Recovery of Zinc and Copper from Mine Tailings by Acid Leaching Solutions Combined with Carbon-Based Materials

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Abstract: Mine tailing storage represents an important environmental issue. The generation and dispersal of dust from mine tailings can contaminate air and surrounding soils. In addition, metals and soluble salts present in these wastes could pollute groundwater and surface water. The recovery of metals from mine tailings can contribute to minimize the environmental risk and to achieve a circular economy model. The main objective of the present work is to study the use of two carbon-based materials, a commercial activated carbon (AC) and a commercial charcoal (VC) in the leaching of zinc and copper from low-grade tailing waste. Experimental results obtained show that it is possible to achieve the recovery of more than 87 wt% of Zn after 6 h of leaching with different sulfuric acid solutions. The addition of carbon-based materials increases the extraction of Zn at high sulfuric acid concentrations (1 M) from 89% to 99%. The addition of VC significantly increases the extraction of Cu in leaching solution with high sulfuric acid concentration (1 M), from 41 to 61%. Future research will be necessary to optimize the properties of carbon-based materials and their recovery after leaching experiments in order to assess their potential for industrial application.

Keywords: hydrometallurgy; mine tailings; raw materials

1. Introduction

Mine tailings are the slurries that remain after the treatment of minerals by separation processes (crushing, grinding, or flotation) and other physiochemical techniques in order to extract the valuable minerals from the less valuable rocks. Worldwide, mine tailings are produced at a rate of anywhere from five to fourteen billion tons per year [1]. Their storage in tailing dam basins represents an important environmental issue [1]. The generation and dispersal of dust from mine tailings can contaminate air and surrounding soils. In addition, metals and soluble salts present in these wastes could pollute groundwater and surface water. Finally, some mine tailings include sulfide minerals that can induce the formation of acid mine drainage (AMD) and acid rock drainage (ARD) [2].

The mining area of Cartagena–La Unión is one of most degraded areas of Spain, exploited for centuries until its closure in the early 1990s. The main minerals obtained are galena (PbS with small amounts of Ag), sphalerite (ZnS), cerussite (PbCO₃), cassiterite (SnO₂), and iron oxides (Fe₂O₃) [3]. During some years, these mines represented 40% of Pb, 60% of Ag, and 12% Zn of the Spanish production [4]. These former mining activities have
produced important amounts of mine wastes deposited in dumps, ponds, and tailings, without sealing or reforesting, which have been and continue to be eroded and dragged through watercourses that make up its orography [5–7].

Four watercourses have their basins in the mountain range of Cartagena-La Unión that flow into the Mar Menor: Rambla de las Matildes, Rambla del Beal, Rambla de Ponce, and Rambla de la Carrasquilla. Among these four watercourses, Rambla del Beal is considered to be one of the most polluted in this region [8]. Watercourses constitute a method of transport for waste materials from mining sites through the peaks and valleys to the Mar Menor and the Mediterranean Sea. These mining wastes also contaminate the surrounded soils with heavy metals [3].

Taking into account the low but torrential rainfall in this region [9], the great amount of sediment deposition with high concentration of metals and sulfates, and the erosion and overland flow, important human health and environmental risks can emerge. According to previous works [10–12], the lagoon is still being affected by trace elements such as Ni, Cu, Zn, As, Cd, Pb, Fe, and Mn [6]. They are contained in the sediments from the watercourses of the mining mountain range and from rock pools located in the surroundings. The influence of this abandoned mining site on the associated ecosystems, land degradation, and its human and environmental risks has been widely studied [3,5,9,10,13]. They highlight the need to work on solutions to counteract the environmental problems associated with mining waste dispersion through the watercourses of this area.

The recovery of metals from mine tailings and surrounding soils can contribute to minimize environmental risk and to achieve a circular economy model [14]. Different approaches to economic tailings valorization can be taken, such as reprocessing to extract residual metals and minerals and the use of final waste matrix as backfill or construction materials. In addition, in some cases, the presence of valuable metals could make mining wastes an appreciable resource with economic benefit [15,16]. However, pyrometallurgical treatment of mine tailings is limited by low metal grade and their mineralogical concentration by classical technologies is limited by the surface modifications of minerals [17,18].

It is well established that hydrometallurgy is one of the most efficient leaching technologies to recover valuable metals from low-grade ores and wastes, sulfuric acid being the most employed leaching system due to price, availability, and dissolution capacity [19–21]. Some mine tailings related to the exploitation of metallic deposits like Cu or Zn are rich in sulfide minerals, which show low dissolution rates [22,23]. Recently, some research has shown that some carbon materials such as black carbon or activated carbon improved the kinetics of leaching of sulfide minerals such as chalcopyrite [24–27]. A substantial increase in the copper extraction rate after carbon material addition was observed, probably due to the low redox potential as well as galvanic interaction between sulfide mineral and carbon material [26,27]. However, to our knowledge there are no previous studies on the effect of carbon-based materials on the Zn leaching from sphalerite or oxidized minerals that are traditionally present in some mine tailings. The use of carbon-based materials as catalysts in the leaching of low-grade ore could be advantageous. Carbon-based materials could be obtained by carbonization/activation of biomass, a renewable resource [25] and the great stability of carbon-based materials may facilitate their recovery after leaching process and re-utilization, in a similar way to the use of activated carbon in gold metallurgy [28].

The main objective of the present work is to study the use of two carbon-based materials in the leaching of zinc and copper from low-grade tailing waste. Furthermore, the effect of different $H_2SO_4$ concentrations was studied in order to optimize the leaching conditions. Zinc and copper extracted from mine tailings was determined at 2, 4, and 6 h. Parameters including pH and redox potential of the leaching solutions were monitored during the process at 1, 2, 4, and 6 h.
2. Materials and Methods

2.1. Materials Selection and Characterization

The selected sample was collected from abandoned mine tailings located in Rambla del Beal (RD), Murcia, Spain. The sample was air-dried, crushed, and sieved below 50 µm. Wavelength X-ray fluorescence (WDXRF) was performed in an ARL ADVANT XP + sequential model from THERMO (SCAI-Malaga University). UNIQUANT Integrated Software was used for concentration data acquisition. XRD was carried out by a Bruker diffractometer, model D8 Advance A25 (SCAI-Malaga University).

The two carbon-based materials used in this work were a commercial activated carbon (AC) supplied by Panreac (Spain) and a commercial charcoal (VC) supplied by Ibecosol (Spain). Both carbon-based materials were air-dried, crushed, and sieved below 100 µm using a mortar mill Retsch RM 100 and characterized according to the following properties: pH, Eh, S\text{BET}, Hg porosimetry, CEC, ash content (wt%), and elemental analysis (C, H, N, O, and S).

pH and redox potential (Eh) were determined with a carbon-based material: distilled water ratio of 0.1:25 (g mL\(^{-1}\)), using a Crison micro pH 2000 and Eh in a pH 60 DHS, respectively. S\text{BET} was determined using a Porosimetry System ASAP 2420 Micromeritics and Hg porosimetry was carried out using a Micromeritics AutoPore IV 9500 equipment. Elemental analysis (C, H, N, and S) was performed using a LECO CHNS 932 Analyzer by dry combustion. Ash content (%) was calculated by combustion of samples at 850 °C in a Labsys Setaram TGA analyzer. Twenty mg of each sample were heated at a rate of 15 °C·min\(^{-1}\) up to 850 °C using 30 mL min\(^{-1}\) of air. O (%) was obtained by difference as 100- (%C+ %H+ %N+ %S+ %Ash). Following that, O/C and H/C ratios were calculated from the elemental analysis results.

2.2. Leaching Experiments

A thermostatic bath with stirring model GFL 1083 (heating power of 1500 W and voltage of 230 V) was used for the leaching tests. The temperature conditions (90 °C) and stirring speed (250 rpm) were controlled during the leaching process for 6 h. Leaching experiments were carried out in 250 mL ISO borosilicate glass jars. Every hour, the leaching systems were aerated to provide O\(_2\) in the solutions.

Leaching agent solutions used were prepared by H\(_2\)SO\(_4\) at different concentrations: 1 M, 0.5 M, and 0.25 M. In a series of experiments, the leaching agent was prepared with H\(_2\)SO\(_4\) at 1 M, 0.5 M, and 0.25 M and 1% H\(_2\)O\(_2\). The purity of Sigma-Aldrich sulfuric acid used was 95–98%. Approximately 2.5 g of RD sample was weighed in each jar with the addition of 50 mL of leaching agent. Except for the control samples, the carbon-based material was added at a 1/0.5 of RD/carbon-based material ratio (weight/weight).

At different reaction times (2, 4, and 6 h), 1 mL of each sample of the supernatant liquor was withdrawn. The sampling was carried out as follows: first, the stirring was stopped to let the sample stand and favor its decantation. After this short period of time, 1 mL of the supernatant solution was removed, and then filtered and transferred to a 25 mL graduated flask and made up to volume with distilled water. To compensate for this extracted mL and to maintain the same conditions throughout the system, 1 mL of the corresponding leaching solution was added.

At the end of each test (6 h), stirring was stopped, and the supernatant was allowed to cool. After that, the pulp was filtered and the solid was washed two times with 50 mL of H\(_2\)SO\(_4\) solution of pH = 2.

pH and Eh of leaching solution were determined at different reaction times (0, 1, 2, 4, and 6 h) using a Crison micro pH 2000 and a pH 60 DHS, respectively. Concentration of Zn and Cu in the leaching and washed solutions was determined using a Perkin Elmer AAnalyst 400 Atomic Absorption Spectrophotometer.
2.3. Statistical Analysis

The normality of data distribution was checked using Kolmogorov–Smirnov’s test, while the assumption of homogeneity of variances was tested using Levene’s test. The significance of the differences among means was assessed by analysis of variance (ANOVA). Duncan’s multiple range test ($p < 0.05$) was used as a post-hoc, using the Statgraphics Centurion XVII. software for the calculations. Every analysis was performed in triplicate.

3. Results

3.1. Materials Characterisation

Table 1 shows content of identified mineral species by XRD analysis. The most abundant species were quartz (38.9%) and muscovite (49.6%). There was no presence of crystalline ZnS. Zn was only present as stannite and probably in the form of amorphous minerals formed by alteration of ZnS.

Table 1. XRD analysis of RD sample.

| Mineral Specie         | Content (%) |
|------------------------|-------------|
| Muscovite              | 49.6 ± 0.1  |
| Quartz                 | 38.9 ± 0.9  |
| Corkite                | 6.9 ± 0.5   |
| Calcite magnesium      | 3.5 ± 0.1   |
| Litharge               | 0.5         |
| Stannite               | 0.4         |
| Calcite                | 0.2         |

Table 2 shows chemical composition of RD. It is important to note the content of Zn (1.38%), Pb (2.18%), and Cu (0.0435%). These metals were lower than exploitable concentrations in ores. Table 3 lists the background ranges and maximum allowable limits of some trace elements in the soils of the Region of Murcia (Spain) [29]. The background or baseline levels of an element or a substance are the natural soil concentrations in an area and therefore, pollution occurs when as a result of human activity an element or a substance is greater than those levels with a net detrimental effect on the environment and its components [30]. According to this concept, different countries/regions determine the regulatory standards over which a soil can be considered contaminated for different uses, including agricultural, industrial, or urban.

Table 2. Chemical composition of RD sample.

| Element | Content (wt%)       |
|---------|---------------------|
| O       | 39.37 ± 0.12        |
| Si      | 20.62 ± 0.12        |
| Al      | 8.32 ± 0.10         |
| Fe      | 9.07 ± 0.12         |
| S       | 1.94 ± 0.04         |
| K       | 2.10 ± 0.07         |
| Pb      | 2.18 ± 0.07         |
| Zn      | 1.38 ± 0.05         |
| Ca      | 0.344 ± 0.17        |
| Mg      | 0.283 ± 0.014       |
| Ti      | 0.252 ± 0.013       |
| Na      | 0.202 ± 0.06        |
| As      | 0.151 ± 0.0075      |
| P       | 0.0339 ± 0.0017     |
| Ba      | 0.0518 ± 0.0048     |
| Cu      | 0.0435 ± 0.0022     |
| Sn      | 0.0424 ± 0.0021     |
| Mn      | 0.0293 ± 0.0015     |
| Zr      | 0.0258 ± 0.0013     |
Table 3. Concentration ranges of some trace elements in soils of the region of Murcia [28] compared to the unusual values from the mine wastes of the Sierra Minera.

| Element | Background Levels 1 (mg kg⁻¹) | Maximum Allowable Limits 2 (mg kg⁻¹) | Mine Waste Levels (mg kg⁻¹) |
|---------|-------------------------------|-------------------------------------|-----------------------------|
| Cr      | 24–45                         | 38–71                               | 25–80                       |
| Co      | 5–9                           | 10–13                               | <52                         |
| Ni      | 17–25                         | 30–34                               | <37                         |
| Zn      | 16–55                         | 43–92                               | 993–14,720                  |
| Cu      | 12–23                         | 23–32                               | 18–268                      |
| As      | 5–8                           | 8–12                                | <1930                       |
| Se      | 0.2–0.6                       | 0.4–0.5                             | n.d.                        |
| Cd      | 0.1–0.4                       | 0.4–0.9                             | <65                         |
| Sb      | 0.5–1.6                       | 2–3                                 | <220                        |
| Hg      | 0.1–0.4                       | 0.4–1.2                             | n.d.                        |
| Tl      | 0.1–0.4                       | 0.5–0.8                             | n.d.                        |
| Pb      | 3–10                          | 5–34                                | 75–27,780                   |

n.d. not determined. 1 Background levels. 2 Maximum allowable limits.

Table 4 summarizes the physicochemical properties of the carbon-based materials (AC and VC) used in the treatment of RD. Two commercial carbon materials showed high C content (>80%).

Table 4. Main characteristics of carbon materials.

| Sample | %C  | %H  | %N  | %S  | %O  | H/C | O/C | Ash (wt%) | pH | Eh (mV) | S BET (m² g⁻¹) | Porosity (%) |
|--------|-----|-----|-----|-----|-----|-----|-----|-----------|----|---------|----------------|--------------|
| AC     | 85.72 | 0.88 | 0.00 | 0.00 | 13.41 | 0.12 | 0.12 | 1.00 | 8.03 | 453 | 1138.96 | 73.26 |
| VC     | 80.21 | 3.12 | 0.92 | 0.00 | 15.74 | 0.47 | 0.15 | 14.94 | 8.31 | 355 | 2.18 | 63.73 |

3.2. Percentage of Zn and Cu Extracted in H₂SO₄ Leaching Solutions

Table 5 shows initial pH and Eh of RD mixed with different leaching solutions. In spite of AC and VC showing alkaline pH, their addition of the sulfuric acid solution did not increase the pH.

Table 5. pH and Eh (mV) of leaching systems.

|                  | pH (25 °C) | Eh (mV) |
|------------------|------------|---------|
| RD+ H₂SO₄ 1 M    | 1.02 ± 0.02| 654 ± 2.5|
| RD+ H₂SO₄ 1 M + AC| 0.99 ± 0.01| 557 ± 5.4|
| RD+ H₂SO₄ 1 M + VC| 0.99 ± 0.01| 627 ± 1.3|
| RD+ H₂SO₄ 0.5 M  | 1.08 ± 0.01| 672 ± 3.3|
| RD+ H₂SO₄ 0.5 M + AC| 1.09 ± 0.01| 558 ± 8.0|
| RD+ H₂SO₄ 0.5 M + VC| 1.09 ± 0.03| 626 ± 1.7|
| RD+ H₂SO₄ 0.25 M | 1.21 ± 0.06| 672 ± 2.9|
| RD+ H₂SO₄ 0.25 M + AC| 1.21 ± 0.03| 530 ± 2.4|
| RD+ H₂SO₄ 0.25 M + VC| 1.22 ± 0.03| 632 ± 1.5|

Figure 1a shows total Zn extracted from RD sample after 2, 4, and 6 h. Three sulfuric acid concentrations (1 M, 0.5 M and 0.25 M) were used as leaching solution. Figure 1a shows that under experimental results used in this work, after 2 h of leaching, the amount of Zn extracted from RD varied between 8 and 28 wt%. At 4 h of leaching, the amount of Zn extracted significantly increased to values between 20 and 55 wt%. From 4 to 6 h, the amount of Zn extracted significantly increased. In all cases, after 6 h of leaching, it was possible to recover more than 70 wt% of Zn. The highest extraction of Zn was achieved using H₂SO₄ 0.25 M as leaching agent with and without AC addition and using H₂SO₄ 0.5 M or 0.1 M in the presence of AC. The addition of AC or VC influenced Zn leaching. Using the highest H₂SO₄ concentrations (1 M or 0.5 M), the addition of AC and
VC significantly increased the amount of Zn extracted. However, the addition of VC to the 0.25 M sulfuric leaching solution decreased the amount of Zn recovered. Figure 1b shows total Cu extracted from RD sample at different times. The addition of VC significantly increased the extraction of Cu in high sulfuric acid concentrations (1 M) leaching solution from 41 to 61%.

**Figure 1.** Extraction degree of Zn (a) and Cu (b) after 4 h and 6 h. Values in column for each hour followed by the same letter are not significantly different ($p = 0.05$) using the Duncan test with a $R^2 = 0.98$ (a) and $R^2 = 0.98$ (b). Error bars indicate standard errors of the mean ($n = 3$).
3.3. pH and Eh Evolution During Leaching Experiments

Figure 2 shows the Eh (mV) evolution during leaching experiments of RD sample and RD at 90 °C treated with AC and VC in H$_2$SO$_4$ 1M (2.a); H$_2$SO$_4$ 0.5M (2.b) and H$_2$SO$_4$ 0.25M (2.c). The addition of AC and VC significantly diminished the Eh (mV) of leaching systems. The lowest Eh values corresponded to leaching solutions of H$_2$SO$_4$ 1M in the presence of AC (561–579 mV).

![Figure 2](image_url)

Figure 2. Eh (mV) evolution in samples with H$_2$SO$_4$ 1 M, (2.a); H$_2$SO$_4$ 0.5 M (2.b) and H$_2$SO$_4$ 0.25 M (2.c). Values in dot for each hour followed by the same letter are not significantly different ($p = 0.05$) using the Duncan test with a $R^2 = 0.73$ (a), $R^2 = 0.84$ (b) and $R^2 = 0.71$ (c). Error bars indicate standard errors of the mean (n = 3).
Figure 3 provides the pH evolution in the control (RD) and RD treated with AC and VC in H$_2$SO$_4$ 1 M, (3.a); H$_2$SO$_4$ 0.5 M (3.b) and H$_2$SO$_4$ 0.25 M (3.c) leaching solutions. With respect to pH evolution during leaching experiments, small differences were observed in the absence or presence of carbon-based materials in spite of carbon materials showing an alkaline pH (Table 4).

![Figure 3](image.png)

**Figure 3.** pH evolution in samples with H$_2$SO$_4$ 1 M, (3.a); H$_2$SO$_4$ 0.5 M (3.b) and H$_2$SO$_4$ 0.25 M (3.c). Values in dot for each hour followed by the same letter are not significantly different ($p = 0.05$) using the Duncan test with a $R^2 = 0.76$ (a), $R^2 = 0.84$ (b) and $R^2 = 0.81$ (c). Error bars indicate standard errors of the mean ($n = 3$).
4. Discussion

According to Table 2, the content of Zn, Pb, and Cu were lower than exploitable concentrations in ores. Nevertheless, the content of these three trace elements were over the background levels and maximum allowable limits of the region of Murcia (Spain) (Table 3) [29]. Comparing data from Tables 2 and 3, RD would be classified as a contaminated soil due to the high concentrations of Zn, Pb, As, and Cu. These metals were in the list of seventeen trace elements that have been identified in soils as very toxic due to their high degree of mobilization (Co, Ni, Cu, Zn, As, Se, Pd, Ag, Cd, Sn, Sb, Te, Pt, Hg, Tl, Pb, and Bi). Most of them are incorporated in the list of priority pollutants established by the US Environmental Protection Agency [31]. The level of Cu is also higher than the Cu concentration in the mine wastes of this area.

Differences in the H/C ratio indicated that carbon in VC was in the form of more aliphatic carbon structures than in CA (Table 4). The two carbon-based materials showed similar alkaline pH, whereas the Eh of AC was higher than that of VC probably due to the presence of some oxygenated functional groups generated during the activation process. Finally, important differences were related to surface area and porosity. As expected, AC shows higher \( S_{BET} \) and porosity than VC.

Sulfuric acid was selected as leaching solution owing to its effectiveness for the selective dissolution of Zn compounds over Pb and Ca [32]. Instead, lead oxides and carbonates present in the sample can dissolve in sulfuric acid solution and then precipitate as lead sulfate. Hussaini et al. [33] studied the use of 17 different inorganic and organic leaching agents for the recovery of Zn from a carbonate-type Pb-Zn ore flotation tailing. These authors concluded that sulfuric acid resulted in 91 wt% of Zn extraction with a high selectivity against Pb.

The main influence of carbon materials in the initial leaching solutions is observed in the Eh values (Table 5). The addition of VC and specially AC decreased the initial Eh of the leaching solutions that continues along leaching time. This result was according to previous works and according to the low Eh values of carbon materials [25,26]. The main reason for Eh decrease was related to low Eh of carbon-based materials due to their high C content (Table 4). Table 4 shows that Eh of AC was higher than that of VC. However, when AC was added to leaching solutions, the decrease of Eh was higher than after VC addition. This fact could be related to different interactions between both carbon-based materials and oxidant species and minerals present in the systems. In fact, Nakazawa [26] observed that Eh decreased in the leaching of chalcopyrite catalyzed by charcoal and attributed this effect to galvanic interactions between mineral and charcoal in the acidic medium.

With respect to pH evolution along leaching time, the pH slightly increased with time (from 1 to 6 h) when sulfuric solution 1 M was used as leaching system whereas there were no significant differences in case the of 0.5 or 0.25 M. In general, there were no significant differences in the solution pH between leaching systems with or without the addition of carbon materials. This result was different to those obtained previously using activated carbon or charcoal in the leaching of sulfide minerals with ferric as oxidant [25]. In this case [25], the addition of carbon-based adsorbent significantly decreased the pH of the solution and it was proposed that this could be due to the reaction of surface functional groups of carbon-based adsorbents with the oxidizing agent (\( \text{Fe}^{3+}/\text{H}_2\text{SO}_4 \)). \( \text{Fe}^{3+} \) can react with different oxygenated groups generating organic acids and releasing protons to the medium. In addition, the addition of carbon-based adsorbents decreased the Eh of the leaching system favoring the generation of \( \text{H}_2\text{S} \). In the present research, leaching was performed without additional ferric agent; there was calcite in the medium and, in addition, the S content of original sample (RD) was only 1.94% (Table 2), instead 13.36% of S in the mineral concentrate used previously [25]. Carbon-based materials seem to act as catalysts in the leaching of Zn and Cu with higher \( \text{H}_2\text{SO}_4 \) concentrations (low pH) (Figure 1). The addition of carbon materials, AC and VC, increased the extraction of Zn and Cu with concentrated sulfuric acid solutions (0.5 and especially 1 M). In spite of the different composition and properties of AC and VC, both can increase the extraction of
Zn and Cu. The use of different carbon materials as catalysts in the leaching of metals was previously studied for the extraction of Cu from different sulfide minerals such as chalcopyrite or enargite [24–27]. In general, leaching of Cu needs reaction times higher than in the case of Zn and values of Cu extracted (Figure 1b) were lower than that of Zn (Figure 1a) [34]. As expected, the highest extractions of Cu were obtained using H$_2$SO$_4$ 1 M solutions [26]. With respect to the effect of carbon-based materials in the leaching of metals, Nakazawa et al. [24] used carbon black in sulfuric acid media at 50 °C as catalysts for the extraction of copper from chalcopyrite and proposed that the enhanced kinetics of chalcopyrite leaching could be attributed to dissolution reactions at the low redox potential in addition to the galvanic interaction between chalcopyrite and carbon black. Olvera et al. [27] proposed that the catalytic effect of carbon on the electrochemical dissolution of enargite was the consequence of carbon acting as a conducting channel and an extension of the surface area for the reduction of oxygen and ferric ions with an important role of the pH [27].

5. Conclusions

The main conclusions obtained in the present works are the following:

It is possible to recover more than 95 wt% of Zn from the selected mine tailings after 6 h of leaching with H$_2$SO$_4$ solutions.

The addition of carbon materials AC and VC increased the extraction of Zn and Cu with concentrated sulfuric acid solutions (0.5 and 1 M).

In spite of the differences of porosities and Eh values between AC and VC, their effect as catalysts in the leaching of Zn and Cu was similar. This opens prospects toward using lower cost carbon materials as catalysts.

Future research will be necessary in order to optimize the properties of carbon-based materials and their influence in the recovery of other metals existing in mine tailings and the characteristics of final waste. In addition, for the potential industrial application of carbon-based materials it is necessary to optimize their recovery from leaching solution and their re-utilization after leaching experiments.

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