Black Mountains and White Deserts – Why are copper mining waste materials not utilised for other products and economic diversification in Zambia?

GERGELY BUDA*

Abstract

Copper mining negatively affects the natural and human environment, pushes mineral-rich economies towards dependence on the extractive sector and generates vast amounts of waste materials. In Zambia, the focus country for this study, copper mining slag is piled up in enormous black mountains. At the same time, mine tailings are released into whitish lagoons, removing thousands of hectares from other activities. Meanwhile, the local road infrastructure is still poor, and there are many reports about a housing crisis and development based on the potential of the copper treasures, which is invisible. Therefore, inspired by industrial symbiosis, a circular economy model, this report explored why copper mining waste materials are not utilised for producing other goods. Industrial symbiosis is when companies use other firms' waste or by-product materials. Based on metallurgy and mineral sciences literature, several "destination" products could be made from these waste materials, such as concrete, cement, and ceramics. Semi-structured and unstructured interviews were employed to collect data from mining companies, potential destination firms, experts, and researchers who studied mining and waste materials. Results are presented in different categories (knowledge-related, technological,

* *Gergely Buda* is a PhD Student at Corvinus University of Budapest, Hungary, and a Junior Research Fellow at the Centre for Economic and Regional Studies, Institute of World Economics, Budapest, Hungary. ORCID: 0000-0002-4185-4892 E-mail: gergely.buda2@stud.uni-corvinus.hu

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economic and legal issues) influencing the utilisation of waste materials for other purposes. The main argument and recommendation for policymakers is setting up a mineral content baseline in the materials below, which other industries can use. This intervention would contribute to economic diversification, research and innovation and free mining companies from significant financial and management burdens.

Journal of Economic Literature (JEL) codes: N57, O13, O14, Q53
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Introduction

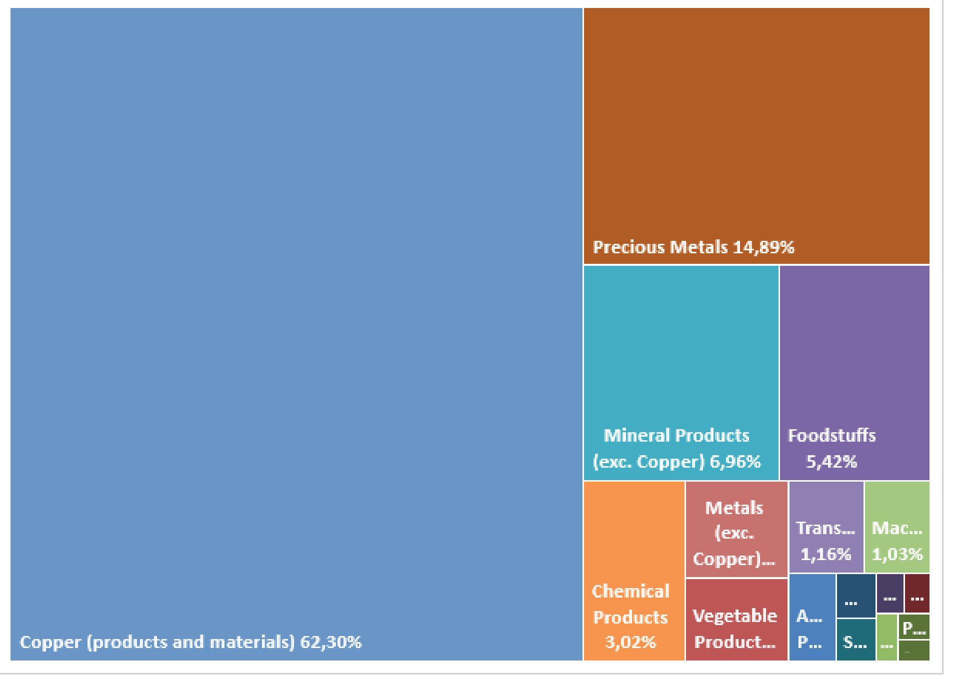
Research on utilising mining waste materials in Zambia is increasingly crucial in light of the substantial environmental and economic challenges the mining industry poses. Copper mining is a key economic activity in Zambia and has positioned the country as the 9th largest copper producer globally as of 2023 (USGS, 2024). With its copper resources concentrated in the Copperbelt Province, the mining sector's contribution to Zambia's export revenues, employment, and foreign exchange earnings is significant, accounting for approximately 70 per cent of exports and 12.9 per cent of GDP in 2022 (AFDB, 2025). (The commodity structure of Zambia's exports is displayed in *Figure 1*.) However, this economic dependency also exposes Zambia to the risks of fluctuating global copper prices and environmental degradation.

The environmental consequences of copper mining are especially troubling. In the Copperbelt Province alone, the mining waste accumulated over the past 90 years includes approximately 791 million tons of tailings and 40 million tons of slag (Dusengemungu et al., 2022). These waste materials, such as copper slag and tailings, pose significant environmental risks, contaminating soil and water and negatively affecting agriculture and human health (Gorai et al., 2003; Roy et al., 2015). Copper production is anticipated to continue rising globally, with 37.7 million tons of copper slag produced annually (Phiri et al., 2021). Waste generation is likely to increase only in the coming decades due to the depletion of non-renewable mineral resources (Lebre et al., 2017; Khorami et al., 2019).

Figure 1

The commodity structure of Zambia's exports in 2023

(Per cent)



Source: The author's construction, based on data from the Observatory of Economic Complexity downloaded on 6th March 2025.

As Zambia's economy becomes more dependent on copper mining, local communities in the Copperbelt Province are forced to adapt to the ongoing environmental pollution surrounding mining operations (Peša, 2022). The circular economy offers a potential solution by recycling mining waste, such as tailings, water, and recovered metals, to reduce environmental impact and improve resource efficiency (Lebre et al., 2017). Transitioning from the current linear economic model, where waste is discarded, to a circular model could mitigate environmental risks and enhance economic resilience by creating value from waste streams. This approach has been successfully implemented in various industrial sectors and could be applied to mining at organisational, mine-area, and systemic levels (Zhao et al., 2012; Balanay & Halog, 2016).

Given the increasing pressure on Zambia's mining sector to balance economic growth with environmental sustainability, researching innovative ways to use mining waste is essential. By embracing circular economy principles, Zambia could reduce its environmental footprint, improve public health, and unlock new economic opportunities by recycling and repurposing mining by-products.

This paper aims to identify how the remaining slag and tailings (after reprocessing) could be utilised, as they represent significant untapped economic potential. The research question it aims to answer is: Why are copper slag and tailings materials not used as input materials for other/new products?

Regarding the research methodology, the paper is based on semi-structured and unstructured interviews conducted in Zambia's Copperbelt Province. The findings are presented in four categories: knowledge-related, technical, economic, and legal. As a policy proposal, arguments are presented for setting up a baseline value of mineral content below which other industries (sidestreams) can use copper mining waste materials as input for producing new goods.

The paper is structured as follows. Following the introduction, the first chapter describes the paper's scope and theoretical framework. The second chapter contains the methodology and the data. In the third chapter, the results are structured along the four categories mentioned above. The subject of the fourth chapter is the discussion of policy implications. The fifth chapter includes the summary and conclusion. The final part embraces the references.

Scope and theoretical framework

The circular economy concept, rooted in Stahel & Reday (1977), gained particular attention among academicians and policymakers during the last two decades as one of the theoretical concepts for sustainable development (Geissdoerfer et al., 2017). The circular economy concept takes nature as an example, where there is no waste, and each output is an input for another process. Thus, the circular approach contrasts with the take-make-use-dispose logic of the conventional "linear economy" (Bakker et al., 2014) and argues for a nature-like circularity in the economic system. This means that the value of products, materials, and resources is maintained in the economy for as long as possible, resulting in a minimised amount of waste and a sustainable management of resources.

In the circular economy mindset, wealth is unrelated to resource use, and waste is converted into economic benefit (Ellen MacArthur Foundation, 2013). By improving design for reuse and recycling, switching to services and renewable products in place of non-renewable ones, and using existing materials, value is created (Ellen MacArthur Foundation, 2015). The circular economy reduces pollution and makes it possible to repair earlier harm with better-built systems (Murray et al., 2017). Closing material loops is a common definition of the circular economy (Bocken et al., 2016), which obviously reduces the use of raw materials. Bocken et al. (2016) strongly emphasise resource efficiency, recycling, and circular resource flows to reduce the resources needed for a given production.

According to Lebre et al. (2017) and Khorami et al. (2019), the mining sector is a significant waste producer and is to blame for the quick depletion of non-renewable mineral resources. Inextricably connected to population expansion, economic development, and technological improvement are the driving forces of depleting mineral resources. As a result, in the coming decades, primary resource extraction and concurrent waste generation are likely to grow significantly (UNEP, 2013, 2016; ISWA, 2015; Kuipers et al., 2018). With an average annual production of 17 million tons and a corresponding rise in the annual production of copper slag waste of 37.7 million tons, copper is one of the metals that has seen high production growth rates globally (Phiri et al., 2021). According to advancements in the knowledge of the environmental consequences caused by anthropogenic activity, extensive mineral resource exploitation hurts the environment (Gorai et al., 2003; Roy et al., 2015; Potysz et al., 2015; Kuipers et al., 2018).

Metalliferous mine tailings and heaped overburden pose significant risks to the environment, human health, and agriculture, in addition to changing the natural landscape. Tailings dams are frequently constructed close to populated areas where contaminated groundwater could endanger farming communities, such as in the Zambian Copperbelt Province (von der Heyden & New, 2004). Moreover, urban and national economies become highly dependent on and exposed to the fluctuation of copper prices, as local communities also had to learn to live with the pollution surrounding them (Peša, 2022).

The circular economy concept might be applied to the mining sector by recycling waste streams such as tailings and water, using recovered metals in products for an extended period of time, and lowering waste production through sophisticated sorting. Identifying the potential for the transition to a circular economy in various industrial sectors is important. Despite the tremendous economic potential of recycling waste into useable resources, very few efforts have been put into running the circular economy concept in mining rather than the existing linear economy approach (Lebre et al., 2017).

The circular economy idea can be implemented in mining in various ways, starting at the organisational level, where materials can be recycled or applied, moving to the mine area level, and finally reaching the value chain and systemic levels, where other businesses and industries can use the sidestreams (Zhao et al., 2012; Balanay & Halog, 2016).

Mine wastes usually include waste rock, overburden, slag, and tailings on land surfaces (Festin et al., 2018). Waste rock contains mineral concentrations in quantities that are too small to be of interest for extracting minerals or metals. Overburden includes soil and rock removed to gain access to ore deposits. Copper slag is a by-product of copper extraction by smelting. During smelting, impurities become slag, which floats on the molten metal. Tailings consist of sand-resembling materials. After extracting and processing the minerals, the residuals and mill rejects are combined into a slurry and disposed into lagoons.

Lottermoser (2010, 2011) defines re-mining, reuse, recycling, reprocessing and treatment in mining. *Re-mining* refers to recovering minerals from previously mined areas/materials (including storing them for future use). *Reuse* denotes using the materials without consideration of the mineral value and without reprocessing, typically for backfilling. *Recycling* converts waste into new valuable products with physical, thermal, biological or chemical treatment. *Reprocessing* refers to using waste materials as feedstock to produce valuable products when the treatment reduces the mine waste's toxicity or volume.

Regarding copper mining waste materials or by-products, this paper specifically focused on copper smelter slag and mine tailings. As the utilisation of other mining by-products is already in economic practice to a certain extent (such as waste rock for construction and copper slag for reprocessing to extract remaining valuable minerals), this report aimed to identify the remaining materials of slag and tailings (after reprocessing), as they may represent significant unused economic potential.

Gorai et al. (2003) and Phiri et al. (2021) identified nine potential products for which copper mining waste materials could be used as production inputs. The study named them "destination products," blended cement, cement clinker, road pavement, abrasives, concrete, tiles, glass, cutting tools, and roofing granules.

The theoretical framework of this article is based on the concept of *industrial symbiosis (IS)*. This business model can be described as a synergy between companies where one firm uses the waste or by-products of another production company

(Chertow, 2000). Businesses in IS can realise additional revenues by selling waste and reducing production costs by saving landfilling costs and accessing cheaper inputs. Lybæk et al. (2020:1) define IS as "the connection of traditionally separate industries in a collective effort to simultaneously increase competitive advantage and reduce environmental impacts using by-product exchange and shared infrastructure". Henriques et al. (2021) identify four levels of IS based on the exchange aspect:

1. *Internal exchange* refers to the development of synergies within one organisation. The main advantage of implementing internal circularity is to achieve lower input material costs and resource efficiency.
2. *External exchange* refers to two or more companies sending or receiving waste to/from other companies, which will use it in their production processes. In this model, the value is captured in two perspectives: the sender (or supplier) through the sale of the waste employed by other companies (or at least to avoid the cost associated with waste disposal) and the receiver through lower production costs.
3. *In eco-Industrial Park*, local companies cooperate to reduce waste and pollution through symbiotic exchanges. Value is captured through material exchanges (by-products, wastes, resources, or real-value products), operational cost reduction, and non-direct revenues such as stakeholder contributions and tax benefits.
4. *Urban Industrial Symbiosis* is a network of community and industrial actors bridging local needs to improve resource deployment by exploring synergies in urban and industrial areas. This approach involves transferring municipal solid waste to industrial companies and, meanwhile, using industries as providers of living resources. In this approach, the government usually facilitates waste exchanges and interactions between companies and communities. A high level of centralisation characterises this approach.

Neves et al. (2019) collected the drivers and barriers of this synergetic phenomenon. Based on their work, questions and later findings are structured into four categories: knowledge, technological, economic and legal.

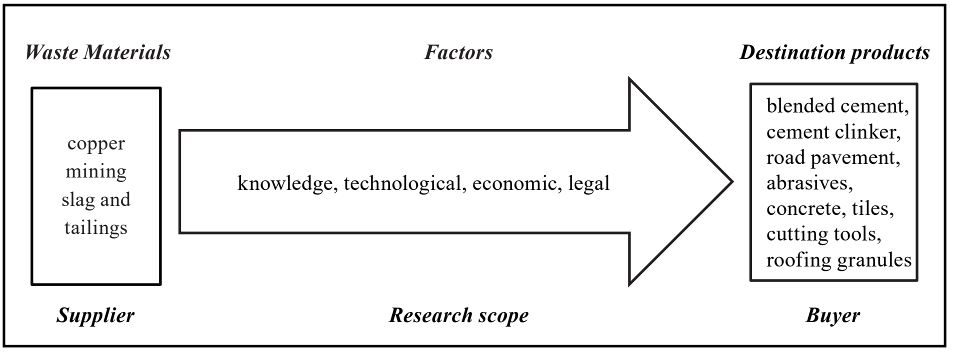
In the *knowledge-related category,* all the factors were gathered connected to the lack of information and the circular economy mindset, the general knowledge of deploying the waste materials for other purposes, and issues related to organisational knowledge or competence. The *technological category* refers to challenges in physical, mechanical, and chemical processes and equipment to turn the given mining waste materials into a suitable form for producing other products. Based on Boons et al.

(2011) and Bertani et al. (2019), the *economic category* originates from the previous one. It includes the general cost factors of IS, such as pre-processing, treatment, handling, storing, transportation and material price. Finally, the *legal category* refers to prevailing regulations and governmental will related to the management and use of copper mining waste materials.

Thus, to answer the research question, the paper aimed to explore the role of these four factors between the place of material generation (supplier) and the producer of nine destination products (buyer). This framework is presented in *Figure 2*.

Figure 2

The conceptualisation of the paper



Source: Own design based on the literature reviewed.

Methodology and data

Regarding methodology, Data collection was conducted in the Copperbelt Province of Zambia (Kitwe, Mufulira and other smaller municipalities and facilities) between 12th and 26th April 2023 in nineteen interviews. This data collection method was chosen against other methods, such as anonymous online surveying because informants may require guidance and explanation for specific questions and site visits and could receive additional information and further observations. Seven interviews were conducted with local experts, lecturers and researchers in an unstructured discussion. A questionnaire was developed for semi-structured interviews for mining or re-mining companies and destination companies. Ten respondents representing the mining industry, working presently or formerly for mining companies, were met and requested to be involved.

Additionally, two producer firms, which were potential destination companies, were interviewed. The sample is appropriate for exploring the views, but it is not statistically representative but indicative. However, in the applied understanding, it does not influence the main results and arguments. All respondents were informed in verbal and written format about the objective of the research, the freedom to answer any of the questions or to stop the interview at any time without explanation, and they were also asked for written consent. The interview discussions were voice recorded, transcribed and then deleted. The anonymised list of respondents is presented in *Appendix 1*. In addition to these interviews, three relevant regulatory documents were analysed to map legal aspects.

Results

As mentioned above, the research focused on exploring the factors hindering or facilitating the utilisation of copper mining waste materials along four categories or factors. The results are summarised in *Table 1*.

Knowledge-related factors

One of the main knowledge-related or informational barriers is well represented by the first answer of Respondent 5, in line with many other respondents, to why mining waste is piled up and not used for other purposes: "No one even thought to use the waste". These materials are considered only as resources for re-mining (Resp. 2). Destination companies never considered using copper mining waste (Resp. 14), even if its transportation would be much cheaper than that of the conventional input materials (Resp. 7). As Respondent 19 precisely expressed: "Nobody has come to ask for it." These results confirm how strongly the general mindset related to mining materials is locked within the linear economy and blocks the out-of-the-box way of thinking and innovation: "As a mine, your main interest is the minerals" (Resp. 16). "It is not our core business" (Resp. 15). Furthermore, the exact amount of the waste materials and the exact mineral content are not precise either (Resp. 4, Resp. 13). The understanding of the composition (Resp. 6) and the destination product what one may use these materials for (Resp. 1.) are also key information in this puzzle. We also detected the lack or shortage of related competence and the need for capacity-building within the organisations (Resp. 10, Resp. 13) and clarification of useability, qualities, properties, and cost-benefit analysis of the materials via further research (Resp. 13, 14, 16, 19). Finally, the main unanswered question is associated with technological development: when, with what intensity and at what costs (both economically and environmentally) can the full mineral content be extracted? Respondents 11 and 12 pointed out the lack of clarity on the time dimension, namely how long the tailings materials will remain within the re-mining process until all minerals can be extracted.

Nevertheless, our research discovered that many respondents know for what purposes these waste materials could be used. By the potential destination products described above, the respondents mentioned tiles or roof tiles (Resp. 1, 3, 6), concrete or bricks (Resp. 3, 7, 11, 16, 17), glass or ceramics (Resp. 4, 11, 12, 15), roads or pavements (Resp. 3, 7, 17) and aggregates (Resp. 15). On the destination side, we also detected that companies consider the potential of these materials as inputs for new products, not as waste, useless matter (Resp. 8).

Technological factors

Most respondents, including destination companies, mentioned technology as the most significant barrier to utilising waste materials. One of the primary technological barriers is the toxicity or unclear status of neutralising these materials, making them not applicable to the human environment. Respondents 1 and 4 mentioned the removal of heavy metals, chromium and cadmium, as one of the biggest technological challenges. Moreover, sulphite and oxide contents typically worsen important properties of concrete and pavements, such as binding (Resp. 4, 5, 6, 18). The technological requirements and equipment for different treatment methods, such as chemical, mechanical or other treatments, are unavailable. As Respondent 1 pointed out, “the processes of how these materials can be utilised is the key problem”; therefore, technology determines the cost of production (Resp. 1), and one must consider the economics for whatever purpose to use these materials (Resp. 7).

Economic factors

Two significant economic aspects were discovered, blocking the deployment of mining waste materials for other purposes. First and most importantly, even if, as mentioned above, the exact quantity of mineral content is not precise, one knows that there is still a certain quantity of valuable minerals within the black mountains and the white deserts (Resp. 7, 10, 11, 12, 13, 16, 17). Older tailings and black mountains contain more valuables since the older technologies were less efficient in mineral extraction (Resp. 4, 5, 7, 13, 16). Respondent 16 stated, "There is a general understanding that they can be of economic value in the near future." Based on the respondents' estimations, the average copper mining slag and tailings contain 0.1-0.3 per cent copper, 0.01-0.02 per cent cobalt, and several additional metals such as lead, zinc, nickel, silver, iron, and a dominant volume of silica. This intensifies the motivation of mining companies to keep and store these materials as long as technological development enables complete extraction and, therefore, blocks access by other actors and sidestream development.

Regarding the destination companies, the cost of necessary treatment against toxicity and for the stability of the materials is much higher than applying conventional input materials, even if imported. Regarding the different cost factors in the analysis, Respondent 3 replied that the material price for other production purposes would be very low regarding tailings and very high regarding using smelter slag. The costs of tailing, treatment and pre-processing would be the highest, followed by storing and handling, and the cost of material could be negligible. For using the smelter slag, the highest cost would still be related to treatment and material, followed by pre-processing, storing and handling (Resp. 3). Similarly, Respondents 11 and 12, working at a tailings re-mining facility, named the highest cost for pre-processing and chemical treatment, followed by transportation, storing, sorting and handling. Respondent 6 also mentioned the cost of equipment, testing facility and the high energy cost necessary for crushing slag material.

Meanwhile, the black mountains and white deserts involve significant management tasks, including environmental and employer safety risks to mining companies. It can be most precisely described by the statement of Respondent 17: "In a smelter, the biggest risk is how to manage your waste." Respondent 3 mentioned the recent construction of two tailings dams costing USD 54 million for one of the leading mining companies. Management costs include security, inspection and monitoring, dust mitigation, keeping the integrity and stability, and reporting. One respondent mentioned the USD 60.000 monthly cost of the tailings dam maintenance, in addition to the USD 150.000 annual cost of molasses to ensure dust mitigation (Resp. 16). At the same time, “We know that the volume of waste will increase” – as Respondent 19 pointed out. To show some examples, the amount of tailings material in one of the dams grows by 181 million tonnes every year (Resp. 15). In comparison, one of the smelters produces approximately 180.000 tonnes of slag, added to one of the black mountains (Resp. 17). Another tailings dam occupies 900 hectares of land that could be used for agricultural purposes (Resp. 10). Finally, as one of the environmental specialists interviewed highlighted. Still, many dams are untouched and contaminated, causing substantial harm to the environment by leaching into natural water bodies, flying dust during the dry season and mud in the rainy season (Resp. 13). The growing quantity increases costs for the mining companies. As Respondent 10 mentioned, “We do realise that there is a little value in them, but until technology goes somewhere, we have to look after it.”

Legal factors

As already mentioned in the context of the economic aspects, the waste materials are the mining companies’ property; thus, they can block access to them for other economic actors (Resp. 14, 15), such as potential researchers or destination companies. Many respondents also drew attention to the lack of political will and government efforts to enact legislation to recycle these waste materials (Resp. 1, 7, 13). The analysis of the three relevant regulatory documents (Environmental Management Act, 2011; Environmental Management Act – Licensing Regulations, 2013; Mines & Mineral Act, 2015) also shows that it is not enshrined in legal rules until what time or mineral content these materials should remain within the mining industry or for what other purposes they could and should be used for. On the other hand, other regulations oblige mining companies to dispose of waste in environmentally friendly ways, while new ones focus on storing it for future mineral extraction.

Table 1

Identified barriers for copper slag and tailings utilisation in four categories

Factors	Identified barriers
Knowledge	Mindset locked within the linear economy – blocks out-of-the-box thinking and innovation Present value of the mineral content Waste materials as resources for other purposes – not clear The exact amount of waste materials Technological development – time and quality/intensity
Technological	Toxicity (neutralised?) Technological requirements (chemical, mechanical, etc.) and equipment Sulphite and oxide content Binding properties
Economic	Mineral content – copper, cobalt, rare earth metals Storage and waiting for technology development for future mining/mineral extraction Blocking sidestream development Cost of treatment compared to conventional inputs for destination products
Legal	Earlier: These materials are useless; the obligation is for environmentally friendly disposal Recently: These materials will have a future value for re-mining, storage for future Waste materials are the property of mining companies Blocking access to materials by other actors (researchers, destination companies)

Source: Own work based on the interviews.

Discussion and policy implications

The Zambian copper mining industry concentrated in the Copperbelt Province is locked in a linear economy mindset, which might block the ways and means for innovation and long-term development. Regarding the impediments in the *knowledge-related category,* the results show that the primary barrier is a mindset deeply entrenched in the linear economy, which restricts out-of-the-box thinking and stifles innovation. This limited perspective prioritises the immediate value of the mineral content, obscuring the potential for employing these waste materials in other productive sectors. The current focus on the economic benefits of mineral extraction leads to an undervaluation of these materials as resources for alternative purposes, such as construction or infrastructure development. Furthermore, the lack of detailed data on the quantity of available waste materials and technological progress's time and quality limitations makes it difficult to move beyond this traditional mindset.

The *technological barriers* are also significant. The primary concern here is the toxicity of copper slag and tailings, which require neutralisation before safe utilisation. The technological requirements for processing these materials—chemical, mechanical, or both—are significant. The need for specialised equipment, the challenges posed by the sulphite and oxide content, and the binding properties of these materials further complicate their involvement in creating alternative products such as concrete, tiles, or road pavements. These technological constraints incentivises innovation and the transition to the circular economy.

From an economic perspective, the mineral content of copper slag and tailings—copper, cobalt, and rare earth metals—remains the primary driver for their economic value. However, the results indicate significant costs associated with storing these materials while awaiting technological advancements for future mining or mineral extraction. The development of sidestreams—secondary products derived from these waste materials—is often hindered by economic barriers such as the cost of treatment and unfavourable comparisons to conventional inputs for destination products, contributing to the slow progress. The potential for economic diversification through the utilisation of these materials is thus blocked by continued focus on mineral extraction and expectations that future technological breakthroughs will unlock their full value.

The legal barriers reflect a shift in perspective over time. Historically, copper slag and tailings were considered useless and required environmentally friendly disposal. More recently, however, these materials are seen as having future value for re-mining, leading to their storage for potential future use. Mining companies' legal ownership of these waste materials restricts access by other actors, such as researchers or companies interested in repurposing these materials for alternative products. This legal constraint further limits opportunities for innovation and diversification in the economy.

The main argument of this paper touches on the time-technology-development nexus. In all the four categories of knowledge, economic, technological and legal factors, the general barrier can be expressed that all actors are only waiting for the unpredictable future technological development as a result of which all mineral content can be extracted from these materials. This work provocatively aims to shed light on the resemblance of these expectations to science fiction. Total material extraction and the "perfect" circular economy exist in the Foundation series of Isaac Asimov (1951), where tools and objects can fall into molecules instantly and be turned back into the circulation of production raw materials. However, these magical technologies will only be available in the distant future.

Indeed, in the linear economy, these materials represent a very important potential income source for mineral extraction in Zambia. However, the road infrastructure is still inferior, and several respondents mentioned a recent housing crisis, namely the limited availability and, therefore, the high price of building blocks. Emerson (1982) concludes that mining projects tend to perform as enclaves, having only weak direct links with the host economies. What this paper aims to express here is that the distance between the tax incomes gained from the mining industry and their transfer to actual development for the benefit of society (infrastructural, educational, health and other social services) is simply too long and unpredictable, as it is filled with several transaction costs (Konte & Vincent, 2021; Adebayo et al., 2021). Moreover, future costs and environmental impacts still embody serious risks.

Table 2

Copper mining waste materials in linear and circular perspectives

Copper slag and tailings	Linear economy	Circular economy
Resources for	Future mineral extraction	Input for new products
Potential	Gain and secure future revenue	Economic diversification, Innovation, Societal development, Lower dependency on one sector
Risks	Time, costs, environment	"Trial and error", competitiveness

Source: Own work based on the interviews and the relevant literature sources.

Meanwhile, in the view of the circular economy, the enormous quantity of these materials might represent resources to produce other products, such as concrete, tiles, and road pavements, among others, and, thus, has implications for the potential for economic diversification, innovation, social development and lower dependency on one single industry, in this case, mineral extraction. This last aspect can also be connected to mitigating or breaking out from the resource curse phenomenon typical for mineral economies (Auty, 1993). The circular economy perspective implies potential risks related to "trial and error" and the emerging competitiveness of new products. However, they are all inherent in creating new structures and solutions. *Table 2* summarises these two different perspectives of the linear and circular economies.

Consequently, in the present policy and regulatory framework, copper mining slag and tailings are stuck in the linear economy. They are typical examples of a linear lock-in (Sopjani et al., 2020). Their volume is growing; maintenance is getting more costly, and environmental risks are still apparent and will increase. They are piled up on huge land surfaces, which might have better uses for society and the environment. The existence of the black mountains and the white deserts is based on future speculations, and, at the same time, they hinder the potential for diversification, innovation and long-term development.

Therefore, our main recommendation to policymakers is to set a baseline value for the mineral content of mining waste until technology is available to extract minerals from these materials. Below this value, they should be available for other purposes. The following argumentation briefly summarises the potential benefits this legal regulation might imply.

First, a centrally set mineral content value would help standardise input materials for destination companies. There have already been some experiments with copper slag and tailings, but they have different compositions and mineral content. Thus, a standard value could ease the way for research and product development projects to adjust, save time and economic costs, and facilitate innovation and development. A standard value opens the way for other sectors and production activities along the sidestreams of copper mining, and so it could contribute to economic diversification and job creation. Considering the large quantity of these materials, once the appropriate product compositions and production lines are realised and ready for commercialisation, a huge potential benefit from economies of scale might improve competitiveness and market advantage for the destination companies and the national economy. Finally, standardisation could also enable a label system to indicate the mineral content of each product.

This recommendation has some similarities with the concept of "materials-as-service" from Marco Aurisicchio and his colleagues (WEF, 2022), who argue:

> "In the future, mining companies could lease raw goods to material suppliers using access-based business models, effectively offering minerals as a service. Moving further, nation-states could stop allowing mining companies to explore or mine certain lands. Instead, they could provide them with 'licence to mine' permits that allow companies to mine but not to own the mined raw goods. For

> example, a nation-state could lease iron ore to a mining company, providing it to a steel and iron supplier. Ownership of mined minerals would remain with the country of origin. The 'licence to mine' permits would come with the expectation that mined resources are eventually returned to the nation states in the original or processed form."

However, their concept assumes clarity about the period materials are leased for. Indeed, the time factor is a crucial and inevitable element for making such a contract along the value chain. This clarity is absent in copper mining waste materials and products potentially created from them. Moreover, following-up ownership or leasing rights of materials requires extremely strong and efficient enforcement capacity and rule of law domestically and, for exported materials or products made from these waste materials, internationally, which are absent for the time being and their intact functioning in the future is also nothing but vague.

This leads to the main point related to the time-technology-development nexus. Even if it sounds banal, once the technology is ready for full mineral extraction, companies could break up and replace road pavements, tiles, concrete blocks, and other products to extract minerals from them. But until this unforeseeable moment, policy making should open the way for these materials to serve development, benefiting the economy and society today and in the near future.

Festin et al. (2018) recommend mainstreaming the restoration of mine wastelands in national research strategies and increased development planning to turn the mining sector green. This paper aims to expand their recommendation by calling for focusing on restoration and the development of other industries based on the sidestreams of copper mining waste materials. This will require a switch in policy approach and support for new research projects aiming to determine non-toxic, non-contaminated prototypes of the destination products that could be ready for commercialisation and mass production. As seen in the results above, many respondents mentioned uncertainty around the utilisation and expressed the need for further research. Once the useability is proven, a massive potential for economic diversification and development will be unleashed.

Summary and conclusions

Mineral extraction has been a cornerstone of human civilisation, advancing technological progress and improving quality of life. However, as humankind continues to extract more resources to meet growing global needs, it simultaneously generates increasing volumes of waste materials, often contributing to environmental degradation. This study underscores the significant potential of repurposing copper mining waste materials—specifically copper slag and tailings—in Zambia's Copperbelt Province as part of a broader transition towards a circular economy. A critical finding is the entrenched linear economy mindset in Zambia's copper mining sector, where mineral extraction remains the primary focus, and waste materials are either discarded or stored with little consideration for their alternative uses. This mindset significantly limits innovation and economic diversification, with mining by-products underutilised despite their potential to be applied in other industries, such as construction, where they could be transformed into concrete, tiles, and road pavements (Lebre et al., 2017; Khorami et al., 2019).

Barriers to utilising these materials are varied. From a *knowledge-related perspective,* there is a notable lack of awareness and understanding of the potential deployment of mining waste, compounded by insufficient data on the composition of these materials. This gap makes it challenging to identify and develop alternative products. *Technologically,* challenges such as toxicity, the need for complex chemical and mechanical treatments, and the absence of specialised equipment for processing these materials into usable forms are significant (Festin et al., 2018; Lottermoser, 2010, 2011). *Economically,* the costs associated with processing mining waste for new applications often exceed those of conventional raw materials, raising barriers to their adoption by other industries. Furthermore, the *legal framework* prioritises storing these materials for future mineral extraction rather than enabling their immediate repurposing (Kuipers et al., 2018; Peša, 2022).

Despite these challenges, embracing a circular economy could unlock substantial economic, environmental, and social benefits. By considering mining waste as a resource for other industries, Zambia could reduce its dependency on mineral extraction, stimulate innovation, and foster sustainable development. This shift could also mitigate the negative impacts of the "resource curse" often experienced by mineral-dependent economies, which suffer from economic volatility linked to fluctuations in global commodity prices (Gorai et al., 2003; Roy et al., 2015). By diversifying the economy, Zambia could create new industries, improve infrastructure, and reduce its overreliance on a single sector, thus contributing to a more diversified, sustainable and resilient economy.

From a *policy standpoint,* this paper suggests a shift in the regulatory framework governing mining waste. Policymakers should consider setting a baseline mineral content for copper mining waste, below which these materials can be repurposed for deployment in other industries. Such a regulatory change would facilitate the standardisation of these materials, making them more accessible to destination industries and could open new markets for secondary products (Lottermoser, 2010). Additionally, greater financial and professional support for research, innovation, and collaboration between mining companies and other sectors is essential to explore new application forms for these materials.

The *theoretical implications* of this paper are straightforward. As a case study, it demonstrates the applicability of the circular economy concept to a specific extractive industry with its diverse backward and forward linkages and spillovers enriching the foundations and the practical and policy implications of this theoretical approach. The conceptual framework and the methodology on which this paper is based can be adopted to analysing other countries and industries as well.

The research on which this paper is based was *limited* by time and budgetary constraints. Therefore, only a small sample of respondents could have been included. *Further research* should target a broader sample, mainly focusing on potential destination companies, mostly in the construction sector. This way, new studies could also explore the economic viability of using mining by-products in various industries, providing empirical evidence of their potential for widespread adoption. Moreover, this paper employed the tools of social sciences and missed natural scientific analysis. Consequently, *further research* could focus on developing specific technologies to neutralise the toxicity of mining waste and enable safe processing for alternative uses. Furthermore, research on the legal and regulatory challenges surrounding access to mining waste and the impact of policy changes encouraging circular economy practices would be valuable in shaping a more conducive environment for innovation (Zhao et al., 2012; Balanay & Halog, 2016). Comparative studies of other countries that have successfully transitioned to circular economy models in mining could also have implications for Zambia.

Ultimately, this study calls for a paradigm shift in managing copper mining waste in Zambia. By adopting circular economy principles, Zambia could reduce environmental damage and stimulate economic diversification, innovation, and long-term sustainable development. With appropriate policy frameworks, enhanced collaboration, and technological advancements, the copper mining waste sector could catalyse broader economic growth, turning waste into a valuable resource for the future.

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Appendix 1
List of respondents

RESP	Category
1	Mining and environmental specialist, lecturer at CBU
2	Metallurgy expert and lecturer, CBU
3	Coordinator, ZCCM
4	Chemical engineer
5	Chemical engineer, former worker in copper mining
6	Lecturer and researcher of architecture, CBU
7	Former ZCCM leader
8	Production manager, concrete producer company
10	Manager, Mining company
11	Chief Metallurgist, Re-mining company
12	Environmental officer, Re-mining company
13	Environmental specialist, waste management expert
14	Production manager, concrete and interior design company
15	Concentrator manager, Mining company
16	Concentrator manager assistant, Mining company
17	Smelter manager, Mining company
18	Concentrator manager, Mining company
19	Superintendent - Environment, Mining company