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## Original Article

# Effective extraction of high purity sulfur from industrial residue with low sulfur content



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## ABSTRACT

In this work, toluene and carbon disulfide have been employed as solvents to obtain sulfur out of sulfur concentrate. Sulfur concentrate is produced as residue in the flotation of zinc industry, coming from the leaching process of zinc concentrate. Up to 86.7% of sulfur is recovered using toluene at 100 °C, and a 96.3% of high purity sulfur recovered at room temperature using carbon disulfide as solvent. The X-ray diffraction of the obtained sulfur is very similar to the commercial sulfur, and the diffraction data of the residue show no peak of sulfur. The results are compared to the evaporation-condensation method previously used with similar samples.

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## 1. Introduction

The Zinc extraction industry produces leaching residue, subsequently concentrated in sulfur by flotation. Such residue contains several metals and presents a significant disposal challenge: they are treated as solid waste, accumulated in tips, and can produce at some point dangerous products like sulfuric acid. The extraction of these elements, like sulfur, has an important economic and environmental interest.

When the elemental sulfur content in the industrial residue is lower than 70% the traditional melting and filtra-

tion procedures are difficult [1], for that reason a different procedure is chosen in this work.

A way of obtaining sulfur by dissolving sulfide concentrates coming from the zinc extraction industry was presented in [2]. This method describes a process for recovering sulfur by means of grinding and mixing it with diaryl disulfide at temperatures below the sulfur melting one (115 °C). Then, the solution containing the dissolved sulfur is isolated from the solid part by filtration. The posterior cooling of the solution leads to the sulfur crystallization, which is separated after filtering. However, when this method was applied in our lab, the filtering process gave negative results, not allowing the recovery of any sulfur. The high viscosity of the mix of diaryl disulfide prevents the first filtration operation from being carried out. Two other solvents (toluene and carbon disulfide)

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were used in order to apply this process to successfully obtain sulfur from sulfurate concentrated residue, thanks to the high solubility of sulfur in these chemicals. These two solvents are among the best solvents of sulfur, even at low temperatures, and could provide a simple method to recover sulfur [3,4]. Results are compared to those obtained by the evaporation-condensation method developed in our laboratory [5]. The evaporation-condensation method needs to heat the residue in order to evaporate sulfur, with higher energy requirements. This is the reason why the extraction of sulfur with solvents was tried, and the results are shown in this work. Although good results have been obtained using [5] in sulfur content samples with a 60% of sulfur, the method used presented in this work still improves the results. Other methods [6,7] based on distillation have been successfully employed, but a high content of sulfur, or high energy is required. In this work, we were able to obtain at room temperature (low energy) up to 96.3 % of sulfur out of sulfurated samples coming from a zinc extraction plant.

Toluene is generally used as solvent for different processes. Other applications are the synthesis of benzene and xylene, the production of polyurethane foam and trinitrotoluene [8].

Toluene is catalogued as dangerous substance. Toluene exposure produces effects similar to those caused by other drugs and all its consequences are not well known yet [9]. The exposure to high concentrations may lead to several problems in the nervous system of humans [10,11]. Regarding its effect in the environment, despite the toluene being degradable by some sort of microorganisms [12,13], it has toxic effects on aquatic environments and aquatic life forms.

Carbon disulfide ( $\text{CS}_2$ ) is known to be a very good solvent of sulfur, and it is heavily employed in many industrial processes. It is historically used to produce viscose rayon, cellophane film and carbon tetrachloride [14]. It has also been employed in purifying single-walled carbon nanotubes [15] and it is also utilized in agricultural chemicals [16].  $\text{CS}_2$  toxicity has been the subject of numerous studies [17,18], indicating wide biochemical effects for  $\text{CS}_2$  toxicity. Its bacteriostatic, fungicidal, nematocidal and insecticidal properties can suppose alterations on the stability of several environments [19,20].

## 2. Experimental process

The material used in this work came from the zinc plant AZSA (Asturiana de Zinc S.A.). Some of our samples were used in order to extract sulfur by an evaporation-condensation method shown in [5]. The rest of the samples are used in this work, with the aim to develop a more effective way to obtain sulfur. Samples from the leaching residue coming from the zinc plant were pulverized and dried. Afterwards their composition and structure were characterized by means of different techniques. An elemental analysis was first performed in order to determine the elemental sulfur in the samples. The percentage of sulfur is calculated from the weight in the samples and in the products (sulfur and residue). The amount of metals in the samples was performed by mass spectrometry. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) was also performed on our samples. The initial amount of sulfur was measured at the beginning of the solution pro-

cedure and at the end, both in the residue and in the solid recovered sulfur. The sulfur content of our initial samples is 60.6%, but other phases are also found:  $\text{FeS}_2$  (20.2%),  $\text{SiO}_2$  (7.1%),  $\text{PbSO}_4$  (6.1%), and other phases in minor quantities.

The XRD technique was performed on pulverized samples, and is based on the well known Bragg's law, that allows to identify the different crystal phases in the sample. This procedure provides different peaks associated with different crystalline phases at known angles.

The SEM technique provides information about the samples structure, showing pyrite cubical particles of about 2–4  $\mu\text{m}$ , spherical particles containing sulfur, silica and some pyrite with a size of 2–4  $\mu\text{m}$ , and agglomerates of particles similar to the spherical ones containing also some Zn, of about 5–12  $\mu\text{m}$ . Fig. 1 shows a micrograph of the initial samples, where the aforementioned type of particles can be seen. The samples structure had already been evaluated through SEM microscopy and XRD for our previous work, published in reference [5]. The structure observed in Fig. 1 is consistent with the XRD results shown in [5].

The chemical analysis of the samples, extracted sulfur and residue was performed by means of the Inductively coupled plasma- Mass spectrometry (ICP-MS) technique. This technique is able to detect metals and several non-metals in concentrations as low as one part in  $10^{15}$ .

In order to evaluate the sulfur's purity and the improvement of this method for its possible use at an industrial level, the same characterization is performed on the obtained sulfur as well as on the filtered tailing residue.

### 2.1. Dissolving flotation concentrate in toluene

Fig. 2 shows the flow diagram of the process used to solve the samples with toluene ( $\text{C}_7\text{H}_8$ ).

First, the solubility of the sulfur in  $\text{C}_7\text{H}_8$  was determined: up to 70 g of sulfur per 250 mL of toluene can be dissolved at 100 °C. Due to the fact that solubility decreases very quickly with decreasing temperature, our filtering equipment was kept in a stove at 150 °C, until the filtration was performed.

The residue samples are pulverized and dissolved with  $\text{C}_7\text{H}_8$ . The procedure consists in heating the components and obtaining a solution where sulfur crystallizes. A sample of 40 g was dissolved in 200 mL  $\text{C}_7\text{H}_8$ , stirring it at 290 rpm. Various attempts with different stirring times were performed in order to see its effect on the results. A first try was carried out at room temperature (RT), but no sulfur was obtained. Changing the temperature was then considered: the same procedure was performed at 50 and 100 °C, with stirring times varying between 5 and 40 min. Then, a first filtration is performed in order to separate both the crystallized sulfur and the not-crystallized sulfur from the initial solution. As the solubility of the sulfur in the toluene decreases with the temperature, the filtration was carried out at high temperature (150 °C). Finally, a second filtration is performed in which crystallized sulfur and recycled  $\text{C}_7\text{H}_8$  were obtained. Consequently, there are three products at the end of the process: recovered sulfur from the residue, recycled  $\text{C}_7\text{H}_8$ , and residue of the filtration with the components that were not dissolved in the mixing.

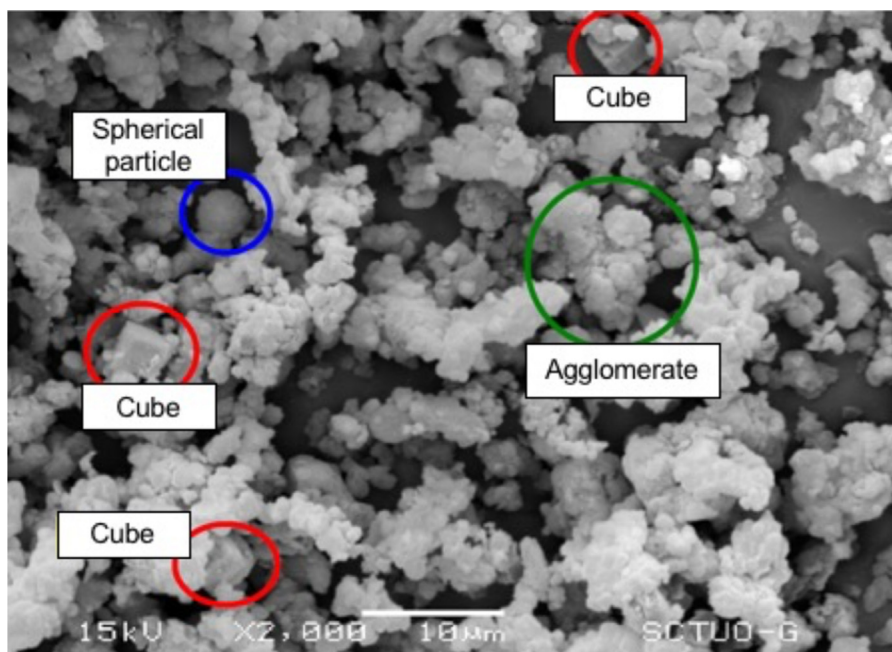


Fig. 1 – Micrograph of the sulfur concentrate samples received from the Zinc Plant. Three type of particles can be observed.

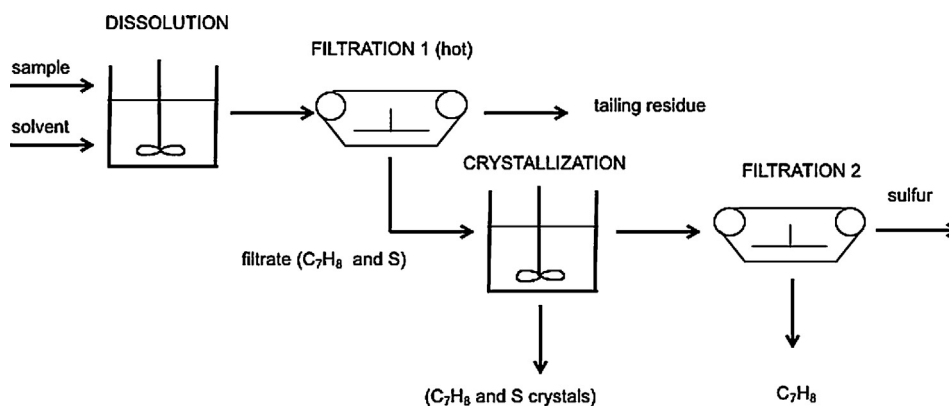


Fig. 2 – Sulfur recovery by dissolution-crystallization using toluene as solvent.

## 2.2. Dissolving flotation concentrate in carbon disulfide

The enormous advantage of carbon disulfide ( $\text{CS}_2$ ) with respect to toluene is the high solubility of sulfur in it (around 24 wt. %). No heating is needed in order to get good results. The whole procedure was developed at RT (20–24 °C). Fig. 3 shows the flow diagram of the process.

This is a three-stages process. At first,  $\text{CS}_2$  at RT is mixed with the residue, with the aim to dissolve the sulfur in the residue. Then, the solution is filtered in order to recover the dissolved sulfur. Since the adopted solvent was not able to dissolve all the sulfur in the initial solution, a new residue is left, containing a small part of sulfur and the rest of elements that were in the original sample. Finally, the filtrate is distilled to obtain elemental sulfur and to recycle the solvent,  $\text{CS}_2$ .

For the experimental work, five samples were used. The solution stage for the first four samples was carried out at RT, with pure carbon disulfide, and varying the mixing times (5, 10,

20 and 40 min, respectively). The solution of the fifth sample was obtained by mixing for 20 min, using the recycled  $\text{CS}_2$  from the first cases as solvent. All the solutions were mixed with a stirring velocity of 250 rpm.

Once the sulfur is extracted, by means of toluene or carbon disulfide, the recovered sulfur and the tailing residue were analyzed. The analysis is performed using ICP-MS, as well as XRD.

## 3. Results

The samples coming from the industrial plant were pulverized, dried and further characterized as detailed in [5]. The low sulfur content of the samples (around 60%) hinders the achievement of sulfur extraction.

The role of the samples stirring time has been analyzed for two different solvents, Toluene and  $\text{CS}_2$ , at different temperatures. Thus, in Fig. 4 the content of recovered sulfur (in percentage) is reported, as well as the ratio of the recovered

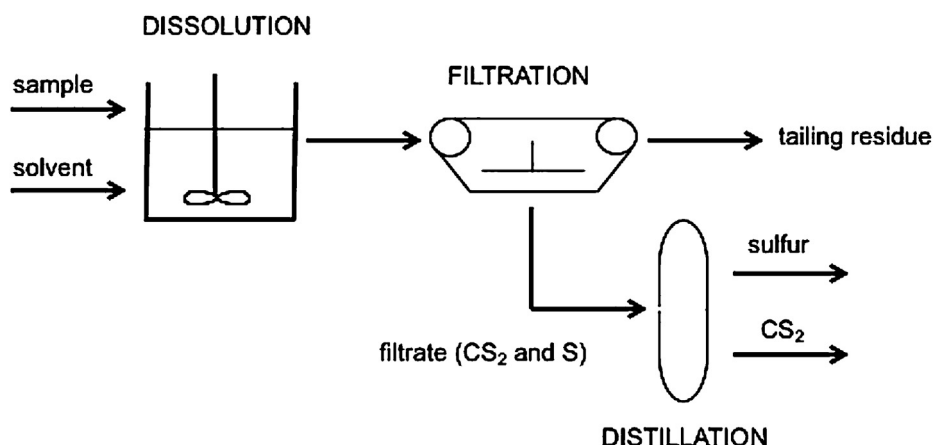


Fig. 3 – Sulfur recovery by dissolution-crystallization using carbon disulfide as solvent.

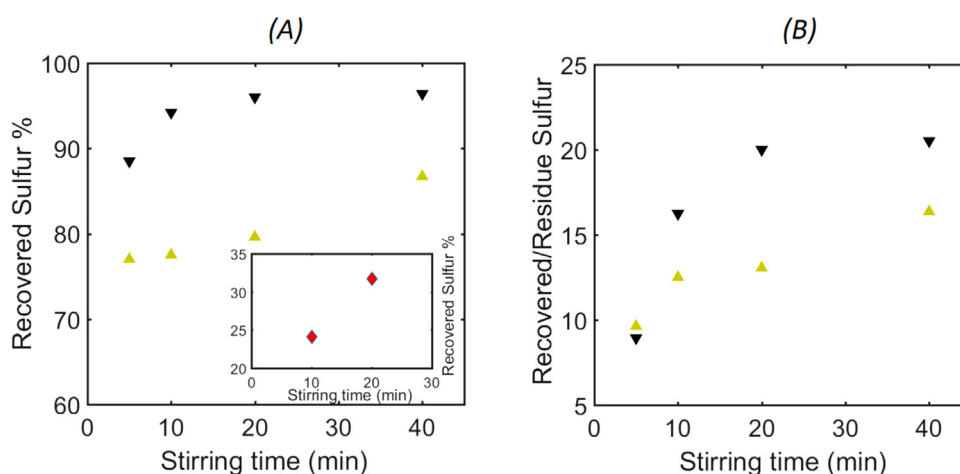


Fig. 4 – Percentage of recovered sulfur and ratio over sulfur in tailing residue as a function of stirring time for samples dissolved in  $C_7H_8$  at 100 °C (upwards green triangles) and 50 °C (inset: red diamonds) and samples dissolved in  $CS_2$  (downwards black triangles).

sulfur over the one in the tailing residue for four stirring times (5, 10, 20 and 40 min). For the case of the samples dissolved in toluene the results for two different temperatures are distinguished, at 100 °C (upwards green triangles) and 50 °C (inset figure: red diamonds). Due to the improvement of the recovered sulfur amount for the higher temperature case, in comparison with the sulfur content of the tailing residue, only two cases at low temperature were performed. The large amount of sulfur in the residue for the low temperature case, ranging between 47–58% for the evaluated stirring times taken into consideration, clearly remarks that not all sulfur in the sample has been dissolved. However, by just increasing the temperature to 100 °C the amount of recovered sulfur drastically increases, reaching values up to three times higher for a fixed stirred time. Thus, a temperature of 100 °C helps solubility and it is more effective to obtain up to 86.7% sulfur by stirring 40 min.

For the case of  $C_7H_8$ , a larger stirring period slightly improves the obtaining of sulfur.

In order to check the feasibility of using recycled toluene, a trial was performed at 100 °C for a 10-minute stirring time, resulting in 85.3% recovered sulfur and 20.47% remained in

the tailing residue. It does not provide a large improvement with respect to using new toluene. The slightly higher value of recovered sulfur with respect to the case of new  $C_7H_8$  can be explained if there is still some sulfur in the recycled toluene.

Fig. 4 also shows the case of  $CS_2$  as a solvent at RT. The amount of recovered sulfur with  $CS_2$ , for a fixed stirring time, is always higher than for toluene at 100 °C. This improvement in the results is also manifested in the ratio of recovered sulfur over the one in the tailing residue. Only for the 5-minute stirring period the use of  $CS_2$  is less effective than  $C_7H_8$  at high temperature. For larger stirring times, the  $CS_2$  as a solvent at room temperature can be up to 50% more successful than toluene at 100 °C. The larger the stirring time, the larger the amount of recovered sulfur, ranging from 88.5% to the highest level of 96.4%, as the amount of sulfur in the residue decreases from 9.9 to 4.7%.

A trial with recycled  $CS_2$  was also performed for a stirring time of 20 min, and a 92.7% of recovered sulfur and remaining 10.3% of sulfur in the residue was obtained. These results are close to the case of using new  $CS_2$ . The percentage of sulfur in the recovered sulfur and the residue suggest that a small amount of sulfur coming from de solvent ends in the products.

Additional experiments should be needed in order to check this.

### 3.1. Characterization of obtained sulfur and tailing residues

In the forthcoming subsections, the characterization of recovered sulfur and tailing residue is presented. The recovered sulfur contained traces of Fe, Pb, Zn, Cu, Ag, Hg and Se.

#### 3.1.1. Toluene

Fig. 5 shows the XRD patterns of the obtained sulfur and tailing residues by means of the  $C_7H_8$  solutions for the case of 100 °C and stirring times between 5 and 40 min. The two upper panels of the figure show the diffractogram of pure sulfur to be compared with the extracted sulfur and the tailing residue.

The left part of Fig. 5 shows (from top to bottom) the diffractograms of pure sulfur and the sulfur recovered with toluene at 100 °C with stirring times of 5, 10, 20 and 40 min, respectively. The highest intensity peak at  $2\theta = 23^\circ$ , corresponding to sulfur, appears in all cases. Although the XRD patterns are somewhat different, the obtained material is yellow and has the properties of sulfur, presenting a boiling point around 120 °C.

The right side of Fig. 5 shows the XRD patterns of the tailing residue left after the filtering process, below the commercial sulfur case. The height of the sulfur peak is very small, as it is expected from the sulfur content in the tailing residue from Fig. 4.

#### 3.1.2. Carbon disulfide

The XRD patterns of the obtained sulfur and the tailing residue left in the filtering process at RT using recycled  $CS_2$  are shown in Fig. 6. The XRD pattern for the pure laboratory sulfur appears in the upper part of the figure for comparison.

The extracted sulfur is very similar to the pure sulfur. The sulfur peak for the tailing residue has disappeared. Only peaks corresponding mainly to iron sulfides and lead sulfates remain.

According to the XRD patterns of the samples shown in [5], the sulfur concentrates coming from the Zn extraction industry contain Fe, Pb and Zn compounds. The XRD patterns of the tailing residue of both cases, i.e. using toluene or carbon disulfide as solvent, iron sulfide, sphalerite, lead sulfate and quartz are found to be the main components, in very similar amounts. The same analysis is performed in the XRD patterns of the obtained sulfur.

A chemical analysis was performed on the recovered sulfur to check for the presence of traces of other elements such as Fe, Pb, Zn, Cu, Ag, Hg and Se. The results related with these traces in Fig. 7 were normalized to those obtained with commercial laboratory sulfur, providing a useful information about the efficiency of the methods. Data corresponding to the solution of  $C_7H_8$  at 100 °C, stirred during 40 min and the solution using recycled  $C_7H_8$  are also compared. The most remarkable results are obtained for the sulfur obtained by means of the  $CS_2$  solution and the recycled  $CS_2$  solution. In this last method, the sample with the 96.4% of recovered sulfur (40 min stirring time) was considered for comparison. To compare our results with another methodology, data of the evaporation-

condensation procedure at 250 °C are shown in confront with a previously studied method that reported the highest amount of recovered sulfur [5].

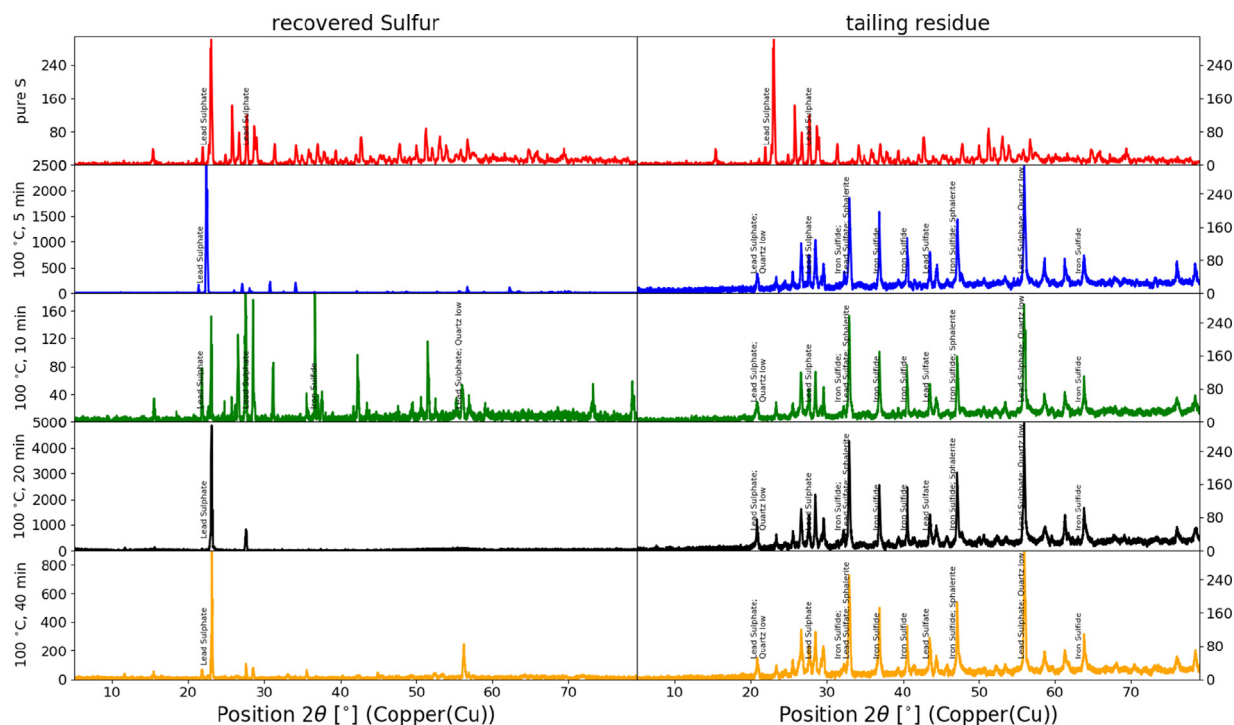
The concentration of Fe traces obtained by dissolving the sample drastically differs from those reported by the evaporation-condensation method [5]. While the former methodology exhibits traces below the commercial laboratory sulfur, the later shows an increase of about 200% in the amount recovered. We may also distinguish the results depending on the solvents case of study, being the Fe traces for the  $C_7H_8$  closer to those of the commercial sulfur, and for  $CS_2$ , both new and recycled, much lower. The concentration of Ag traces shows a particularly noteworthy improvement for the case of dissolving the sample with  $CS_2$ , being the only technique capable to reduce the traces in comparison with the commercial sulfur. By contrast, the evaporation-condensation method shows a somewhat higher amount of Ag, but still lower than the sulfur recovered with  $C_7H_8$ . The content of Pb and Cu traces look alike for the different solvents, being always orders of magnitude higher than those of the commercial sulfur. However, we may notice that the case of sulfur recovered by dissolving with  $C_7H_8$  exhibits the highest Pb and Cu concentration. These concentrations are even larger than the evaporation-condensation method, with similar results to the  $CS_2$  case. The Zn traces show, however, a dissimilar trend regarding the techniques. Thus, by dissolving with  $CS_2$ , both new and recycled, we recovered the largest amount of Zn, almost double with respect to dissolve with  $C_7H_8$ . The concentration of Hg improves by dissolving the sample with respect to evaporation-condensation technique. It is noticeable that only in the case of using recycled solutions, both  $CS_2$  and  $C_7H_8$ , the results are similar to the Hg traces in commercial sulfur. Lastly, the traces of Se for the  $CS_2$  method are close to the ones obtained in the evaporation-condensation method, but lower than in the sulfur extracted with the  $C_7H_8$  solution.

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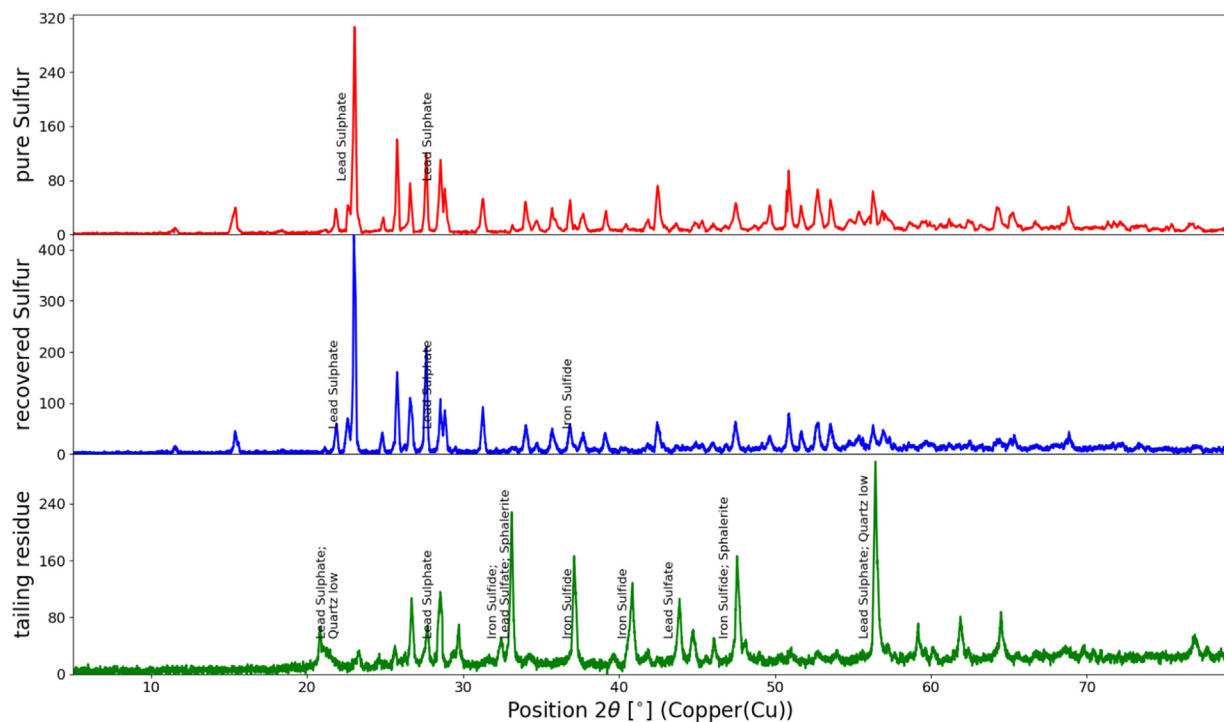
## 4. Discussion

In this work, sulfur is successfully recovered from sulfur content materials coming from the zinc extraction industry. This sulfur is not easily recovered in industry by the usual fusion and filtering method, due to their low sulfur content, and the remains may likely end up in industrial tips, being dangerous for the environment. The goal of this work is to find in the laboratory an effective way for the recovery of sulfur out of the low sulfur content residue (below 70%) from the zinc extraction industrial plants. This method could be further studied in order to check the feasibility of employing it at an industrial level.

The method used here is based in dissolving the samples with two different solutions. Two known good solvers of sulfur have been chosen [3,4] due to their high solubility at low temperatures. Satisfactory results are obtained, the method performing even better than the one in [5]. The evaporation-condensation method consists on the evaporation of sulfur out of the samples and its further condensation. This method requires a high energetic demand due to the need of heating the sample at 250 °C. The method employed here not only recovers a higher amount of sulfur, but also improves the qual-



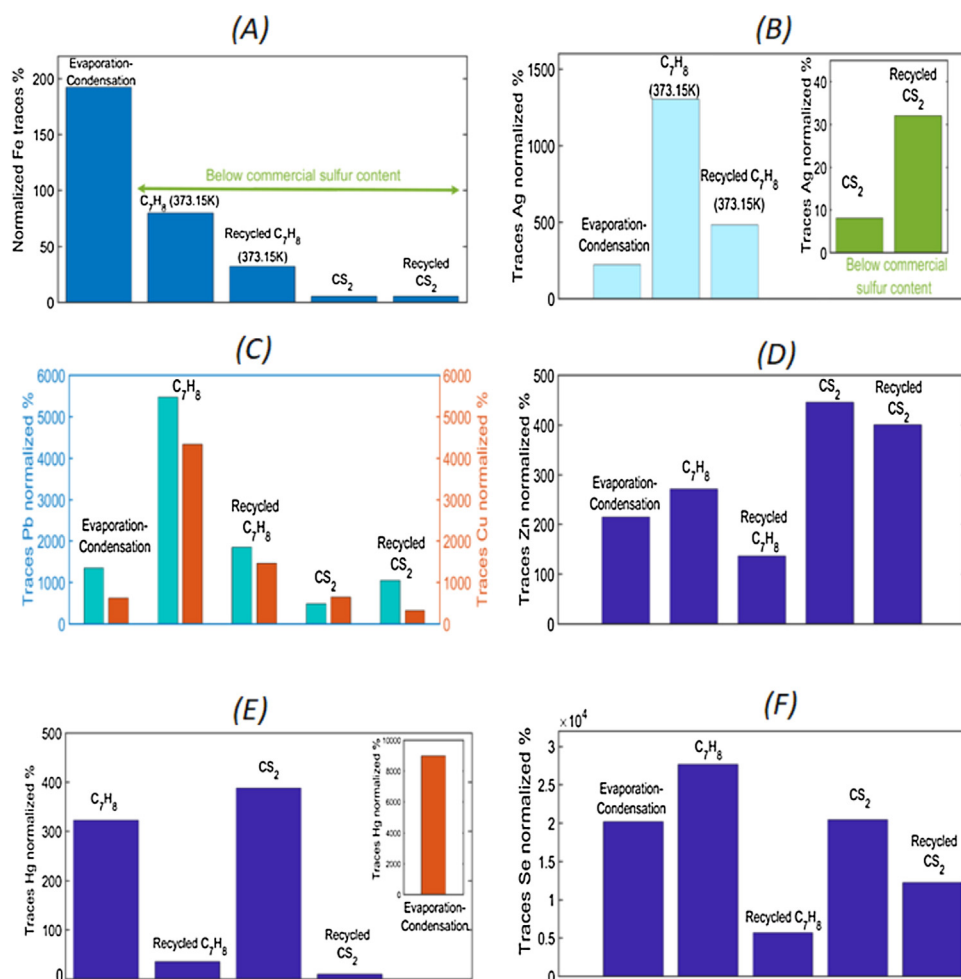
**Fig. 5 – X-ray diffraction patterns of commercial sulfur, recovered sulfur and the corresponding tailing residue after dissolution with toluene at 100 °C for 5, 10, 20 and 40 min.**



**Fig. 6 – X-ray diffraction patterns of commercial sulfur, recovered sulfur and the corresponding tailing residue after dissolution with recycled carbon disulfide for 20 min.**

ity and purity of the obtained sulfur. Using  $\text{CS}_2$  to solve the samples allow us to obtain up to 96.4% of Sulfur at RT. This largely improves the result of 64% recovered sulfur in the previous evaporation-condensation method [5]. This last case of

$\text{CS}_2$ , both for the new and recycled samples, shows a decrease in traces of other elements like Fe, Pb, Cu, Ag and Hg, compared to the commercial laboratory sulfur. The traces of Fe improve greatly, although it still contains similar traces of Zn and Se.



**Fig. 7 – Traces of different elements obtained via diverse methods of sulfur extraction. The data has been normalized by the traces concentration obtained in the commercial laboratory sulfur: [Fe] = 19.624 ppm, [Pb] = 0.085 ppm, [Zn] = 0.972 ppm, [Cu] = 0.103 ppm, [Ag] = 0.005 ppm, [Hg] = 0.105 ppm, [Se] = 0.043 ppm.**

The purity of the sulfur extracted using CS<sub>2</sub> is higher than the other cases, as it was proved in the XRD and traces analysis. The influence of the possible content of sulfur coming from the solvent in the case of CS<sub>2</sub> should be analyzed in a future work.

Another advantage of the procedure employed in this work is that both solvents are recovered after the sulfur extraction. Although catalogued as dangerous substances they can be recycled to be used again for sulfur extraction out of the leaching residue of zinc industry or in many other industrial applications.

The use of this method in industry could be further investigated, but according to the results obtained in our laboratory, it turns out to be a simple method for the recovery of sulfur, and its development for industry is expected to provide a higher efficiency in terms of recovered sulfur.

## 5. Conclusions

The proposed method of dissolving, filtering, crystallizing and filtering does not depend on the content of sulfur in the sample. Other methods, like melting and filtering,

require a large amount of sulfur in the sample to be successful.

The highest amount of extracted sulfur, 96.3%, is achieved with the method of dissolving the samples with CS<sub>2</sub>. Using recycled CS<sub>2</sub> does not improve the extraction of sulfur in this case; it decreases to 92.9% instead. The greatest advantage of this method is that no heating is required, so no additional energy, is needed.

The increase in stirring time enlarges the amount of recovered sulfur, but the possible gain is not worth the effort.

The X-ray diffractograms show that the product obtained with the process described in this work is sulfur, and the chemical analysis illustrates its purity. In particular, a better purity of extracted sulfur is achieved when dissolving the initial sample with CS<sub>2</sub>, both with new or recycled CS<sub>2</sub> solvent.

In conclusion, the use of CS<sub>2</sub>, both new and recycled, has been proven to be a very effective way of extracting the remaining sulfur in industrial waste.

## Conflicts of interest

The authors declare no conflicts of interest.

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## REFERENCES

- [1] Halfyard JE, Hawboldt K. *Hydrometallurgy* 2011;109:80–9.
- [2] Carrasco RM. Process for dissolving sulfur ore using diaryl disulfide, US7635460B2; 2009.
- [3] Wermink WN, Spinu D, Versteeg GF. *J. Natural Gas Eng* 2018;2:71–95.
- [4] Meyer B, Austin JM, Jensen D. *J.Chem. Eng. Data* 1971;16:364.
- [5] Suárez-Gómez S, Sánchez ML, Blanco F, Ayala J, de Cos Juez FJ. *J. Hazard. Mater* 2017;336:168–73, <http://doi.org/10.1016/j.jhazmat.2017.04.051>.
- [6] Zi-yang WANG, Xiao-lan CAI, Ze-biao ZHANG, Li-bo ZHANG, Shi-xing WANG, Jin-hui PENG. *Trans. Nonferrous Met. Soc. China* 2015;25:640–6.
- [7] Li H, Wu X, Wang M, Wang J, Wu S, Yao X, et al. *Sep Purif Technol* 2014;138:41–6.
- [8] Fabri Jörg, Graeser Ulrich, Simo Thomas A. Toluene. In: *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH; 2005.
- [9] Braunscheidel KM, Gass JT, Mulholland PJ, Floresco SB, Woodward JJ. Persistent cognitive and morphological alterations induced by repeated exposure of adolescent rats to the abused inhalant toluene. *Neurobiol Learn Mem* 2017;144:136–46.
- [10] Shih Hsu-Tzu, Chin-Lin Yu, Ming-Tsang Wu, Liu Chiu-Shong, Tsai Chon-Haw, Hung Dong-Zong, et al. Subclinical abnormalities in workers with continuous low-level toluene exposure. *Toxicol Ind Health* 2017;27(8):691–9.
- [11] Aguilera F, Méndez J, Pásaro E, Laffon B. Review on the effects of exposure to spilled oils on human health. *J Appl Toxicol* 2010;30:291–301.
- [12] Lovley DR, Lonergan DJ. Anaerobic oxidation of toluene, phenol, and p-cresol by the dissimilatory iron-reducing organism, GS-15. *Appl Environ Microbiol* 1990;56:1858–64.
- [13] Alvarez PJ, Vogel TM. Substrate interactions of benzene, toluene, and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries. *Appl Environ Microbiol* 1991;57:2981–5.
- [14] Lay Manchiu DS, Sauerhoff Mitchell W, Saunders Donald R. Carbon disulfide. In: *Ullmann's encyclopedia of industrial chemistry*. Weinheim: Wiley-VCH; 2000.
- [15] Park Tae-Jin, Banerjee Sarbajit, Hemraj-Benny Tirandai, Wong Stanislaus S. Purification strategies and purity visualization techniques for single-walled carbon nanotubes. *J Mater Chem* 2006;16(2):141–54.
- [16] Worthing Charles R, Hance Raymond J. *The pesticide manual, a world compendium*. 9th ed. British Crop Protection Council. ISBN; 1991, 9780948404429.
- [17] Schramm A, Uter W, Brandt M, Goen T, Kohrmann M, Baumeister T, et al. Increased intima-media thickness in rayon workers after long-term exposure to carbon disulfide. *Int Arch Occup Environ Health* 2016;89:513–9.
- [18] Martino Anthony WDe, Zigler David F, Fukuto Jon M, Peter C. Carbon disulfide. Just toxic or also bioregulatory and/or therapeutic? *Chem Soc Rev* 2020;46:21–39.
- [19] Hartel PG, Haines BL. Effects of potential plant CS<sub>2</sub> emissions on bacterial growth in the rhizosphere. *Soil Biol Biochem* 1992;24:219–24.
- [20] Canessa EF, Morrell JJ. Effect of mixtures of carbon disulfide and methylisothiocyanate on survival of wood-colonizing fungi. *Wood fiber Sci* 2007;27:207–24.