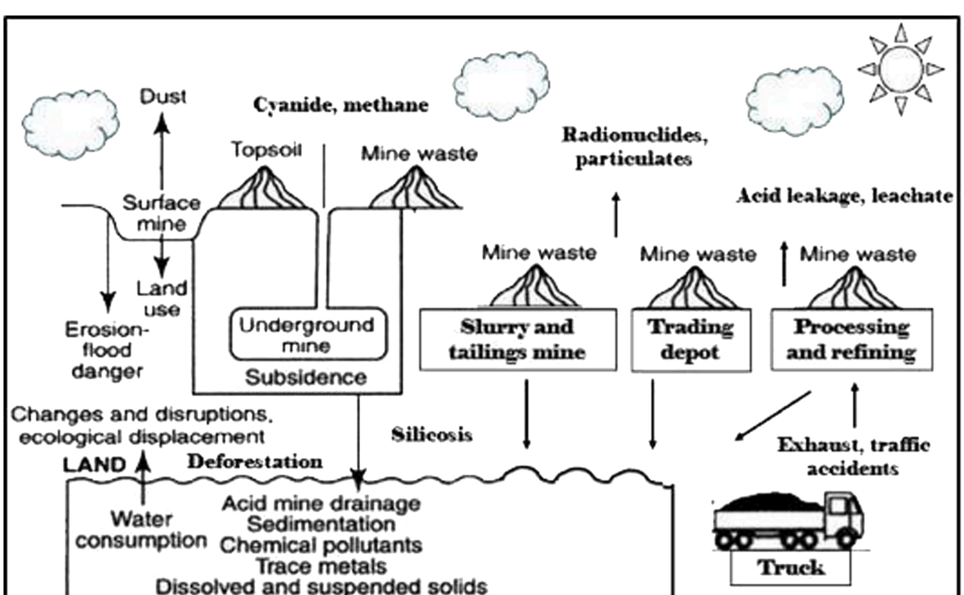

Fig. 1. The multi-dimensional environmental impacts of cobalt mining in the Democratic Republic of the Congo (Sovacool et al., 2020; Lee et al., 2020).

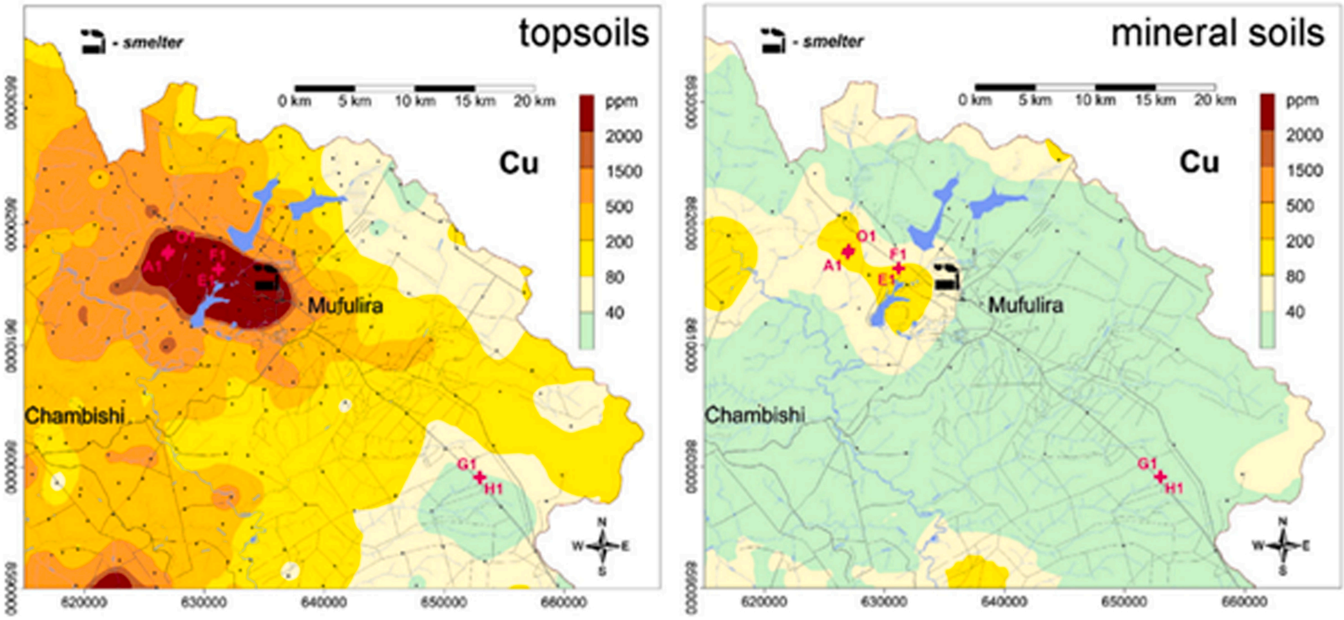

Fig. 2. Location of the soil profiles in the Mufulira copper smelter area. The spatial distribution of Cu as a major contaminant in topsoil and mineral soils (depth: 80 cm) (Ettler et al., 2014, Kříbek et al., 2013).

activities is often difficult to immediately gauge (Boiral, 2013; Lee et al., 2020). Even among third-party evaluated sustainability reports, environmental disclosures by mining companies were found to be disconnected from reality and fundamentally misleading (Boiral, 2013). An emphasis on a mining firm's positive achievements, virtuous commitments, and use of inaccurate pictures (that showed pristine nature), only served to advance misrepresentation (Boiral, 2013; Lee at al, 2020). This misrepresentation can undermine efforts to create remediation projects.

When combined with poor or weak resource governance, the inability to assign and identify environmental impacts can be perilous for surrounding communities. Many Sub-Saharan countries have unsatisfactory governance scores (Table 1), which means that mining can help societies, but it is unlikely they will gain long-term benefits related to increased quality of life (Natural Resource Governance Institute (NRGI), 2019). Poor scores also imply that regions are limited in their ability to stop environmental degradation before it happens. These effects are especially problematic in the context of growing material needs, as projected increases in demand will make projects near environmentally vulnerable sites (coastlines, rivers, communities) more attractive (Ali et al., 2017; Bloomberg, 2019; Church and Crawford, 2018; DNV GL's Energy Transition Outlook, 2018; Giurco et al., 2019; Graedel et al., 2015; IRENA, 2019; Raymond et al., 2011; World Bank, 2017).

With mining companies not reporting on their impacts, the industry already having a history of polluting the region, and no clear path forward for remediation, it is clear that many Sub-Saharan African countries should not rely on local governance as a safety net. The environmental impacts across Sub-Saharan Africa need to be addressed from a technological perspective, and it is possible to start the process with phytoremediation.

3. Phytoremediation

Phytoremediation is the use of plants to remove or degrade pollutants from the environment and is a viable option for Sub-Saharan Africa. The process involves the accumulation of pollutants, including heavy metals, into the plant through its root structure from the surrounding soil. The uptake of these pollutants, and the effects on the plant are variable, and can further be modified using chemicals, genetically engineered plants, agricultural techniques, plant microbes, and post-treatment of phytoremediation biomass (Bagga and Peterson, 2001; Bañuelos et al., 2015; Bauddh and Singh, 2012; Conner et al., 2003; Eapen and D'Souza, 2005; Ho et al., 2013; Huang and Cunningham, 1996; Shahbaz et al., 2019; Shahid et al., 2014; Song et al., 2001; Tauqeer, Fatima et al., 2021; Turan, 2019).

For Sub-Saharan Africa specifically, there are more than 30 known hyperaccumulator plant species in the Central African Copperbelt, and the use of these plants for phytoremediation could allow for agricultural development, successful remediation of surrounding lands, and potentially serve as a source of valuable minerals and metals. This is further made possible through phytoextraction (Fig. 3), which is a subset of phytoremediation that involves the absorption of pollutants through the roots followed by transportation to aerial parts of the plant to be harvested. The cornerstone of this approach comes from the plants that accumulate heavy metals in high concentrations without toxicity or agricultural concerns, which can then be harvested or processed to remove the metals (phytoextraction). These metals can be recovered and sold for profit, while the biomass value addition at appropriate stages can also present further economic opportunities in the form of biofuels and bioenergy (Fig. 3) (Favas et al., 2014; Sinkala, 2018; van der Ent et al., 2015; Muthusaravanan et al., 2018; Sinkala, 2021).

3.1. Challenges of phytoremediation

Despite poor governance and growing environmental drawbacks leading to cascading problems caused by mining in Sub-Saharan Africa, phytoremediation has not been widely adopted. When reviewing phytoremediation efforts, issues have primarily arisen from a lack of social understanding and interest, particularly around costs. Odoh et al. (2019) examined the "status, progress and challenges of phytoremediation" on the African continent and ascribed limited adoption to minuscule funding from African governments, a lack of consistency across environments, and no continent-wide initiatives or policy frameworks. Similarly, Gerhardt et al. (2017) found limitations in adoption stemming from the lack of proper conveyance of analysis and findings — the better understanding of which would help incentivize the policy frameworks needed to support phytoremediation deployment (Gerhardt et al., 2009,

Table 1
Governance Scores for Sub-Saharan Africa, adapted from the National Resource Governance Index (NRGI) (2019).

Sub-Saharan Country	Index Score (out of 100) for Mining Sector
Botswana	61
Burkina Faso	59
South Africa	57
Ghana	56
Niger	54
Mali	53
Zambia	50
Tanzania	49
Sierra Leone	46
Liberia	44
Ethiopia	40
Guinea	38
Madagascar	36
Democratic Republic of Congo	33
Zimbabwe	29
Eritrea	10
Good ≥ 75	A country has established laws and practices that are likely to result in extractive resources being used to help citizens, although there may be some costs to society
Satisfactory 60-74	A country has some strong governance practices, but some areas need improvement. It is reasonably likely that extractive procedures will benefit citizens, but there may be costs to society.
Weak 45-59	A country has a mix of strong and problematic governance areas. Resource extraction can help society, but it is likely eventual benefits will be weak.
Poor 30-44	A country has established minimum procedures and practices to govern resources, but most elements to help society are missing.
Failing < 30	A country has almost no governance framework to ensure resource extraction benefits society. It is highly likely that benefits only flow to come companies and elites.

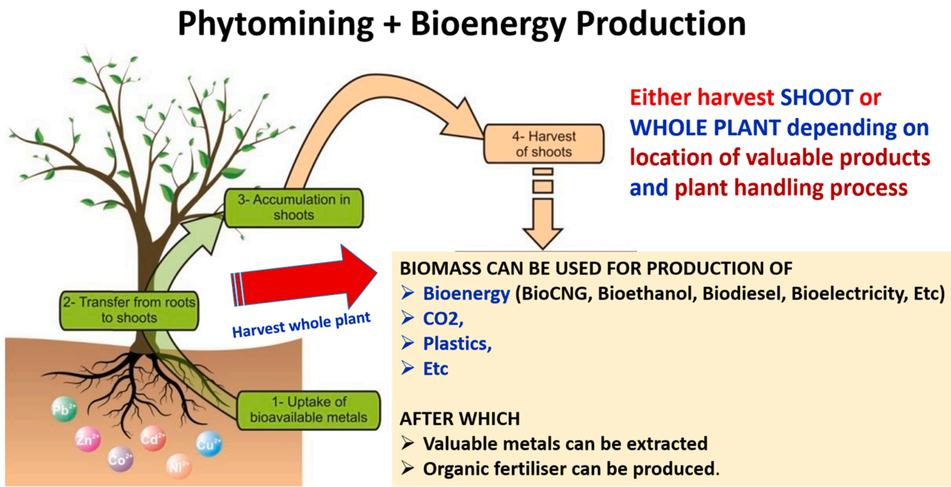

Fig. 3. Phytoextraction and phytomining.
Adapted from Favas et al. (2014) (Favas et al., 2014; Sinkala, 2021).

2017).

To this end, educating the public and private sectors on the benefits provided by phytoremediation is an achievable task, but academic studies often fall short in building confidence because they do not adequately translate the concepts for public consumption (Gerhardt et al., 2017). Furthermore, few studies provide financial analysis with realistic cost estimates, which are an important direct requirement for governments and communities in determining the viability of phytoremediation implementation.

These cost studies are especially important in Sub-Saharan Africa, where estimates are crucial for evaluating feasibility in communities that often lack the funds for traditional remediation approaches. Because of this disparity between the researchers and the individuals who actually attempt to utilize phytoremediation, the efforts are often run by people with low agronomic and chemical expertise, ultimately causing failures in their implementation. These problems are then made worse by a misunderstanding of phytoremediation and its limitations (Odoh et al., 2019).

3.2. *The solution of advanced phytoremediation: a conceptual approach*

As a way to elevate interest, and potentially generate revenue while maximizing remediation efforts, phytoextraction, combined with phytoremediation, could be a solution to some of Sub-Saharan Africa's environmental and economic concerns. It is possible to use phytoremediation and phytoextraction to mine heavy metals from polluted land and sell them for a profit to advance phytoremediation adoption (Fig. 4). This is possible due to extreme hyperaccumulator plants, which can be burned to economically extract metals.

This can best be demonstrated with two hyperaccumulating, phytoremediation plants: *Haumaniastrum robertii* and *Aeolanthus biformifolius*. The most extreme cobalt hyperaccumulator, *Haumaniastrum robertii*, is able to accumulate up to 1 wt% cobalt, whereas the most extreme copper hyperaccumulator, *Aeolanthus biformifolius,* can accumulate up to 1 wt% copper (van der Ent et al., 2015). Through this accumulation, large-scale use of Haumaniastrum robertii can translate to 200 kg of cobalt for 20 tonnes of dry biomass per hectare per annum. At 100% cobalt recovery, and $31,374 price per tonne, this can potentially translate to $6275 per hectare per annum for the surrounding

Table 2
Yield and revenue from phyto-mining.

	Tonnes/ Hectare/Year	Price/ Tonne	Land used (Hectares)	Annual yield
Haumaniastrum robertii (Cobalt)				
Conservative Scenario	0.2	$31,374	10,000	$62,748,000
Low-Yield Scenario	0.2	$25,465	3000	$15,279,000
High-Yield Scenario	0.2	$60,680	30,000	$364,080,000
Aeolanthus biformifolius (Copper)				
Conservative Scenario	0.2	$6650	10,000	$13,300,000
Low-Yield Scenario	0.2	$4974	3000	$2,984,400
High-Yield Scenario	0.2	$8246	30,000	$49,476,000

Yields with three estimates: conservative scenario estimate (10-year median price with 33% land use), Low-Yield scenario estimate (10-year P10 price with 10% land use), and High-Yield scenario estimate: (10-year P90 price with 100% land use).
Source: Authors' calculations.

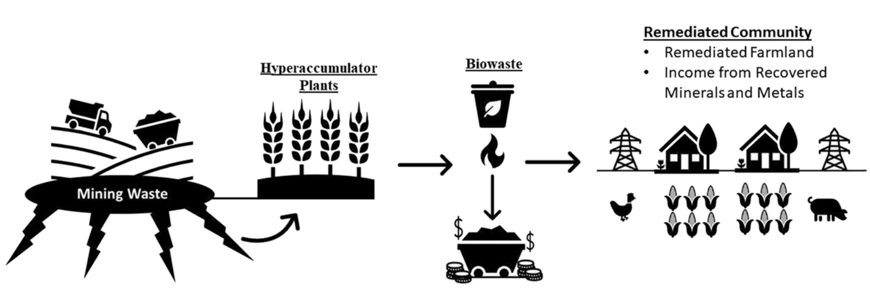

Fig. 4. Phyto mining approach.

community (Table 2).

Aeolanthus biformifolius, with its ability to accumulate up to 1 wt% copper, similarly translates to 200 kg of copper for 20 tonnes of dry biomass per hectare per annum. At 100% copper recovery, and $6650 copper price per tonne, this quantity can translate to $1330 per hectare per annum for the surrounding community.

The Zambian Copperbelt alone bears more than 30,000 ha of land occupied by mine dumps. Assuming 10,000 ha are used for phytoremediation, cobalt yield at the example recovery rate given would be $62 million per annum, while copper yield would be $13 million per annum. This calculation assumes perfect yield and perfect recovery but still serves as an indication of scale for recovering what is traditionally considered "waste" from phytoremediation and the use of toxic lands.

The phyto-mined metal grades would progressively reduce and eventually become uneconomic to extract, but compared to traditional mining the cutoff grades in phytoextraction are likely to be much lower. This is because phytoremediation has relatively low costs, and many of the phytoremediation plants can also potentially be used for biobased products until the soils become food-grade once again. Furthermore, the continued advancement of research regarding the ability of soil bacteria to facilitate phytoremediation, the genetic engineering of plants, the increased understanding of phytoremediation mechanisms, and other enhancements of the phytoremediation process will further extend the economic feasibility of phyto-mined metals and the overall remediation process (Ali et al., 2013; Bauddh and Singh, 2012; Eapen and D'Souza, 2005; Favas et al., 2014; Glick, 2010; Muthusaravanan et al., 2018; Wiszniewska et al., 2016; Yan et al., 2020).

Once phyto-mined metals become uneconomic to extract, the land can return to "perpetual" status for use in agriculture. The immobilization of pollutants through additives (e.g., organic amendments or non-health/environmental threatening chemicals), and enhanced phytoremediation (e.g., bacteria aided) without a phyto-mining focus can help address any remaining pollution concerns (Elbehiry et al., 2020; Tauqeer, Fatima et al., 2021; Turan, 2021). This will then conclude the phytoremediation process, which will potentially have served as an economic boon for surrounding communities that were struggling with environmental waste. In summary, this approach suggests that communities:

1. Examine the feasibility and suitability of hyperaccumulator plants.
2. Plant and cultivate phytoremediation plants.
3. Collect and process the waste from bioproduction to sell entrapped minerals and metals.
4. Use the associated economic benefits from phytoremediation to further work with surrounding communities, return the land to food-grade levels, and continue to benefit from land development.

4. Conclusion and future work

The failure of existing environmental safeguards and a lack of accountability from the mining industry demonstrates a growing need for new approaches to remediation. With phytoremediation, the heavy metals in soils and water could be brought down to acceptable levels for food-grade agricultural activities. The selling of recovered metals and biobased products derived from the remediation biomass could create economic opportunities for nearby communities without having to rely on mining governance or external funds. More importantly, these approaches might help improve the health status of communities in areas with mines, assure livelihoods for host communities, and reclaim land for food production and activities. This paper demonstrates that all of these changes are economically feasible and could potentially change and save the lives of millions of people living in Sub-Saharan Africa.

More work is needed for development and validation of this approach, especially in regard to coordinating with local communities. With this in mind, and to stimulate further research, areas of future focus include:

- Developing a better understanding of current pollution issues from past mining activities.
- Engaging communities in both active and abandoned mine areas to further understand the feasibility of phytoremediation and phytoextraction.

Creating a fund for initiating local phytoremediation programs as a way of minimizing communal burdens during feasibility studies.

- Engaging with African learning institutions to bring in expertise on reducing environmental risks to host communities through phytoremediation.

As a novel approach, phytoremediation with mineral extraction can help to reinvigorate a currently stagnating environment. Current approaches are not working, existing mining practices are making things worse, and the mining companies are not being held accountable. It is time to examine new pathways towards better practices to ensure environmental and economic stability for Sub-Saharan African communities.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alamu, E.O., Ntawuruhunga, P., Chibwe, T., Mukuka, I., Chiona, M., 2019. Evaluation of cassava processing and utilization at household level in Zambia. Food Secur. 11 (1), 141–150.

Ali, H., Khan, E., Sajad, M.A., 2013. Phytoremediation of heavy metals–concepts and applications. Chemosphere 91 (7), 869–881.

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature 543 (7645), 367–372.

Bagga, D.K., Peterson, S., 2001. Phytoremediation of arsenic-contaminated soil as affected by the chelating agent CDTA and different levels of soil pH. Remediation 12 (1), 77–85.

Bañuelos, G.S., Arroyo, I., Pickering, I.J., Yang, S.I., Freeman, J.L., 2015. Selenium biofortification of broccoli and carrots grown in soil amended with Se-enriched hyperaccumulator Stanleya pinnata. Food Chem. 166, 603–608.

Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1 (9), 495–504.

Bauddh, K., Singh, R.P., 2012. Cadmium tolerance and its phytoremediation by two oil yielding plants Ricinus communis (L.) and Brassica juncea (L.) from the contaminated soil. Int. J. Phytoremediat. 14 (8), 772–785.

Bloomberg, N.E.F., 2019. New Energy Outlook 2019. BloombergNEF. ⟨https://about.bnef.com/new-energy-outlook/⟩.

Boiral, O., 2013. Sustainability reports as simulacra? A counter-account of A and A+ GRI reports. Account. Audit. Account. J. 26 (7), 1036–1071. Accounting Auditing & Accountability Journal, 26(7), 1036–1071.

Bortey-Sam, N., Nakayama, S.M.M., Akoto, O., Ikenaka, Y., Fobil, J.N., Baidoo, E., Mizukawa, H., Ishizuka, M., 2015. Accumulation of heavy metals and metalloid in foodstuffs from agricultural soils around Tarkwa area in Ghana, and associated human health risks. Int. J. Environ. Res. Public Health 12 (8), 8811–8827.

Church, C., Crawford, A., 2018. Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-carbon Economy. IISD. ⟨https://www.iisd.org/sites/default/files/publications/green-conflict-minerals.pdf⟩.

Conner, A.J., Glare, T.R., Nap, J.-P., 2003. The release of genetically modified crops into the environment. Part II. Overview of ecological risk assessment. Plant J.: Cell Mol. Biol. 33 (1), 19–46.

DNV GL's Energy Transition Outlook, 2018. ⟨https://eto.dnvgl.com/2018/⟩.

Dominish, E., Teske, S., Florin, N., 2019. Responsible Minerals Sourcing for Renewable Energy. Institute for Sustainable Futures, University of Technology Sydney,

Earthworks. ⟨https://earthworks.org/cms/assets/uploads/2019/04/MCEC_UTS_Report_lowres-1.pdf⟩.
Eapen, S., D'Souza, S.F., 2005. Prospects of genetic engineering of plants for phytoremediation of toxic metals. Biotechnol. Adv. 23 (2), 97–114.
Elbehiry, F., Elbasiouny, H., Ali, R., Brevik, E.C., 2020. Enhanced immobilization and phytoremediation of heavy metals in landfill contaminated soils. Water Air Soil Pollut. 231 (5), 204.
Etim, E.E., 2012. Phytoremediation and its mechanisms: a review. Int. J. Environ. Bioenergy 2 (3), 120–136.
Ettler, V., Konečný, L., Kovářová, L., Mihaljevič, M., Sebek, O., Křίbek, B., Majer, V., Veselovský, F., Penížek, V., Vaněk, A., Nyambe, I., 2014. Surprisingly contrasting metal distribution and fractionation patterns in copper smelter-affected tropical soils in forested and grassland areas (Mufulira, Zambian Copperbelt). Sci. Total Environ. 473–474, 117–124.
Favas, P.J.C., Pratas, J., Varun, M., D'Souza, R., Paul, M.S., 2014. Phytoremediation of soils contaminated with metals and metalloids at mining areas: potential of native flora. In: Hernandez-Soriano, M.C. (Ed.), Environmental Risk Assessment of Soil Contamination. IntechOpen.
Festin, E.S., Tigabu, M., Chileshe, M.N., Syampungani, S., Odén, P.C., 2019. Progresses in restoration of post-mining landscape in Africa. Res. J. For. 30 (2), 381–396.
Gerhardt, K.E., Gerwing, P.D., Greenberg, B.M., 2017. Opinion: taking phytoremediation from proven technology to accepted practice. Plant Sci.: Int. J. Exp. Plant Biol. 256, 170–185.
Gerhardt, K.E., Huang, X.-D., Glick, B.R., Greenberg, B.M., 2009. Phytoremediation and rhizoremediation of organic soil contaminants: potential and challenges. Plant Sci.: Int. J. Exp. Plant Biol. 176 (1), 20–30.
Giurco, D., Dominish, E., Florin, N., Watari, T., McLellan, B., 2019. Requirements for minerals and metals for 100% renewable scenarios. In: Teske, S. (Ed.), Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for + 1.5 °C and + 2 °C. Springer International Publishing, pp. 437–457.
Glick, B.R., 2010. Using soil bacteria to facilitate phytoremediation. Biotechnol. Adv. 28 (3), 367–374.
Graedel, T.E., Harper, E.M., Nassar, N.T., Reck, B.K., 2015. On the materials basis of modern society. Proc. Natl. Acad. Sci. USA 112 (20), 6295–6300.
Ho, Y.-N., Hsieh, J.-L., Huang, C.-C., 2013. Construction of a plant-microbe phytoremediation system: combination of vetiver grass with a functional endophytic bacterium, Achromobacter xylosoxidans F3B, for aromatic pollutants removal. Bioresour. Technol. 145, 43–47.
Huang, J.W., Cunningham, S.D., 1996. Lead phytoextraction: species variation in lead uptake and translocation. New Phytol. 134 (1), 75–84.
IRENA, 2019. A New World: The Geopolitics of the Energy Transformation. IRENA, Global Commission on the Geopolitics of Energy Transformation. ⟨https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/Global_commission_geopolitics_new_world_2019.pdf⟩.
Kara, S., 2018. Is your phone tainted by the misery of 35,000 children in Congo's mines? The Guardian. ⟨http://www.theguardian.com/global-development/2018/oct/12/phone-misery-children-congo-cobalt-mines-drc⟩.
Křίbek B., Majer V., Knésl I., Nyambe I., Mihaljevič M., Ettler V., Sracek O., 2013. Metals and arsenic in cassava: indicators of contamination in the Zambian Copperbelt mining district.
Lee, J., Bazilian, M., Sovacool, B., Greene, S., 2020. Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains. Environ. Res. Lett. 15 (10), 103009.
Lee, Jordy, Bazilian, Morgan, Sovacool, B., 2020. Reviewing the material and metal security of low-carbon energy transitions. Renew. Sustain. Energy Rev. 124, 109789.
Marrugo-Madrid, S., Turull, M., Montes, G.E., Pico, M.V., Marrugo-Negrete, J.L., Díez, S., 2021. Chapter 7 – phytoremediation of mercury in soils impacted by gold mining: a case-study of Colombia. In: Saxena, G., Kumar, V., Shah, M.P. (Eds.), Bioremediation for Environmental Sustainability. Elsevier, pp. 145–160.
Muthusaravanan, S., Sivarajasekar, N., Vivek, J.S., Paramasivan, T., Naushad, M., Prakashmaran, J., Gayathri, V., Al-Duaij, O.K., 2018. Phytoremediation of heavy metals: mechanisms, methods and enhancements. Environ. Chem. Lett. 16 (4), 1339–1359.
Odoh, C.K., Zabbey, N., Sam, K., Eze, C.N., 2019. Status, progress and challenges of phytoremediation – an African scenario. J. Environ. Manag. 237, 365–378.
Raymond, M., Evangelos, T., Hudai, K., Peter, W., Jaakko, K., 2011. Critical Metals in Strategic Energy Technologies – Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. Publications Office of the European Union.
Natural Resource Governance Institute, 2019. Resource Governance Index: Sub-Saharan Africa Highlights. (2019). Natural Resource Governance Institute. ⟨https://resourcegovernance.org/sites/default/files/documents/resource-governance-index-sub-saharan-africa-highlights.pdf⟩.
Salt, D.E., Smith, R.D., Raskin, I., 2003. Phytoremediation. ⟨https://doi.org/10.1146/annurev.arplant.49.1.643⟩.
Sarwar, N., Imran, M., Shaheen, M.R., Ishaque, W., Kamran, M.A., Matloob, A., Rehim, A., Hussain, S., 2017. Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere 171, 710–721.
Shahbaz, A.K., Adnan Ramzani, P.M., Saeed, R., Turan, V., Iqbal, M., Lewińska, K., Abbas, F., Saqib, M., Tauqeer, H.M., Iqbal, M., Fatima, M., Rahman, M.-U., 2019. Effects of biochar and zeolite soil amendments with foliar proline spray on nickel immobilization, nutritional quality and nickel concentrations in wheat. Ecotoxicol. Environ. Saf. 173, 182–191.
Shahid, M., Austruy, A., Echevarria, G., Arshad, M., Sanaullah, M., Aslam, M., Nadeem, M., Nasim, W., Dumat, C., 2014. EDTA-enhanced phytoremediation of heavy metals: a review. Soil Sediment Contam.: Int. J. 23 (4), 389–416.
Sikaundi, G., 2008. Copper Mining Industry in Zambia Environmental Challenges. Environmental Council of Zambia.
Sinkala, T., 2009. Mining and Environment in Africa: A Comprehensive Review Report. United Nations Environmental Programme. ⟨https://www.scribd.com/document/23618617/Mining-and-Environment-in-Africa⟩.
Sinkala, T., 2018. Integrated phytomining and ethanol production in the Zambian Copperbelt to minimize mine decontamination costs and environmental and social impacts: a review. J. South Afr. Inst. Min. Metall. 118 (8) https://doi.org/10.17159/2411-9717/2018/v118n8a4.
Sinkala, T., 2021. Potential of Integrated Phytomining and Bioenergy Production in the Zambian Copperbelt. Global Bioenergy Partnership (GBEP) Week. ⟨http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2021_events/Online_Bioenergy_Week/PPTs_18_March/Bioeconomy/18_March_bioeco_Sinkala_Thomro_Biofuels.pdf⟩.
Song, L.S., Wang, S.Q., Xiao, R.P., Spurgeon, H., Lakatta, E.G., Cheng, H., 2001. beta-Adrenergic stimulation synchronizes intracellular Ca(2+) release during excitation-contraction coupling in cardiac myocytes. Circ. Res. 88 (8), 794–801.
Sovacool, B., Hook, A., Martiskainen, M., Brock, A., Turnheim, B., 2020. The decarbonisation divide: contextualizing landscapes of low-carbon exploitation and toxicity in Africa. Glob. Environ. Change 60, 102028.
Tauqeer, H.M., Fatima, M., Rashid, A., Shahbaz, A.K., Ramzani, P.M.A., Farhad, M., Basharat, Z., Turan, V., Iqbal, M., 2021a. The current scenario and prospects of immobilization remediation technique for the management of heavy metals contaminated soils. In: Hasanuzzaman, M. (Ed.), Approaches to the Remediation of Inorganic Pollutants. Springer, Singapore, pp. 155–185.
Tauqeer, H.M., Karczewska, A., Lewińska, K., Fatima, M., Khan, S.A., Farhad, M., Turan, V., Ramzani, P.M.A., Iqbal, M., 2021b. Chapter 36 – environmental concerns associated with explosives (HMX, TNT, and RDX), heavy metals and metalloids from shooting range soils: prevailing issues, leading management practices, and future perspectives. In: Hasanuzzaman, M., Prasad, M.N.V. (Eds.), Handbook of Bioremediation. Academic Press, pp. 569–590.
Tchounwou, P.B., Yedjou, C.G., Patlolla, A.K., Sutton, D.J., 2012. Heavy metal toxicity and the environment. Exp. Suppl. 101, 133–164.
Tembo, B., Sichilongo, K., Cernak, J., 2006. Distribution of copper, lead, cadmium and zinc concentrations in soils around Kabwe town in Zambia. Chemosphere 63 (3), 497–501.
The United Nations, 2001. Report of the Panel of Experts on the Illegal Exploitation of Natural Resources and Other Forms of Wealth of the Democratic Republic of the Congo. The United Nations. ⟨https://www.globalsecurity.org/military/library/report/2001/357e.pdf⟩.
The World Bank, 2016. Zambia – Mining and Environmental Remediation and Improvement Project (No. PAD1513). The World Bank, pp. 1–100. ⟨http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP//⟩.
Togoh, I., 2019. Apple and Tesla Among Tech Giants Being Sued over the Deaths and Injuries of Child Cobalt Miners in DRC. Forbes Magazine. ⟨https://www.forbes.com/sites/isabeltogoh/2019/12/17/apple-and-tesla-among-tech-giants-being-sued-over-the-deaths-and-injuries-of-child-cobalt-miners-in-drc/⟩.
Turan, V., 2019. Confident performance of chitosan and pistachio shell biochar on reducing Ni bioavailability in soil and plant plus improved the soil enzymatic activities, antioxidant defense system and nutritional quality of lettuce. Ecotoxicol. Environ. Saf. 183, 109594.
Turan, V., 2021. Calcite in combination with olive pulp biochar reduces Ni mobility in soil and its distribution in chili plant. Int. J. Phytoremediat. 1–11.
Uchida, Y., Banda, K., Nyambe, I., Hamamoto, T., Yoshii, Y., Munthali, K., Mwansa, M., Mukuka, M., Mutale, M., Yabe, J., Toyomaki, H., Beyene, Y.Y., Nakayama, S.M.M., Naruse, N., Ishizuka, M., Takahashi, Y., 2017. Multidisciplinary field research in Kabwe, Zambia, towards better understanding of lead contamination of the city – a short report from a field survey. bioRxiv 096164. https://doi.org/10.1101/096164.
van der Ent, A., Baker, A.J.M., Reeves, R.D., Chaney, R.L., Anderson, C.W.N., Meech, J. A., Erskine, P.D., Simonnot, M.-O., Vaughan, J., Morel, J.L., Echevarria, G., Fogliani, B., Rongliang, Q., Mulligan, D.R., 2015. Agromining: farming for metals in the future? Environ. Sci. Technol. 49 (8), 4773–4780.
Walt, V., Meyer, S., 2018. Blood, Sweat, and Batteries. Fortune. ⟨http://fortune.com/longform/blood-sweat-and-batteries/⟩.
Wiszniewska, A., Hanus-Fajerska, E., Muszyńska, E., Ciarkowska, K., 2016. Natural organic amendments for improved phytoremediation of polluted soils: a review of recent progress. Pedosphere 26 (1), 1–12.
Woodroffe, N., Grice, T., 2019. Beyond Revenues: Measuring and Valuing Environmental and Social Impacts in Extractive Sector Governance. Natural Resource Governance Institute. ⟨https://resourcegovernance.org/sites/default/files/documents/beyond-revenues_measuring-and-valuing_environmental-social-impacts.pdf⟩.
World Bank, 2017. The Growing Role of Minerals and Metals for a Low Carbon Future (No. 117581). The World Bank (pp. 1–0). ⟨http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP//⟩.
Yan, A., Wang, Y., Tan, S.N., Mohd Yusof, M.L., Ghosh, S., Chen, Z., 2020. Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. Front. Plant Sci. 11, 359.