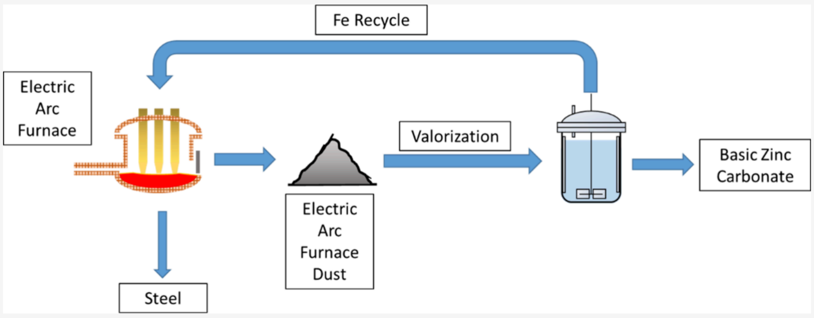
JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc | Laboratory Experiment

From a Hazardous Waste to a Commercial Product: Learning Circular Economy in the Chemistry Lab

Nieves Iglesias-Gonzalez,* Pablo Ramírez, and Juan Lorenzo-Tallafigo

Cite This: *J. Chem. Educ.* 2024, 101, 3485−3492 | Read Online



ABSTRACT: We are currently facing a change in the production model, moving from the traditional linear model to a model based on circular economy. This new paradigm implies minimization of waste. In this context, this work presents a laboratory practice focused on introducing the concept of circular economy and waste valorization to undergraduate students. The experimental procedure is a simpler adaptation of earlier work by the research group in which metals were recovered from electric arc furnace dust (EAFD) and it is composed of four stages: acid leaching to dissolve the zinc, selective precipitation to eliminate dissolved iron, cementation to recover metals more noble than zinc, and finally obtaining basic zinc carbonate by precipitation. In this way, students can convert a residue into a valuable product while cleaning it, so that it can be reintroduced into the steel-producing process. Fourth year students of the Materials Engineering Degree at the University of Seville (Spain) have successfully performed this laboratory experiment since the 2015−16 academic year. In addition, to evaluate the achievement of the pedagogical objectives, pre- and postlaboratory questionnaires have been carried out in the past two academic years showing that more than 75% of the students improve their answers after performing the laboratory practices.

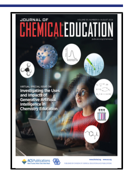
KEYWORDS: *circular economy, waste, valorization, recycling, metals, leaching, solubility, precipitation, cementation, upper-division undergraduate, waste management, material engineering degree*

■ INTRODUCTION

One of the greatest challenges confronting contemporary society is balancing economic and social development with respect to and preservation of natural resources. It is estimated that to sustain our current way of life for the projected population by midcentury, we would require natural resources equivalent to three times the current amount on our planet. In response to this pressing issue, initiatives from leading international organizations have emerged, setting forth guidelines for achieving sustainable development.[1] Within these initiatives, the development of a circular economy emerges as a fundamental paradigm. This concept is rooted in the fundamental idea that in the initial stages of any production process, consideration should be given to how the resources used can remain within the production cycle, minimizing losses through reuse, repair, and recycling. Therefore, the minimization of generated waste is crucial for any production process. The circular economy is designed especially with the purpose of minimizing waste in mind, hence the need for good waste management. Materials in a circular economy are not a disposable commodity, but a valuable asset that must be tracked and preserved for reuse.[2] This means that reuse takes priority over recyclability, and good management ensures that materials are reused sufficiently and effectively before reaching the recycling point. However, materials cannot always be reused since after use they lose their properties or are contaminated and are no longer useful. In this case, we are faced with waste that, however, may contain valuable components and that we must recover.

The advancement of such processes represents the primary objective of the sustainable chemistry field, which emphasizes

Received: May 2, 2024
Revised: July 10, 2024
Accepted: July 12, 2024
Published: July 30, 2024



the concepts of reuse and recycling.[3] The significance of this field is evident through the growing inclusion of courses and subjects within academic curricula.[4]

Waste valorization is presented as a fundamental part of learning and implementing sustainable processes based on the circular economy. Thus, in recent years, a large number of papers have been published describing laboratory activities to acquire skills and knowledge in this field. For example, laboratory activities have been developed for the valorization of electronic waste.[5,6] Also, laboratory activities have been proposed for the recycling of waste from the food industry and waste from biomass[7−9] and plastic recycling.[5] In all of these works, the importance of the scientific and technical knowledge that students acquire in their academic training for the implementation of processes based on the concepts of circular economy in accordance with the principles of sustainable development is evident.

This work presents a laboratory practice carried out with university students with the fundamental objective of introducing the concept of the circular economy. To do this, a simplified adaptation of a recycling process developed by the teachers is carried out.[10] The aim is to awaken interest in research in students and show them how waste can be treated to use it in the production cycle, which leads to better use of natural resources and protection of the environment.

Specifically, waste that is generated during steel production and contains heavy metals will be studied, which is dangerous and cannot be reused. Through treatment, some of its components are transformed into commercial products and iron is cleaned and recirculated to produce more steel.

In the steel production process from the fusion of iron scrap in electric arc furnaces, dangerous waste is generated because, under the temperature conditions of the furnace, some components of the scrap, such as Fe, Zn, Cd, and Pb, volatilize, passing into the vapor phase, which subsequently cools and condenses, generating a solid residue known as electric arc furnace dust (EAFD).

EAFD is a very fine-grained material whose main characteristic is the high content of heavy metals in the form of oxides. This characteristic makes it a dangerous waste. EAFD appears in the *European List of Wastes* (LoW) coded as hazardous waste (10 02 07*) and in the Industry and EPA Hazardous waste (No K061) coded as toxic waste (T). Table 1 shows the typical composition of EAFD (data provided by the company that supplied the sample). It is worth highlighting the high Zn content, normally between 25 and 30%. It is paradoxical that primary ores of this metal are being processed with grades around 3%, when this material exceeds 25%.[10]

Table 1. Composition of Electric Arc Furnace Dust

Fe (%)	Zn (%)	Pb (%)	Al (%)	Mn (%)	Mg (%)	Na (%)
24.0	28.5	1.5	0.6	2.9	1.7	4.16
K (%)	Cu (%)	Cr (%)	Cl^- (%)	CO_3^{2-} (%)	SO_4^{2-} (%)	Ca (%)
1.2	0.4	0.2	2.9	9.0	1.5	2.9

Sometimes, EAFD is not treated but is stored in hazardous waste landfills (Figure 1).

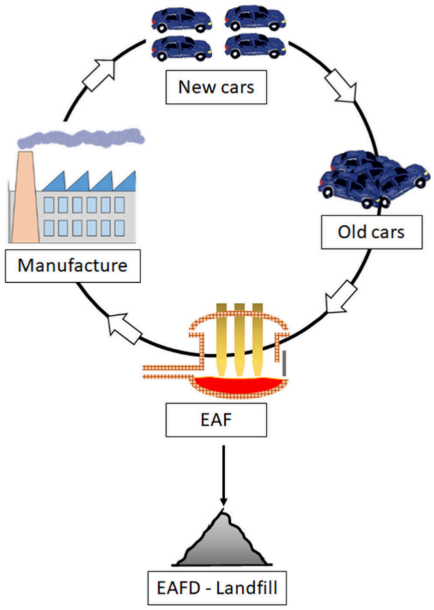


Figure 1. Schematic diagram of the reuse of steel from the automotive industry using an electric arc furnace with generation of electric arc dust as waste.

An alternative, consistent with the circular economy, is the valorization of its Zn content (Figure 2). About 80% of the EAFD is recycled through pyrometallurgical methods, through treatment with a Waeltz furnace, this being the most used process. These furnaces have plant capacities of 50,000 t/year and can process EAFD with a zinc content between 15 and 20%.[11] However, this method has several drawbacks, such as high investment and operating cost and the need to transport the waste to the treatment site, which makes the process more expensive and less efficient.[12]

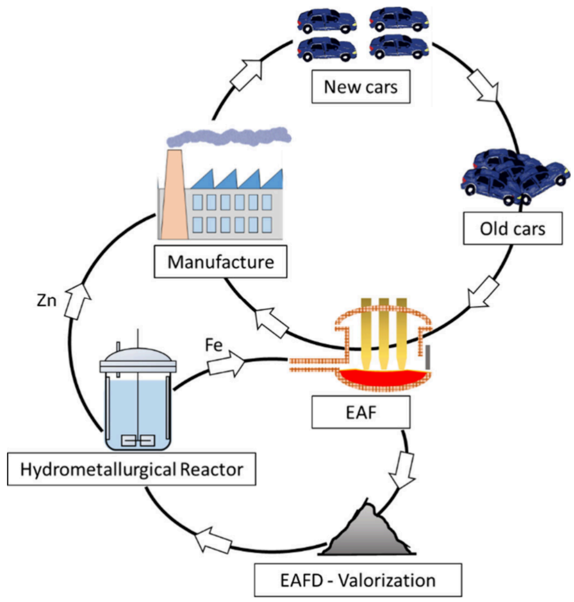


Figure 2. Schematic diagram of the reuse of steel from the automotive industry using the electric arc furnace with electric arc furnace dust valorization.

Hydrometallurgical processes have important advantages, such as the ability to adapt to smaller production scales, low energy consumption, high solubility of zinc in different lixiviants, and lower initial investment and operating costs.

EAFD has also been used in civil construction or as filler in acoustic or thermal insulators,[13] but it would be downcycling since these applications do not take advantage of the high value of the metals it contains.

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492

This laboratory practice has been carried out with students of the subject "Waste Management" in the Degree in Materials Engineering at the University of Seville for the significant learning of one of the key concepts within the circular economy, such as recycling, since the 2015−16 academic year.

The objective of this work is to present the results of the implementation of this teaching experience during the 2022−23 and 2023−24 academic years and measure its impact on the achievement of the teaching objectives.

AUDIENCE

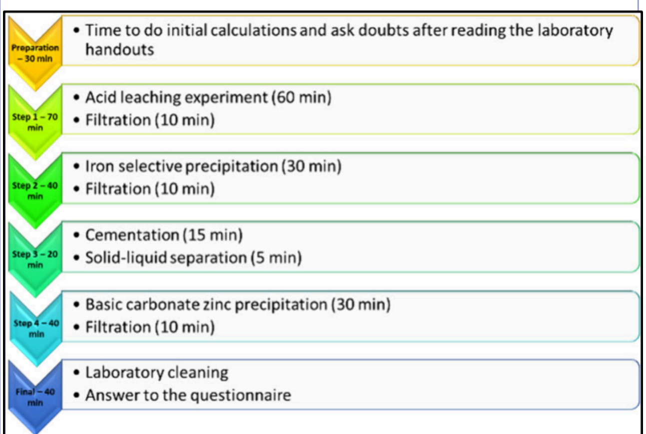
This laboratory exercise has been designed for fourth-year students of the Materials Engineering degree and is suitable for upper-undergraduates in Chemistry, Physics or Environmental Sciences. Also, there is potential for this experiment to be used earlier in the Chemistry curriculum, since it is based on basic concepts such as redox reactions or precipitation equilibria, and the procedures are simple. The experimental procedure is divided into four well-defined stages that can be easily separated and carried out in a single session, as is the case described, or in several sessions to be able to explain in more detail each of the basic reactions of each stage to students of lower grades.

EXPERIMENTAL SECTION

The exercise has been conducted uninterruptedly since the 2015−16 academic year. The total number of students, which ranges between 35 and 40 every year, is divided into smaller groups (8−12) for practical classes. In the laboratory, four practices are taught simultaneously, and each practice is carried out by a pair (sometimes a trio) of students. Prior to the session, the student has a detailed student handout (see the Supporting Information) where the theoretical foundation and the experimental procedure are described. Before the experiment was started, time is left to resolve any doubts that may have arisen after a comprehensive reading of the handouts.

The laboratory sessions are 4 h long, and during this time the pair of students completes the four stages of the experimental procedure. The laboratory timeline is detailed in Box 1.

Box 1. Laboratory timeline



The experimental objective of this practice is to separate zinc contained in a sample of an industrial waste to convert it into pure basic zinc carbonate. To do this, a process consisting of four stages is carried out, namely: (1) leaching with sulfuric acid, (2) iron precipitation, (3) cementation of divalent cations with zinc metal, and (4) basic Zn carbonate precipitation.

1. Leaching with Sulfuric Acid

Leaching is widely used in metallurgical processes to recover metals from ores. It is also used for recovery of metals from solid residues such as EAFD, fly ash, or electronic waste. It is a more environmentally friendly process than most used pyrometallurgy.

In the leaching stage, sulfuric acid reacts with zinc oxide contained in the residue, generating a Zn sulfate solution. In this way, we managed to extract the Zn from the residue.

This stage consists of acid leaching in which the pH is kept constant by adding sulfuric acid with the objective of dissolving zinc, according to reaction 1. Other metals such as iron, aluminum, copper, manganese or cadmium are dissolved from EAFD. Lead oxide (PbO) is transformed into lead sulfate ($PbSO_4$), which remains in the solid residue.

$$ZnO + H_2SO_4 \rightarrow ZnSO_4 + H_2O \quad (1)$$

In these tests, sulfuric acid must be continuously added to maintain the target pH.

The acid leaching of zinc presents fast kinetics and an important dependence of pH. In laboratory practices, the pH can be selected in the range 1.5−3.0, in order to reach high zinc dissolution yields. Additionally, each group of students can test a pH value in this range and compare the different results obtained. Students add 5 M sulfuric acid to the solution every 5 min to maintain the pH constant. When the pH does not vary with respect to time, it is considered that the reaction has ended. At least 30 min are recommended to ensure the maximum level of zinc dissolution.

After leaching, we filtered to separate the solid residue from the solution that contains the Zn and other components that have been dissolved.

2. Iron Precipitation

The solution from acid leaching contains a mixture of different metal cations, such as zinc, iron, copper, manganese, etc. In this second stage of the procedure, selective precipitation will be carried out. This is a process in which the solubility of a mixture of ions of the same sign in solution can be modified by the addition of a reagent that dissociates in water, giving an ion of the opposite sign to form insoluble compounds (precipitates) with the ions of interest. In this case sodium hydroxide will be used as reagent to add hydroxide anions into solution that form metal hydroxides which precipitates as a function of solution pH. This is shown in Figure 3 where it is shown the solubility of the different metals (Me) in solution as a function of pH. This solubility curve has been determined for the reactions (reaction 2), with the solubility values given elsewhere.[14]

$$Me(OH)_n \rightarrow Me^{n+} + nOH^- \quad (2)$$

It is seen that $Fe(OH)_3$ precipitates at pH values lower than those of the rest of the dissolved metals. However, the Fe(2+) curve overlaps with the curve for Zn(2+).

This means that to separate iron from the rest of the metals it must be in its oxidized state. If we guarantee that all of the iron in the system is a ferric ion, we can precipitate it by the controlled addition of hydroxide. This is the case of EAFD, because the iron leaves the furnace completely oxidized; therefore, only iron(III) will remain in solution, and fractional

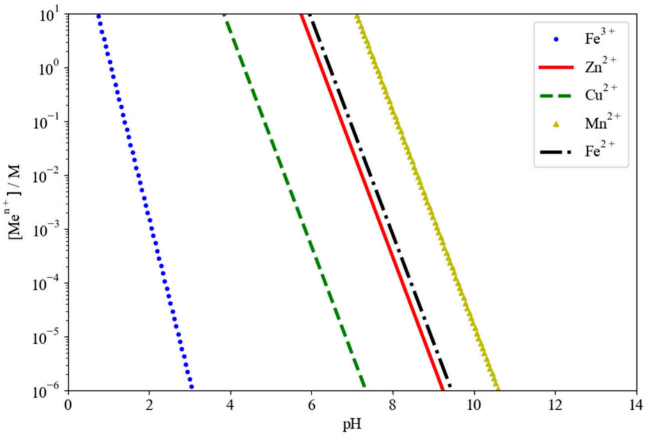


Figure 3. Solubility versus pH curves for metal hydroxides are indicated in the legend.

precipitation can be carried out. According to Figure 3 a pH value of 5 assures the complete precipitation of Fe(III).

After the precipitation step, the generated pulp is filtered, and the liquor is collected for the next steps. Before filtration, flocculation of the precipitate is recommended.

3. Cementation with Zinc Metal

Other metals, such as Cu^{2+}, Ni^{2+}, Cd^{2+} and Mn^{2+} remain in solution after Fe precipitation. These metals will contaminate the final zinc product ($ZnCO_3{\cdot}2Zn(OH)_2{\cdot}H_2O$) and decrease its quality and value. Metals with a higher reduction potential than Zn can be removed by cementation. This is a redox process where metallic cations more noble than zinc are reduced to their elemental state on the zinc surface, forming a crust or cement, while the zinc oxidizes and goes into solution. Cementation can be expressed according to redox half-reactions that takes place:

$$Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^- \quad (3)$$

$$Me^{2+}_{(aq)} + 2e^- \rightarrow Me_{(s)} \quad (4)$$

where Me stands for any of the divalent metals (Cu^{2+}, Ni^{2+} or Cd^{2+}).

Metallic Zn is used as a cementing agent instead of other suitable metals such as iron because it is not an impurity and will be recovered in the final product. As shown in Figure 4, cementation exhibits a fast kinetics that could be monitored by copper, nickel and cadmium measurement by Atomic Absorption Spectrophotometry (AAS), if it is not possible the assay can be run during 15 min to ensure the maximum yield without additional analyses (see Figure 4). As a result, a solution rich in zinc sulfate contaminated with traces of Mn^{2+} and a metal cement composed of Cu, Ni and Cd will be obtained.

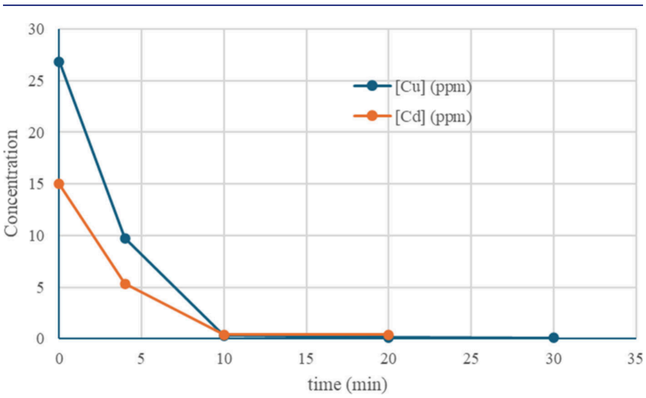


Figure 4. Evolution of the Cu and Cd concentrations during the cementation stage.

4. Basic Zn Carbonate Precipitation

The final product is prepared by treating the solution of zinc sulfate with 1 M sodium carbonate at 70 °C to promote the selective precipitation of basic zinc carbonate, according to reaction 5. In this step, pH control is essential to minimize manganese precipitation; for that reason, the precipitation is stopped when reaching a pH value of 7. At this pH value Mn(2+) remains in solution as shown in the solubility versus pH curve in Figure 3.

$$3ZnSO_4 + 3Na_2CO_3 + 3H_2O \rightarrow ZnCO_3{\cdot}2Zn(OH)_2{\cdot}H_2O + 2CO_2 + 3Na_2SO_4 \quad (5)$$

The solid is filtered, dried in an oven, and weighed to calculate the performance of the process.

During the experimentation, there is a fluid dialogue between teacher and student. Every time the students obtain a compound, they are asked about its status as a product, byproduct, or residue. Students must justify their answers and give treatment options for waste and use for products and byproducts.

The chemical reagents required are 5 M sulfuric acid, 1 M NaOH, zinc metal pellets, and 1 M Na_2CO_3, plus a sample of EAFD. Optionally, a flocculant can be used. High-molecular-weight polyacrylamide is recommended.

The necessary laboratory material consists of magnetic stirrers, pH meter, vacuum filtration equipment, balance, 250 mL Erlenmeyer flasks, beakers, and pipettes.

The experimental procedure is exhaustively detailed in the protocol that is given to the student before starting the laboratory exercise and is included in the Supporting Information.

■ HAZARDS

EAFD is an environmentally hazardous waste that is not available to any teacher who wants to replicate this laboratory experience. For this reason, it is proposed to make synthetic waste from the typical composition (Table 1) with commercial reagents commonly used in the laboratory. Table 2 indicates the quantities of reagents necessary to prepare 10 g of synthetic powder. Note that to reduce the hazard, no lead has been included in the synthetic sample composition.

Whether the original waste or the prepared synthetic is used, the solid must be handled with caution to avoid contact with the skin, eyes and mouth or inhalation. To this end, students will use personal protective equipment (PPE): laboratory coat, mask, glasses, and gloves.

■ RESULTS AND DISCUSSION

In order to guide the students in the presentation of the results, they are asked some questions that they must answer and deliver to the teacher for evaluation. The answer to these questions is presented below.

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492

Table 2. Composition of 10 g of Synthetic EAFD

Reagent	Fe_2O_3	$Fe_2(SO_4)_3$	ZnO	SiO_2	Na_2CO_3	CuO	NaCl	$CaCO_3$
Weight (g)	3.00	0.90	3.55	0.50	0.50	0.05	0.50	1.00

Question 1: Plot the acid consumption versus the leaching time of the EAFD. Explain the result obtained and calculate the sulfuric acid consumed as a function of the leached EAFD expressed as kg of acid/t of EAFD.

This question is related to zinc leaching. On the one hand, a graphical representation of sulfuric acid consumption versus time, whose interpretation reveals the evolution of leaching, is requested. On the other hand, the consumption of acid during the leaching of zinc is asked since the consumption of reagents is a critical issue when evaluating the sustainability of the process.

For the leaching test, 1.5 g of residue and 100 mL of acid solution at the target pH have been placed in an Erlenmeyer flask, and once the stirring begins, the test starts (time = 0). Every 5 min, the pH is measured, and 5 M sulfuric acid is added until the target pH is reached, and the added acid is represented against time. The added acid is the one that has been consumed in the leaching reaction (reaction 1) and gives an idea of the amount of zinc that has gone into the solution. When the pH remains constant and it is not necessary to add more acid, then the leaching reaction is complete. As an example, Figure 5 shows the consumption of sulfuric acid versus time for a target pH of 1.5.

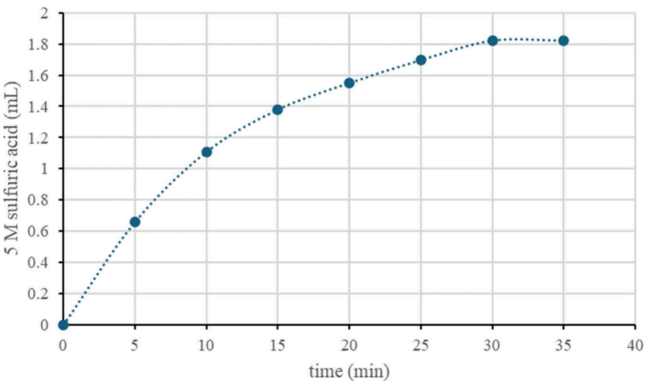


Figure 5. Acid consumption versus time for a target pH = 1.5.

It can be observed how acid consumption decreases over time until it becomes constant after 30 min. It can be considered that at this pH reaction 1 has finished. In this case (pH = 1.5) a total of 1.82 mL of 5 M H_2SO_4 have been consumed for 1.5 g of sample, which is equivalent to 594 kgH_2SO_4/t EAFD. At pH higher than 1.5, the reaction is slower, and acid consumption is lower since fewer species are solubilized. In all cases, an initial rapid leaching rate followed by a decrease in rate is observed.

After acid leaching, the pulp must be filtered, collecting a solution rich in zinc sulfate.

Question 2: Plot the pH versus the mass of NaOH added for iron precipitation. Explain the result obtained and calculate the NaOH consumption expressed as kg of NaOH/tons of EAFD.

This question is about iron precipitation and asks for the interpretation of the graphic representation of pH as a function of the mass of NaOH added for iron precipitation and the calculation of NaOH consumption per ton of waste.

The iron that has been dissolved along with zinc in the acid leaching is eliminated by precipitation with sodium hydroxide at pH 5. To do this, a 1 M NaOH solution is added drop by drop to the filtrate from the leaching process until pH 5 is reached. It is requested that the pH and the mass of solution added be noted, and the precipitation course is followed by pH measurement. Figure 6 shows the NaOH consumption as a function of pH. At pH close to 3 a plateau is observed due to the Fe precipitation, which consumes the added alkali. Once all iron is precipitated, a rapid pH increase is observed. The rapid increase in pH indicates that there is no longer consumption of OH^- ions for the precipitation of iron (reaction 2), and therefore, the pH increases with the addition of NaOH.

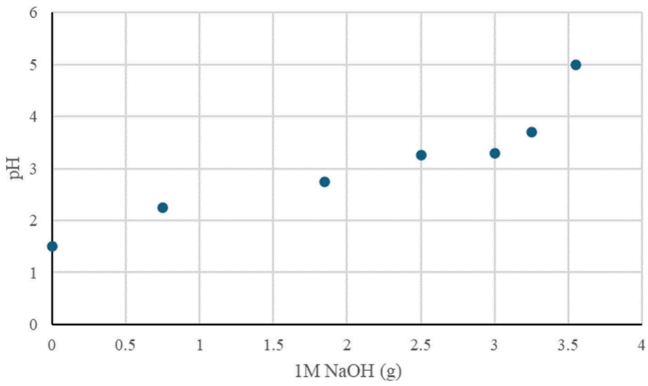


Figure 6. 1 M NaOH consumption as a function of pH in the Fe precipitation step.

In total, 3.55 g of 1 M NaOH (density 1.04) were needed to reach pH 5, which represents a consumption of 90 kg of NaOH/t EAFD.

Question 3: Explain briefly what the fundamental aspects of cementation are and why is it applied after the iron precipitation?

This question is about the rationale for cementation and why it is applied after precipitation. To remove other impurities from the solution such as Cu and Cd, cementation is performed. Cementation is a redox process in which a metal in solution displaces another less noble metal in the solid state. Copper, which has a higher reduction potential than zinc (Table 3), will be reduced to metallic Cu and the Zn will be

Table 3. Standard Reduction Potentials

Half-reaction	$\Delta\varepsilon°$ (V)
$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.77
$Cu^{2+} + 2e^- \rightarrow Cu$	+0.16
$Ni^{2+} + 2e^- \rightarrow Ni$	−0.25
$Cd^{2+} + 2e^- \rightarrow Cd$	−0.40
$Zn^{2+} + 2e^- \rightarrow Zn$	−0.76
$Mn^{2+} + 2e^- \rightarrow Mn$	−1.18

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492

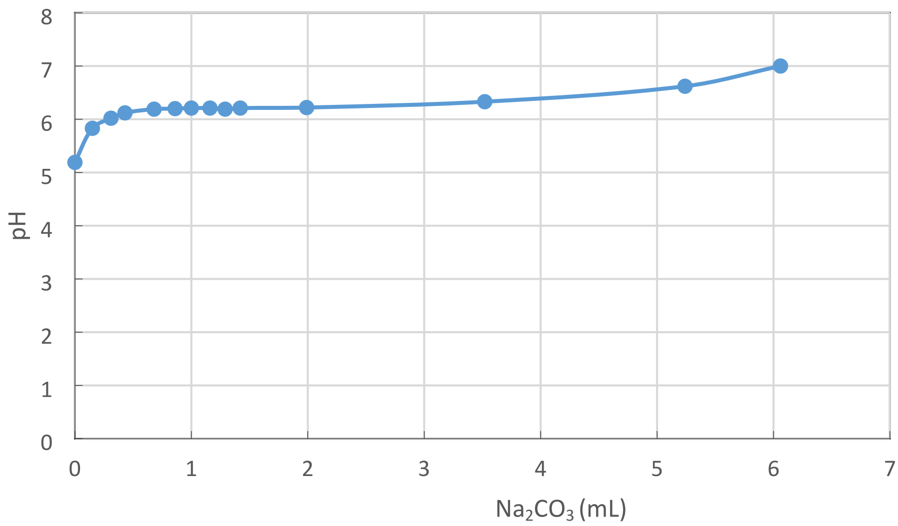


Figure 7. pH evolution due to 1 M sodium carbonate addition.

oxidized into solution. According to the standard reduction potentials ($\Delta\varepsilon°$) shown in Table 3, other metals more noble than Zn such as Cd and Ni will also cement. The result is a cement containing Cu, Cd, Ni and Zn, and a Zn solution clean of impurities. Zinc has been wisely chosen as the cementing agent since its dissolution does not introduce any impurity to the final product.

Cementation is after iron precipitation because Fe(III) that has a potential of 0.77 V would oxidize the zinc powder (−0.76 V) and be reduced to Fe(II) according to reaction 6, and therefore selective precipitation could not be carried out after cementation (see Figure 3).

$$2Fe^{3+} + Zn \rightarrow 2Fe^{2+} + Zn^{2+} \quad (6)$$

Question 4: Plot the pH versus the mass of sodium carbonate added during the precipitation of basic zinc carbonate. Explain the result obtained and calculate the consumption of Na_2CO_3 expressed as kg of Na_2CO_3/t of EAFD.

Finally, the solution free of impurities is precipitated with sodium carbonate to obtain basic Zn carbonate, and the graphic representation of pH as a function of the mass of carbonate added is requested to be interpreted and to calculate sodium carbonate consumption. Figure 7 shows the evolution of pH as 1 M sodium carbonate is added. It can be seen how the pH remains constant in the carbonate precipitation range and begins to rise slightly from pH 5. At pH 7 zinc carbonate ($ZnCO_3{\cdot}2Zn(OH)_2{\cdot}H_2O$) is precipitated.

Question 5: Calculate the Zn recovery yield.

The last question asks about the performance of the process for obtaining basic zinc carbonate from EAFD.

The theoretical yield, that is, the maximum yield that can be obtained from the reactions if they go to completion, is calculated as follows:

$$\%Zn_{EADF}\ g_{EADF} \frac{1\text{ mol Zn}}{65.37\text{ g Zn}} \frac{1\text{ mol ZnSO}_4}{1\text{ mol Zn}} \frac{1\text{ mol basic zinc carbonate}}{3\text{ mol ZnSO}_4} = 0.285 \times 1.5 \times \frac{324.24\text{ g}}{65.37 \times 3} = 0.75\text{ g basic zinc carbonate}$$

The percentage yield gives the efficiency of the process and calculated as

$$\text{Percentage yield} = \frac{\text{actual yield}}{\text{theoretical yield}} 100$$

A typical and acceptable result is to obtain a mass of 0.46 g of basic zinc carbonate; therefore, a correct result will be a percentage yield of 61.3% (0.46/0.75 × 100).

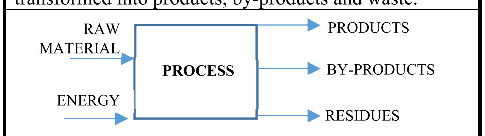
■ LEARNING ASSESSMENT

To evaluate the improvement of the learning process and the achievement of pedagogical objectives, pre- and postlab quizzes were carried out.

A questionnaire about the key concepts and objects of this activity was designed. The questionnaire, whose content is presented in Box 2, consists of 4 questions, each of which was

Box 2. Questionnaire to evaluate student learning

In a production process, raw materials and energy are transformed into products, by-products and waste.



1. Define product, by-product, and residue.
2. What is done with each of them?
3. Similarities and differences between byproducts and residues.
4. As this process is described, does it contribute to the circular economy? If the answer is yes, please state how. If not, what modifications would you include so that if it contributed.

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492

Table 4. Example of the Responses of a Random Student to the Pre- And Postquiz

Question	Answer 09/14/2022	Answer 11/03/2022
1 Product	Result of a process that generates economic benefit.	Result and objective of the production process. Subject to a legal framework.
1 Byproduct	Elements from the production process that have the potential to generate an economic benefit.	Result of the production process that is not the main objective. It must be able to be marketed without the need for treatment outside the normal industrial process.
1 Residue	Of the productive process is that which does not generate any economic value.	Object or substance that its possessor gets rid of or has the obligation or intention to get rid of.
2 What is done with each of them?	Product: sold.	Product and by product are marketed.
	Byproduct is processed and sold.	Waste must be treated according to the hierarchy.
	Waste: according to the law it must be treated in certain ways or simply abandoned.	First you should try to avoid their production, then reuse them, then recycle them and as a last option eliminate them.
3 Similarities	Product and byproduct generate profit and are the objective of the production process.	They are all results of a productive process. They are regulated by a legal framework.
3 Differences	The waste cannot be used by humans.	The waste has no market and must be disposed of.
4 As this process is described, does it contribute to the circular economy? If the answer is yes, please state how. If not, what modifications would you include so that if it contributed.	No, it does not contribute to the circular economy.	It does not contribute unless the waste can be recovered or recycled. Some modifications to achieve the circular economy are eco-design, for example. From the design of the product, we seek to avoid waste and facilitate its management.
	Waste is the end of the production chain. A step is necessary that allows waste to be transformed into raw materials or energy. Likewise, at the end of their useful life, the products must be recycled.	

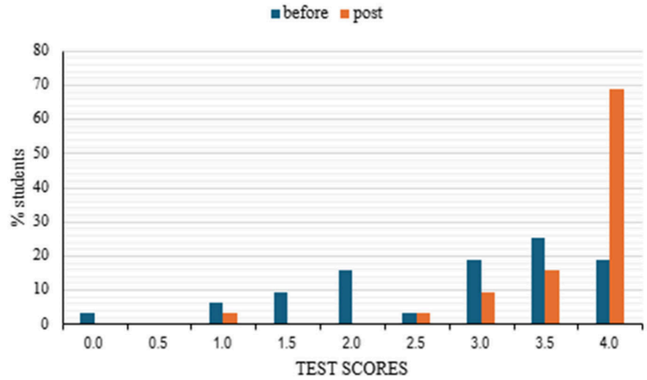


Figure 8. Scores of students.

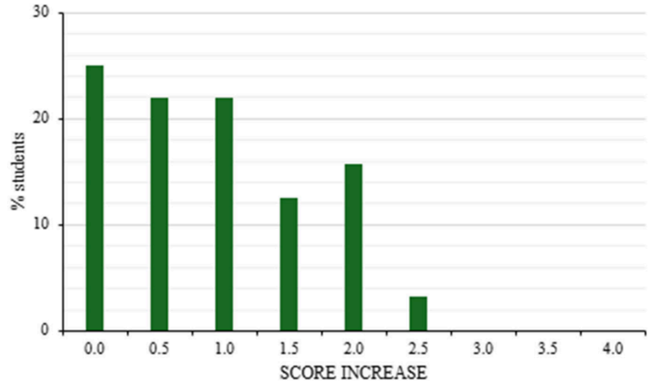


Figure 9. Improvement in student results.

scored from 0 to 1 point, with the scores varying from 0 to 4 points. At the beginning of the course, in the theory class, students are introduced to the concepts of product, waste, and byproduct. The economic differences between the latter two and the importance of the definition of byproduct in preventing waste from being hidden under its name are emphasized. The obligation to manage waste according to the residue hierarchy is also explained. Moreover, the concept of a circular economy is presented. The same questionnaire was given to the students before and after the laboratory experience. Although in the laboratory students work in pairs, each student answers the questionnaires individually.

Table 4 shows an example of the responses of a random student to the questionnaire before (09/14/2022) and after (11/03/2022) carrying out the laboratory experience. The original document (in Spanish) is provided as a supporting material. In this case, the student improved his score from 2.5 to 4 points.

Figure 8 shows the percentage of students who achieved each score before and after their time in the laboratory.

A lot of variability can be observed in the scores achieved before the laboratory: 81.3% of the students exceed 2 points, 62.5% exceed 3, 25% obtain 3.5 points, and only 18.8% achieve the maximum score.

After the laboratory experience, the results improved considerably, 93.8% of the students exceeded 3 (previously 62.5%), and 68.8 achieved the maximum score. Furthermore, a qualitative improvement is observed in the responses in terms of the use of a more precise language appropriate to the context of the subject. For example, in relation to question 4, after completing the laboratory exercise, it is observed how students understand the complexity of the circular economy.

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492

They warn that waste must be treated before recirculation, that intermediate waste is generated in treatment that must also be treated, and that the streams generated during treatment.

Figure 9 shows the increase in the scores of students. 75% of students improve their grade between 0.5 and 2.5 points, with improvements of 2 points for 15.6% of students and 1 point (21.9%) and 0.5 point (21.9%). These results show the improvement in learning achieved after the practices.

■ CONCLUSIONS

This work presents a laboratory practice that, based on simple chemical reactions, valorizes a hazardous waste (EAFD) as a commercial product (basic zinc carbonate). It has been successfully performed since the 2015−16 academic year. Although the exercise was designed and put into practice for and with fourth-year students of the Materials Engineering degree, it is also an interesting exercise for students of other grades, such as Chemistry or Environmental Sciences, and it is suitable even for students of introductory levels. The results show that after completing laboratory practice, students improve their understanding of key concepts of circular economy.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00509.

Student handouts (PDF) (DOCX)

Quiz example (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Nieves Iglesias-Gonzalez − *Chemical Engineering Department, University of Seville, Calle Profesor García González, Facultad de Química, 41012 Sevilla, Spain*; orcid.org/0000-0003-0708-8167; Email: mnieves@us.es

Authors

Pablo Ramírez − *Chemical Engineering Department, University of Seville, Calle Profesor García González, Facultad de Química, 41012 Sevilla, Spain*

Juan Lorenzo-Tallafigo − *Chemical Engineering Department, University of Seville, Calle Profesor García González, Facultad de Química, 41012 Sevilla, Spain*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.4c00509

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) United Nations. Sustainable Development Goals. Goal 12: Ensure sustainable consumption and production patterns. https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ (accessed on April 29, 2024).

(2) Ashby, M. F. *Materials and Sustainable Development*, 2nd ed.; Butterworth-Heinemann, 2022. ISBN: 9780323983617.

(3) Blum, C.; Bunke, D.; Hungsberg, M.; Roelofs, E.; Joas, A.; Joas, R.; Blepp, M.; Stolzenberg, H.-C. The concept of sustainable chemistry: Key drivers for the transition towards sustainable development. *Sustainable Chem. Pharm.* **2017**, *5*, 94−104.

(4) Zuin, V. G.; Eilks, I.; Elschami, M.; Kümmerer, K. Education in green chemistry and in sustainable chemistry: perspectives towards sustainability. *Green Chem.* **2021**, *23* (4), 1594−1608.

(5) Barceló-Oliver, M.; Cabello, C. P.; Torrens-Serra, J.; Miró, M.; Cabot, C.; Bosch, R.; Delgado, M. R. Scientific activities for the engagement of undergraduate students in the separation and recycling of waste. *J. Chem. Educ.* **2021**, *98* (2), 454−460.

(6) Liu, K.; Huang, S.; Jin, Y.; Lam, J. C. H. Teaching electrometallurgical recycling of metals from waste printed circuit boards via slurry electrolysis using benign chemicals. *J. Chem. Educ.* **2023**, *100* (2), 782−790.

(7) Austen, L. I.; Dugmore, T. I.; Matharu, A. S.; Hurst, G. A. Byproduct Valorization: From Spent Coffee Grounds to Fatty Acid Ethyl Esters. *J. Chem. Educ.* **2023**, *100* (1), 327−335.

(8) Hudson, R.; Glaisher, S.; Bishop, A.; Katz, J. L. From lobster shells to plastic objects: a bioplastics activity. *J. Chem. Educ.* **2015**, *92* (11), 1882−1885.

(9) Mackenzie, L. S.; Tyrrell, H.; Thomas, R.; Matharu, A. S.; Clark, J. H.; Hurst, G. A. Valorization of waste orange peel to produce shear-thinning gels. *J. Chem. Educ.* **2019**, *96* (12), 3025−3029.

(10) Carranza, F.; Romero, R.; Mazuelos, A.; Iglesias, N. Recovery of Zn from acid mine water and electric arc furnace dust in an integrated process. *Journal of environmental management* **2016**, *165*, 175−183.

(11) Lin, X.; Peng, Z.; Yan, J.; Li, Z.; Hwang, J.-Y.; Zhang, Y.; Li, G.; Jiang, T. Pyrometallurgical recycling of electric arc furnace dust. *Journal of Cleaner Production* **2017**, *149* (4), 1079−1100.

(12) Stewart, D.; Barron, A. Pyrometallurgical removal of zinc from basic oxygen steelmaking dust—a review of best available technology. *Resources, Conservation and Recycling* **2020**, *157*, 104746.

(13) Walburga Keglevich de Buzin, P. J.; Heck, N. C.; Vilela, A. C. F. EAF dust: an overview on the influences of physical, chemical and mineral features in its recycling and waste incorporation routes. *J. Mater. Res. Technol.* **2017**, *6* (2), 194−202.

(14) Scholz, F.; Kahlert, H. The calculation of the solubility of metal hydroxides, oxide-hydroxides, and oxides, and their visualisation in logarithmic diagrams. *ChemTexts* **2015**, *1*, 1−9.

https://doi.org/10.1021/acs.jchemed.4c00509
J. Chem. Educ. 2024, 101, 3485−3492