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Economic potential and environmental impact of metal recovery from copper slag flotation tailings

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ABSTRACT

Copper slag has long been the subject of metal recovery. However, it has become apparent that copper slag flotation tailings can meet resource requirements under certain circumstances. Besides copper, zinc and cobalt can also be obtained from slag tailings. This study investigated the potential of copper slag tailings alongside global metal supply and demand dynamics. It has been emphasized that, such as copper slag, slag tailings can be a new potential resource for global base metals, considering global and domestic copper production, consumption, and base metal prices. In addition, its economic and environmental sustainability was evaluated from a waste management perspective.

1. Introduction

People primarily rely on mineral resources and mines for these indispensable civilization materials. The mining and metal industry, one of the oldest industries in the world, focuses on research and development activities to meet this increasing demand (D`Amato et al., 2019). These industries generate vast amounts of waste compared to other industries (Phiri et al., 2021; Zhai et al., 2022). Since the desired metals are found in reserves with very low concentrations, waste generation is an inevitable result of material requirements to sustain daily life and civilization. For example, for every ton of smelted copper, 2.2–3 tons of slag are generated (Gabasiane et al., 2021; Gorai et al., 2003; Tian et al., 2021). The waste must be treated before disposal to neutralize or minimize its hazardousness to protect the environment and human health. However, waste treatment, neutralization, and storage require capital, labor, and time. Therefore, reducing the waste volume is crucial. Another critical aspect of waste is the metal residues it contains. These residues are the result of optimal production. There are still considerable amounts of metals in the waste, i.e., copper slag (CS) and copper slag flotation tailings (CSFT) (Bulut et al., 2007; Kart, 2021). The recovery of metals from these wastes is another critical issue. Therefore, metallurgical waste needs to be evaluated from an economic and environmental perspective in the context of waste management due to the decrease in the reserve grade, high metal prices, and sustainability approach (Xavier et al., 2021).

After iron and aluminum, base metals are the most produced among other metals. Base metals are widely used due to their excellent chemical and physical properties (Geman and Smith, 2013). The CS and CSFT contain considerable amounts of base metals such as Cu, Zn, and Co. This paper focuses on these three metals, their production, and international trade figures.

Copper is the third largest metal produced, and zinc is the fourth largest after iron-steel and aluminum, with 21Mton (ICSG, 2021; Lepan, 2020) and 13.8 Mton, respectively (ILZSG, 2021a; Lepan, 2020). However, cobalt production is 170Kton, which is very low compared to Cu and Zn (Cobalt Institute, 2021a; USGS, 2022a). The end uses of Cu, Zn, and Co are shown in Fig. 1.

Large-scale mining and metallurgical activities are carried out to extract these metals. Since high-grade ores have been primarily mined, low-grade ores have become economically mineable. Approximately 80% of primary copper production comes from low-grade or poor sulfide ores (Robertson et al., 2005). Nearly half of the cobalt is produced as a byproduct of nickel/cobalt ore processing; a significant portion (35%) is produced from Central African copper-cobalt ore. Other primary sources, such as Moroccan cobalt–arsenic ores, account for the remaining 15% (Mills, 2014). As a result of ever-increasing consumption, the production of base metals must not only be from high-grade primary resources but the recovery of these metals from metallurgical wastes must also be explored (Jadhav and Hocheng, 2012).

Metallurgy follows mining and mineral processing. For copper, the main production route is pyrometallurgy. Almost 80% of copper is produced by pyrometallurgical processes (Dimitrijević et al., 2009).

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Pyrometallurgical processes produce a considerable amount of slag and copper (Dimitrijevic et al., 2016). The global amount of slag is 37.7Mton (Phiri et al. (2022) . Nonetheless, the journey of CS does not end here. The path and evaluation of CS for metal recovery or storage as waste depends on two factors. First, the concentration of the metal to be recovered in the slag must be more than or equal to the concentration in the ore from which the slag is obtained (Guo et al., 2018). The second factor is that metal recovery from slag must be low cost (Wu et al., 2010). Since these criteria generally cannot be met, a large amount of the slag produced as a by-product is stored as waste in the plants (Zheng and Kozinski, 1996).

The slag is rather than simply “waste”. It is another complex resource for metals. Therefore, it is processed by flotation after crushing-grinding by smelting plants. In principle, the same conditions apply to the flotation of CS as to the flotation of sulfide ores. In the flotation of copper slags, only metallic copper and sulfide copper compounds can be recovered. Since copper in some slags is in the form of oxide compounds, other metals (Co, Zn, Ni, etc.) are included in the slag as oxide compounds. Therefore, the recovery of metallic values from CS by flotation is limited (Shen and Forssberg, 2003).

After copper recovery by flotation, the remaining part of the slag is considered waste and disposed of in the slag dump area. However, even after copper recovery, copper slag flotation tailings (CSFT) may still contain several metals in varying amounts. However, the complexity and low metal concentration have undermined the potential of CSFT. A limited number of scholars have addressed these issues and conducted experimental studies to resolve them. Their studies, methodologies, and recovery rates on CSFT are shown in Table 1.

Based on the results of the listed studies in Table 1, the recovery of Cu, Co, and Zn may be economically feasible. This paper relies on the findings of these studies as its theoretical backbone. All calculations are based on the results of the listed studies and smelter data.

Given the existing literature and previous studies, this study aims to reveal that CSFT, generated in large quantities during copper production worldwide, can be evaluated as a new potential resource for base metals. Second, it aims to demonstrate how the circular economy and current projects can be integrated while ensuring the supply of imported precious metals. The final objective is to demonstrate the environmental impact of metal recovery from CSFT. Lower waste volume and less metal-bearing residue could be a better waste treatment and management option.

The rest of the paper is organized as follows: Section 2 provides information on the generation and composition of CS and CSFT. Moreover, from a global perspective, the possible amount of recoverable Cu, Zn, and Co are given in upper and lower boundaries. The third section is devoted to the results and discussion. The fourth section represents the conclusion. The fifth section gives implications and recommendations. Finally, the study ends in section 6 with the limitations of the study.

Table 1
Summary of operating conditions for metal recovery from CSFT.

Reference	Process	Reaction Parameters	Results
Carranza et al. (2009)	Ferric leaching for reducing Cu content in the tailing.	Ferric leaching for 8 h.	66% Cu extraction
Uzun Kart (2021)	Sulphation baking with H_2SO_4 and water leaching for 1 h for base metal extraction.	Baking at 350–650 °C with 4–10 ml H_2SO_4.	The recovery of Cu, Co, and Zn at 650 °C are 99%, 95%, and 95%, respectively.
Uzun Kart et al. (2021)	Hematitization baking with H_2SO_4 and water leaching for 1 h to investigate the selectivity of iron.	Baking at 650-690-700-710-730 °C with 10 ml H_2SO_4.	At 700 °C, the hematitization is high, and the sulfates of base metals are retained.

2. Materials and methods

2.1. Generation and composition of CS and CSFT

In the absence of silica (SiO_2) in the ore, copper oxide and sulfide compounds form Cu–Fe–O–S phases by covalent bonding. SiO_2 released into the environment during the pyrometallurgical smelting processes combines with oxides to form silicate anions (1) linked together by strong chemical bonds. This structure then combines and grows to form the slag phase (Guo et al., 2016).

$$2FeO + 3SiO_2 \rightarrow 2Fe^{2+} + Si_3O_8^{4-} \quad (1)$$

During the formation of the glassy silicate phase, small metal inclusions are doped into this phase, making their recovery almost impossible. The base metals (Ni, Co, and Zn) in the CS form silicate and ferrite phases by binding to silicon or iron instead of forming independent mineral compounds in the slag (Arslan and Arslan, 2002).

Several plants recover the copper contained in the copper slag by flotation. This method is generally appropriate for liberated metallic copper and sulfide minerals. It is unsuitable for recovering base metals such as cobalt, zinc, and nickel and forms of oxides or doped slags (Aatach et al., 2020). CSFT with 32–52% Fe content is formed after the copper slag flotation process (Li and Guan, 2009). When iron sulfide is

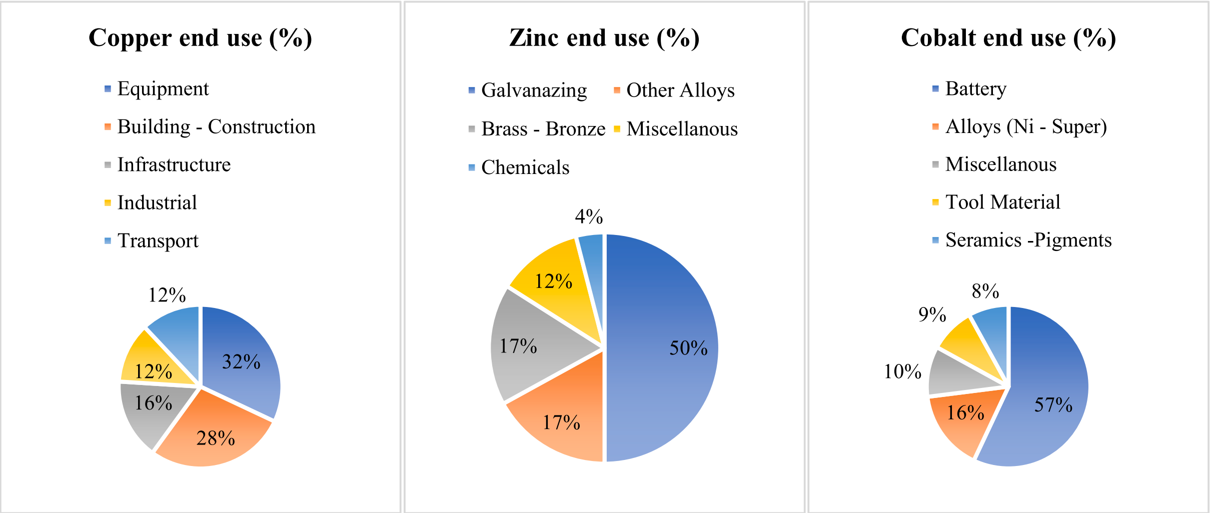

Fig. 1. Cu, Zn, and Co end-uses by proportion (%) (Cobalt Institute, 2021a; ICSG, 2021; ILZSG, 2021b).

oxidized and doped into the crystal structure of base metals under rapid cooling, fayalite ($FeO.SiO_2$) is formed as an amorphous phase due to the chemical reaction with silica (Yang et al., 2010). The copper content of CS from different countries and Cu, Zn, and Co compositions of CSFT from various regions are shown in Tables 2 and 3, respectively.

2.2. Current Cu, Zn, and Co resources and their distribution

The abundance of copper, zinc, and cobalt in the earth's crust is 60 ppm, 70 ppm, and 25 ppm, respectively (Haynes et al., 2016). The USGS (2022b) points out that copper reserves correspond to approximately 880Mton of Cu content. In contrast, zinc reserves are larger than copper reserves, and zinc reserves are reported to be 250Mtons (USGS, 2022c). For cobalt, the global reserves are 7Mtons, as reported by USGS (2022a).

Since the size of reserves affects production and import/export levels, current reserve levels are shown in Table 4. Congo, by far, has the largest Co reserves. Nonetheless, the distribution of Cu and Zn is more diversified. Reserve diversities were determined by the CR4 index and given in Table 4 and Table 5).

2.3. Global Cu, Zn, and Co production

While Chile is the largest copper producer, China is the largest smelter country (ICSG, 2021; USGS, 2022b). Chile mines more than a quarter of the world's copper ore. On the other hand, China imports a considerable amount of ore/concentrates and smelts almost 40% of the world's copper. In the case of zinc, China produces a third of the world's zinc. More than 70% of the cobalt ore/concentration is mined in Congo (Table 4). The impact of this enormous share is reflected in the market, and Congo is the number 1 exporter of cobalt products, both ore and metal (ICSG, 2021; ILZSG, 2021a; OEC, 2020a, 2020b; USGS, 2022a, 2021).

The CR4 index values were also determined for the production shares. The production distribution was found to be less diverse than reserve diversity.

2.4. Theoretical Cu, Zn, and Co potential of the CSFT

For every ton of smelted copper, 2.2–3 tons of CS are produced (Phiri et al., 2021). Since the copper content in the slag is relatively high (2%), the slag is reprocessed to recover the remaining copper. However, still, there is copper in the CSFT due to the yield rate of the selected copper recovery method. The yield of the methods ranges from 88% to 91% (Urosevic et al., 2015). Due to the low concentrations of base metals, the complex structure of the CSFT, and the economic restrictions, the CSFT was not considered a feasible resource. However, due to increasing metal prices, diminishing resources, growing demand, and economic and technical limitations of low-grade ores, CSFT could become economically recoverable under certain conditions.

Based on literature and smelter data, recoverable amounts of base metals were calculated.

Table 2
The copper content of the slag of CS from different regions (Phiri et al., 2021; Panda et al., 2015).

Country	Cu (% weight in slag)	Country	Cu (% weight in slag)
Australia	0.54	Mexico	1.45
Canada	0.67	Poland	0.87
Chile	1.05	Russia	0.56
China	1.48	USA	1.40
Congo	1.48	Zambia	1.43
Kazakhstan	1.53	Others	1.65
India	0.60		
[a]Average value of Cu (% weight in slag) = 1.13			

[a] This value is not weighed on average. Therefore, results may differ from real values.

Table 3
Cu, Zn, and Co compositions in CSFT from different regions and studies.

Study	Location	Element (% weight)		
		Cu	Zn	Co
Uzun Kart et al. (2021)	Turkey	0.35	4.48	0.16
Carranza et al. (2009)	Chile	0.78	N/A	N/A
Stanojlović and Sokolović (2014)	Serbia	0.22	N/A	N/A
Zhou et al. (2021)	China	0.34	1.74	N/A
Muravyov et al. (2012)	Russia	0.56	4.74	N/A
Holland et al. (2019)	Finland	0.28	2.60	0.08
Reutov and Halezov (2015)	Russia	0.50	4.00	N/A
Bulut et al. (2007)	Turkey	0.29	N/A	0.57
Grudinsky et al. (2020)	Russia	0.44	4.40	N/A
Grudinsky et al. (2021)	Russia	0.41	3.11	N/A
Urosevic et al. (2015)	Serbia	0.59	N/A	N/A
Shengo (2021)	Congo	0.75	N/A	0.36
Yucel et al. (1992)	Turkey	1.00	N/A	0.43
(Uyan Yuksel et al., 2017)	Turkey	1.00	N/A	0.30
Ziyadanogullari (2000)	Turkey	2.40	N/A	0.38
Turan et al. (2021)	Kazakhstan	0.70	4.2	N/A
(Panda et al., 2015; Shanmuganathan et al., 2008)	India	0.60	N/A	0.12
[a]**Average**		0.66	3.66	0.33

[a] These values are based on published/undisclosed papers and reports. Disclosed data may affect these values.

Global copper production has reached a production level of 21Mton (ICSG, 2021). Literature states that for each tone of copper, 2.2–3 tons of slag are produced; therefore, the total amount of slag generated during smelting operations varies between:

21 Mton of copper is produced annually by the smelting process

$$\begin{aligned}&\text{Upper limit of slag (tons) } 3.0 \ast 21,000,000 = 63,000,000\\&\text{Lower limit of slag (tons) } 2.2 \ast 21,000,000 = 46,200,000\end{aligned} \qquad \text{Equation 1}$$

On average, the slag contains 1.13% copper. Therefore, the amount of copper in copper slag is:

$$\begin{aligned}&\text{Upper limit of Cu (tons) } 63,000,000 \ast 0.0113 = 711,900\\&\text{Lower limit of Cu (tons)} 46,200,000 \ast 0.0113 = 522,060\end{aligned} \qquad \text{Equation 2}$$

85% of the copper is recovered from the slag by regrinding and froth flotation. Therefore, the amount of the residual copper is:

$$\begin{aligned}&\text{Upper limit of Cu (tons) } 711,900 \ast (1 - 0.85) = 106,785\\&\text{Lower limit of Cu (tons)} 522,060 \ast (1 - 0.85) = 78,309\end{aligned} \qquad \text{Equation 3}$$

The amount of the unrecovered copper approximately varies between 78309 and 106785 tons. Using the recovery method of Uzun Kart (2021), the recovery rate is 0.99 (Table 4). The recoverable amount of copper is:

$$\begin{aligned}&\text{Upper limit of Cu (tons) } 106,785 \ast 0.99 = 105,718\\&\text{Lower limit of Cu (tons) } 78,309 \ast 0.99 = 77,526\end{aligned} \qquad \text{Equation 4}$$

The amount of the recoverable cobalt and zinc was similarly calculated using the concentration values in Table 4 and Equation (4). The cobalt content of the CSFT:

$$\begin{aligned}&\text{Upper Limit of Co(tons)}(105,718/0.0066) \ast 0.0033 = 52,859\\&\text{Lower Limit of Co (tons) } (77,526/0.0066) \ast 0.0033 = 38,367\end{aligned}$$

Equation 5

The recoverable amount of cobalt;

$$\begin{aligned}&\text{Upper limit of Co (tons)}52,859 \ast 0.95 = 52,216\\&\text{Lower limit of Co (tons) } 38,367 \ast 0.95 = 36,449\end{aligned} \qquad \text{Equation 6}$$

The zinc content of the CSFT;

$$\begin{aligned}&\text{Upper limit of Zn (tons)}(105,718/0.0066) \ast 0.0366 = 586,254\\&\text{Lower limit of Zn (tons) } (77,526/0.0066) \ast 0.0366 = 429,917\end{aligned}$$

Equation 7

The recoverable amount of zinc;

Table 4
World Cu, Zn and Co reserves (USGS, 2022b, 2022c, 2022a).

Copper Reserves (Cu Content)			Zinc Reserves (Zn Content)			Cobalt Reserves (Co Content)		
Countries	Amount (Mton)	Shar (%)	Countries	Amount (Mton)	Share (%)	Countries	Amount (Kton)	Share (%)
Chile	200	22.7	Australia	68.0	27.2	Congo	3600	51.4
Australia	93	10.6	China	44.0	17.6	Australia	1200	17.1
Peru	77	8.8	Russia	22.0	8.8	Cuba	500	7.1
Russia	62	7.1	Mexico	22.0	8.8	Philippines	260	3.7
Mexico	53	6.0	Peru	19.0	7.6	Russia	250	3.6
USA	48	5.5	Kazakhstan	12.0	4.8	Canada	230	3.3
Congo	31	3.5	ABD	11.0	4.4	Madagascar	120	1.7
Zambia	31	3.5	India	7.5	3.0	China	80	1.1
China	26	3.0	Bolivia	4.8	1.9	Turkey	78	1.1
Indonesia	24	2.7	Sweden	3.6	1.4	Papua NG	56	0.8
Others	235	26.7	Others	34.3	13.8	Others	613	8.8
Total	880	100	Total	250.0	100	Total	7000	100
$CR4_{Cu}$		49.2	$CR4_{Zn}$		62.4	$CR4_{Co}$		79.3

Table 5
World copper mine, copper smelter, zinc mine, and cobalt mine production.

Copper Mine Production (Cu Content)			Copper Smelter Production (Cu Content)			Zinc Mine Production (Zn Content)			Cobalt Mine Production (Co Content)		
Countries	Amount (MTon)	Share (%)	Countries	Amount (Mton)	Share (%)	Countries	Amount (Mton)	Share (%)	Countries	Amount (Kton)	Share (%)
Chile	5.6	26.7	China	10	38.5	China	4.2	32.3	Congo	120	70.6
Peru	2.2	10.5	Chile	2.2	8.5	Peru	1.6	12.3	Russia	7.6	4.5
China	1.8	8.6	Japan	1.5	5.8	Australia	1.3	10.0	Australia	5.6	3.3
Congo	1.8	8.6	Congo	1.5	5.8	India	0.8	6.2	Philippines	4.5	2.7
Australia	0.9	4.3	USA	1.0	3.9	USA	0.7	5.7	Canada	4.3	2.5
Zambia	0.8	4.0	Russia	0.9	3.5	Mexico	0.7	5.5	Cuba	3.9	2.3
Russia	0.8	3.9	S. Korea	0.7	2.5	Bolivia	0.5	3.8	Papua NG	3.0	1.8
Indonesia	0.8	3.9	Germany	0.6	2.4	Russia	0.3	2.2	Madagascar	2.5	1.5
Mexico	0.7	3.4	Poland	0.6	2.3	Canada	0.3	2.00	Morocco	2.3	1.4
Canada	0.6	2.8	Mexico	0.5	1.8	Sweden	0.2	1.8	China	2.2	1.3
Others	4.9	23.5	Others	6.5	25.2	Others	2.4	18.2	Others	14.1	8.3
Total	21	100	Total	26	100	Total	13	100	Total	170	100
$CR4_{Cu}$		54.4	$CR4_{Cu}$		58.6	$CR4_{Zn}$		60.8	$CR4_{Co}$		81.1

$$\begin{array}{l}\text{Upper limit of Zn (tons)}586,254 * 0.95 = 556,941\\ \text{Lower limit of Zn (tons)}\ 429,917 * 0.95 = 408,421\end{array} \qquad \text{Equation 8}$$

According to Equations (4), (6) and (8), it is possible to recover 105,718tons of Cu, 52,216tons of Co, and 556,941tons of zinc in the best-case scenario. When copper content is considered, the retreatment of the copper flotation slag increases copper production by approximately 0.5%.

2.5. Life cycle analysis

Albeit recovering precious metals from CSFT is beneficial, the recovery process still puts pressure on the environment. Even though by removing the volume of the waste, and lowering the hazardous content, the environmental impact and sustainability of precious metal recovery should be evaluated. Therefore, Life Cycle Asssesment (LCA) was carried out.

A large number of researchers have used LCA for different metals/minerals. Farjana et al. (2019a) used LCA for cobalt extraction process. Memary et al. (2012), Chen et al. (2019) and Hong et al. (2018) incorporated LCA for copper while Qi et al. (2017), Arguillarena et al. (2022), and Farjana et al. (2019a) incorporated LCA for zinc.

Among the LCA methods, the ReCiPe method is the most commonly used ones in mining and metallurgy sectors. Therefore, the ReCiPe method was selected. All the analysis were carried out by OpenLCA software. As for the database Environmental Footprints (EF) 3.0 was used. Since the most prominent metal is cobalt in this scenario LCA was conducted for only cobalt.

3. Results and discussion

In the previous section, the potential of the CSFT was given for Cu, Zn, and Co. Fortunately, the obtained figures supported their potential after subsequent calculations. Even for the copper ore/, concentration importing countries can increase their metal recovery and production levels. Globally, it is possible to recover 111,330tons of copper from CSFT, which is 0.5% of the global production. For Zn (556,941tons) and Co (52,216tons), these figures are even higher, 4.35% and 30.72%, respectively.

3.1. Impact of the CSFT on the electric vehicle manufacturing

The Net Zero Emissions (NZE) by 2050 scenario is a normative scenario that sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO2 emissions by 2050. This scenario limits the global temperature increase to 1.5 °C. According to NZE, new internal combustion engine automobile sales will be halted in 2035. As a result, the share of EVs in total sales needs to reach around 60% by 2030 to achieve the NZE plan (zero CO_2) in 2050. The number of EVs on the road has already exceeded 16.5 million (IEA, 2022; Paoli and Gül, 2022).

By 2030, EVs are expected to be around 350 million (Hu et al., 2010). However, this unusual but necessary future growth will depend heavily on critical minerals and the development of battery technologies. Otherwise, supply shortages and/or insufficient technologies will jeopardize the NZE scenario. Cobalt is one of these critical metals and a crucial component of EV batteries. According to Castelvecchi (2021), an average car battery requires 14 kg of cobalt, 8 kg of lithium, 25 kg of nickel, and 8 kg of manganese. In addition to these metals, an electric vehicle requires approximately 83 kg of copper (IEA, 2022; Paoli and Gül, 2022). In this respect, the CSFT can contribute to this great supply and partially prevent the bottlenecks.

With 350 million EVs targeted by 2030 and 16 million already manufactured (Tsiropoulos et al., 2022), the required amount of Co and Cu is needed with current technology (European Commission, 2020).

$$\text{Co requirement}336,000,000\text{ cars} * 0.014\text{tons} = 4,704,000\text{ tons}$$

Equation 9

$$\text{Cu requirement}336,000,000\text{ cars} * 0.083\text{tons} = 27,888,000\text{ tons}$$

Equation 10

The potential Co recovery from CSFT annually varies between 55,665 and 40,821 tons, while Cu recovery is 111,330–82,467 tons. If the production rate is considered to remain constant over the following eight years, then;

$$\begin{aligned}\text{Co from CSFT}36,449 * 8 &= 291,592\text{tons}\\ 52,216 * 8 &= 417,728\text{tons}\end{aligned}$$

Equation 11

$$\begin{aligned}\text{Cu from CSFT}77,526 * 8 &= 620,208\text{tons}\\ 105718 * 8 &= 845,744\text{ons}\end{aligned}$$

Equation 12

According to these figures, the coverage ratio will be;

$$\begin{aligned}\text{Coverage ratio for Co from CSFT}291,592/4,704,000 * 100 &= 6.20\%\\ 417,728/4,704,000 * 100 &= 8.88\%\end{aligned}$$

Equation 13

$$\begin{aligned}\text{Coverage ratio for Cu from CSFT}620,208/27,888,000 * 100 &= 2.22\%\\ 845,744/27,888,000 * 100 &= 3.03\%\end{aligned}$$

Equation 14

Equations (13) and (14) shows the potential of CSFT for the global EV target. The amount of cobalt can cover almost 1/10 of the required Co. Albeit its coverage rate is significantly lower than the Co, the amount of the Cu can still meet more than 3% of the Cu demand of electric vehicle EVs projects.

3.2. Supply security and decentralization of cobalt production

According to the USGS (2022a), Congo has 51.4% of the world's Co reserves. However, it controls almost 90% of the Co ore market and 47.6% of metallic Co (OEC, 2020b, 2020a). In addition to these huge shares, Congo is politically unstable and risks Co supply (Nkulu et al., 2018; Sun et al., 2022). Moreover, many reports show that Co is mined through intensive child labor (Kobie, 2020). This pattern raises significant concerns about Co supply.

Another risk to Co supply is the price of the Co. Price fluctuations (Fig. 2) threaten the market and investors (Kobie, 2020). The rate of mining sometimes lags behind demand. In recent years, several Co crises have been reported (Bold Business, 2018; Deign, 2017; Kobie, 2020; Miller, 2015).

Fortunately, CSFT is a new source of Co with recent developments. Recovering Co from CSFT has increased the importance of copper ore, copper miners, and copper smelters. For example, Chile, with the sheer size of its copper reserves, and China, with the sheer size of its smelted products, can be new subcenters for international Co supply. Other smelter countries such as Japan, S. Korea, the USA, and Germany would benefit from additional Co recovery as they all manufacture EVs. Moreover, an increment in domestic production and shifting toward copper would increase market diversity of a critical raw material (European Commission, 2020), decreasing foreign dependence and ensuring the security of supply to some extent (Başyiğit, 2021).

3.3. Impact of CSFT on copper and zinc

Even though the CSFT can only increase global recovery by 0.43%, the recoverable amount exceeds 105Kton due to the sheer size of global production. According to Fitch, copper mine production will increase by an average of 2.8% annually between 2022 and 2031 (Mining.com, 2022). However, a copper supply crisis is expected to occur very soon (Attwood, 2022; Moors and Keen, 2022). The CSFT may contribute to the expected/needed copper supply and mitigate the crisis.

However, for zinc, the increment from CSFT recovery is 4.58%. Moreover, the zinc demand and supply have not changed significantly and are quite stable (ILZSG, 2021a; USGS, 2022c). Besides, it is reported that zinc demand is weakening (Home, 2022). In addition to a 4.35% surplus, zinc prices could decline.

3.4. Environmental issues

Mining is being scrutinized locally and internationally as environmental awareness grows, especially the damage caused by prior mining (Rahman et al., 2020). Environmental incidents at existing operations cause major problems for the mine in question and cast a shadow over the industry in general (Hilson, 2000). There is an urgent need to address cumulative impacts, the additional effects of multiple operations in an area, and historical mining legacy issues (Arndt et al., 2017). Disposing of slags and wastes from mining and mineral processing industries has become a major environmental challenge (González et al., 2005). In the metallurgical industry, slag is a serious problem because it is dumped onto heaps where millions of tons have accumulated over time.

Furthermore, they threaten the ecosystem by occupying vacant land (space problems). Copper slag containing heavy metals such as copper, nickel, cobalt, iron, and lead can seep into underground water and is dumped directly outside the mine, posing a significant environmental hazard (Gabasiane et al., 2019). The metals in the unprotected heaped slags become active through biochemical and physical erosion and cause environmental pollution. Therefore, slags are classified as "potentially hazardous" (Kierczak et al., 2013). Slags should be properly recycled, changed, and processed considering the environmental impacts (Li and Guan, 2009).

The global concern is to produce economically friendly metals at lower costs with less harmful environmental effects (Murari et al., 2015). Creating a sustainable system that can transform all waste into useful products is an important attempt toward environmental

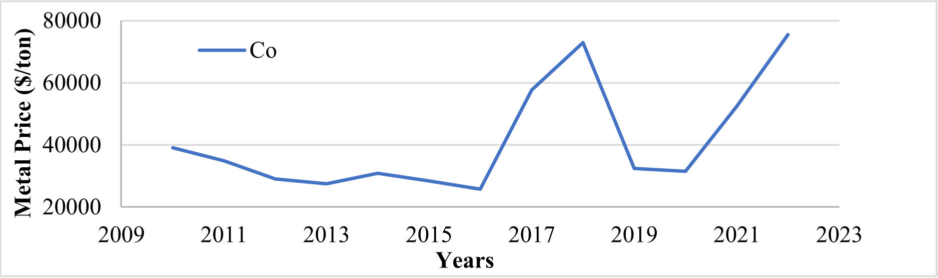

Fig. 2. Cobalt prices by year between 2010 and 2022 ($/ton).

sustainability (Erzurumlu and Erzurumlu, 2015). In this context, CS and CSFT are raw materials that can be evaluated with idealized sustainability and environmental approach due to their essential value as base metals (Sharma and Khan, 2017).

3.4.1. Life cycle analysis of cobalt

For dataset input and dataset output, findings of Nuss and Eckelman (2014) Farjana et al.(2019a) were used after certain justifications. For example, CSFT was already crushed-grinded from the recovery of CS. Moreover, it was not blasted therefore there is no emissions for blasting. Another important assumption is all the recovered cobalt is in metallic form. The results were given in Table 6.

The results show the effects of possible recovery of Co on both environment and human health (Table 6). Even though treating CSFT can boost metal production and decrease waste volume, and lower the toxic/harmful material concentration, the recovery process is still a burden on environment.

4. Conclusion

Since the markets for most base metals are relatively well balanced in terms of supply and demand, small changes in either can impact metal prices (Backman, 2008). The price of metal significantly impacts the development of novel materials and applications (Ljungberg, 2007). Significant price increases incentivize the search for new resources that can improve performance and alternatives for existing applications. Despite changing uses, global demand for most base metals has increased steadily over the last century, owing to the growing global population. In the foreseeable future, the flow of base metals is likely to increase (Arndt et al., 2017).

Copper and base metal production is expanding exponentially worldwide, and every mine will eventually be exhausted (Rötzer and Schmidt, 2018). Thus, metal recycling, primarily copper, has become economically and environmentally important (Kademli and Aydogan, 2019).

As shown in Fig. 3, copper consumption has been steadily increasing. The consumption of cobalt and zinc is not different from that of copper (Cobalt Institute, 2021b; ILZSG, 2021a). To sustain these levels of metal production, as mentioned earlier, 24.6–37.7 million tons of slag are released annually during copper production in the world (Al-Jabri et al., 2011; Phiri et al., 2021). These wastes generated in many parts of the world are not only a resource for copper but also important for producing industrially critical metals such as nickel, cobalt, and zinc. Re-evaluating the waste of copper production plants (CS and CSFT) as a “secondary metal resource” will effectively minimize the problems mentioned above. Also, this resource can withstand the increasing demand and prices, as stated by Millar et al. (2019). The production of base metals and alloys from CS and CSFT through various metallurgical processes improves the economy of mining and metallurgy plants and reduces disposal costs.

Table 6
Life cycle assessment output. (Open LCA Database and Authors Own Calculations)

	Per kg Co	Unit	Total Production Co (Min-Max)	
			Min. production level	Max. production level
Acidification	0.60419	mol H eq.	22022121	31548385
Climate Change	36.05336	kg CO2 eq.	1314108919	1882562246
Ecotoxicity	49.66855	CTUe	1810368979	2593493007
Eutrophication marine	0.04647	kg N eq.	1693785	2426478
Eutrophication freshwater	0.00706	kg P eq.	257330	368645
Eutrophication terrestrial	0.41261	mol N eq.	15039222	21544844
Human toxicity, cancer	2.59E-06	CTUh	94	135
Human toxicity, non-cancer	6.58E-06	CTUh	240	344
Ionising radiation	3.90701	kBq U-235 eq.	142406607	204008434
Land Use	1.4427	m2	52584972	75332023
Ozone depletion	6.62E-06	CFC11 eq.	241	346
Particulate Matter	6.30E-06	Disease inc.	230	329
Photochemical Ozone Formation	0.1399	kg NMVOC	5098122	7303452
Resource use, fossils	553.934	MJ	20190341095	28924218788
Resource use, minerals - metals	0.00109	kg Sb eq.	39729	56915
Water use	33.15748	m3	1208556989	1731350976

The findings of this study can be summarized as follows:

- The CSFT is not a waste but a complex structure containing precious metals. Reprocessing the CSFT can increase global Cu, Zn, and Co production by 0.50%, 4.35%, and 30.72%, respectively.
- The CSFT can help meet the world’s Cobalt demand by boosting production by nearly 1/3. This is essential as a cobalt crisis is around the corner
- The recoverable amount of Cu and Co would significantly contribute to the NZE Scenario EV’s goals.
- It is possible to decentralize Cobalt production to some extent, primarily mined in Congo. Domestic production of Co will decrease the foreign-source dependency. Thus, production and market diversity would be improved.
- Copper recovery, while small, would not affect the current market structure. However, zinc recovery could create a surplus and drag prices down since the demand has already begun to shrink.
- Cobalt recovery from CSFT and cobalt refinement (along with Cu and Zn) have impact on environment. According to findings of this paper, the toll on the environment is heavier in comparison with Farjana et al.‘s study (2019b)

In summary, the results indicate that the studied tailings are an essential source of secondary raw materials for copper extraction, providing an alternative way to greening copper extraction. Finally, it has been proved that tailing reprocessing by flotation is reliable, economical, and promising in the copper mining industry; therefore, cleaner copper concentrate production is feasible.

5. Implications and recommendations

Excessive CO2 emissions and dealing with environmental issues related to metal production are forcing governments to produce green energy and greener raw materials. These environmentally friendly technologies are leading to an increase in price and demand. This transformation wave significantly affects battery materials such as cobalt and copper, the main conductor metal. However, the impact of this green frenzy on importing countries can be severe. Nearly half of the cobalt supply comes from the Democratic Republic of Congo. Besides being the largest miner and exporter, Congo also raises significant issues regarding production methods, namely “child workers”. Recovering cobalt from CSFT could reduce dependence on Congo and its cobalt.

Based on the current situation in the world or for any country, CSFT should be considered a resource and handled accordingly. Treatment of slag and tailings leads to metal production while exposing the environment to less polluting and less hazardous waste, which is undoubtedly a win-win situation.

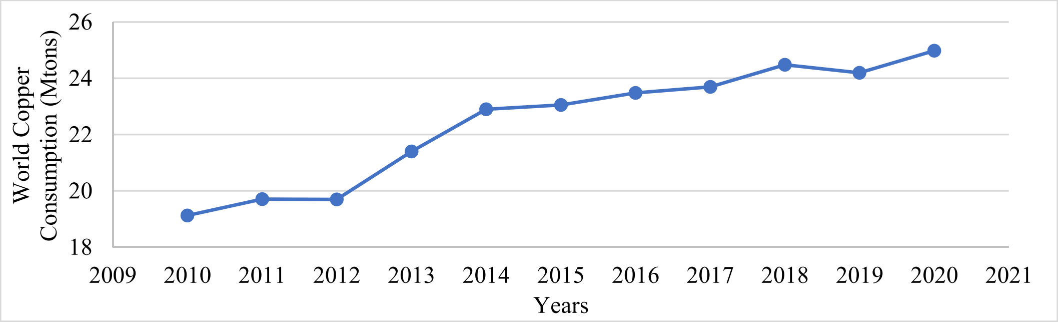

Fig. 3. World Copper Consumption by Years 2010-2021 (ICSG, 2021).

6. Limitations

The findings of this study are limited by the disclosed, published, and shared data. Therefore, the addition of new data may change the figures presented in this paper.

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Credit authors contribution statement

Author 1: Conceptualization, Writing – original draft, Writing – review & editing, Methodology, Visualization Supervision. **Author 2:** Conceptualization, Formal analysis**,** Methodology, Writing – review & editing, Visualization, Data Curation. **Author 3:** Resources, Funding acquisition, Writing – review & editing, Project management.

Declaration of competing interest

The authors declare no conflict of interest.

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