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Laboratory Experiment

Becoming Aware of Endangered and Critical Elements: Spent Batteries as Metal Mines

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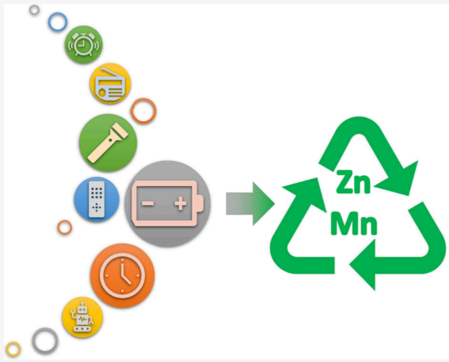
ABSTRACT: The importance of spent battery collection and related treatments in terms of circular economy is the starting point for a laboratory education path focusing on alkaline batteries. While using a project-based learning approach, students at a high school or university are made more aware of critical raw materials, learn about the chemistry of batteries, and investigate the composition of the black mass from spent alkaline batteries. They also investigate the methods used to extract and analyze critical raw materials such as zinc and manganese.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Inorganic Chemistry, Laboratory Instruction, Hands-On Learning/Manipulatives, Problem Solving/Decision Making, Inquiry-Based/Discovery Learning*

■ SCIENTIFIC AND SOCIAL BACKGROUND

Of the 118 elements reported in the Periodic Table, about 40 will pose moderate to serious problems concerning their future availability. The European Chemical Society[1] and the American Chemical Society[2] have each published a revised version of the Periodic Table that highlighted these limitations. At a political level, in 2011 the European Commission made a list of *critical raw materials* (CRMs) that are considered crucial to Europe's economy. This list is subject to regular review and update (fifth edition, 2023) and combines raw materials of high importance in everyday life and modern technologies and of high risk associated with their supply.[3]

Most of these critical materials are transition elements or rare earth metals, and many are essential parts of electronic equipment, catalysts, fuel and photovoltaic cells, integrated circuits, batteries, and so on. Furthermore, extraction processes have environmental consequences and mining also has large social impact and drives inequality.[4] Therefore, facing the limited availability of these elements at present, or in the future, requires sustainable management, also including the search for alternatives,[5] reuse and recycle[6,7] for a green inorganic chemistry.[8]

Potential recovery of these critical materials from different sources (acid mine waters, waste, ash, byproducts of coal processing, etc.) is a topic of considerable current interest, and the extraction of such elements is the subject of many ongoing investigations.[9] With this in mind, the waste of electric and electronic equipment (widely known as WEEE or e-waste) and its batteries could be considered a modern version of a *mine of metals*.[10] All of these sources represent a good starting point to make young people aware of the problem of critical elements and their recovery from waste (circular economy),[11] including discussion, engagement, and laboratory activities.

Among the different types of batteries, the most accessible and least hazardous ones are certainly alkaline batteries. This single-charge (primary) battery produces energy through the reaction between zinc and manganese dioxide. Briefly, the cathode is made of graphite and MnO_2 powder separated by a porous material, from the anode situated in the center of the battery. The anode is composed of gelled Zn powder with potassium hydroxide as an alkaline electrolyte and surrounds an anodic brass current collector. To prevent short circuiting, the latter is separated from the metal base by a plastic seal (Figure 1).

Different versions of the electrochemical reactions at the electrodes have been reported in the literature. According to Kuntzleman et al.[12] and to the "Alkaline manganese dioxide – handbook and application manual" (Energizer),[13] the reactions can be written as follows:

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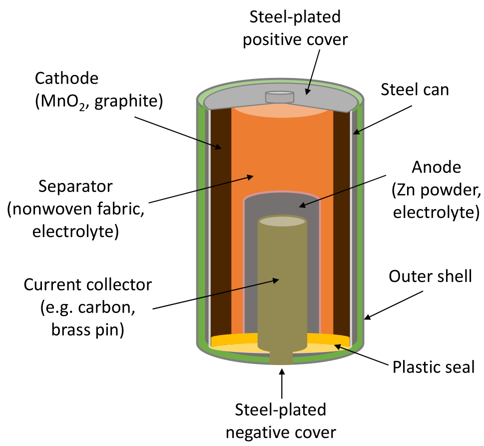

Figure 1. Simplified scheme of an alkaline battery.

Anode:

$$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \qquad (1)$$

Cathode:

$$MnO_2 + e^- + H_2O \rightarrow MnOOH + OH^- \qquad (2)$$

Therefore, the simplified overall reaction is as follows:

$$Zn + 2MnO_2 + H_2O \rightarrow ZnO + 2MnOOH \qquad (3)$$

However, other oxides containing reduced Mn (e.g., Mn_2O_3 and Mn_3O_4) can form during the reaction, thus forming complex mixtures and making the chemistry of such batteries not easy to model.[6,12,14]

At present, alkaline batteries account for almost 80% of the tens of billions of batteries produced annually,[6,15] because they are reliable, safe, and cheap. Nevertheless, because of their nonrechargeable nature, the accumulation of spent alkaline batteries is increasing year by year, and they need to be recycled to avoid environmental problems and allow recovery of useful elements. The most relevant recycling processes are pyrometallurgical treatments, which are generally inexpensive, with high molten metal recovery and without complex pretreatment; on the down side, however, they are characterized by high energy consumption and the production of dust and harmful gases. Therefore, expensive systems are required to prevent environmental contamination. Alternatively, hydrometallurgical methods have been developed to limit the above-mentioned negative aspects.[16]

In the latter case, prior to chemical treatment, some mechanical and physical pretreatments are necessary. Among the others, the latter can shred, cut-crashing, thermal treatments, and separation of ferrous metals from inert components (e.g., paper and plastic) by means of magnets and sieves. From the resulting *black mass* (BM), consisting largely of electrolytes, graphite, and zinc and manganese oxides), processes such as leaching and separation steps, allow recovery of the metal.

Leaching has the purpose of extracting metals from the solid matrix into the aqueous phase.[6,17] Generally, strong acidic or alkaline solutions are used with or without reducing or complexing agents. As a result of the complex nature of the black mass and the following separation steps, these processes are currently an important field of research.

In this framework, a didactic pathway, developed within the partnership between an Italian high school and the University, was designed to sensitize students to critical elements and to teach them the chemistry of batteries and metal recovery.

■ DESCRIPTION OF THE PROJECT

The project deals with the step-by-step planning of an extraction process focused on two CRMs (i.e., zinc and manganese), as can be done in the R&D laboratory of a recycling company. In addition, simple analytical methods are needed to quantify the extracted metals to complete and evaluate the results of the project. This multifaceted activity represents an example of project-based learning (PBL), a teaching method through which students work on a project to solve a real-world problem, or answer a complex question, thus getting new insight on a subject.[18] This method allows students to develop deep content knowledge together with critical thinking, collaboration, creativity, and communication skills. It can also create a contagious imaginative energy among students and teachers. It is based on open-ended problems and improves a broad range of skills, including problem solving across disciplines, managing projects and holding leadership roles, teamwork and independent work, self-awareness and evaluation of group processes, self-directed learning, oral and written communication.[19]

Importantly, the project was developed by students in years four and five of technical high school (17 and 18 years old), but it could also be incorporated into a university degree program for students in chemistry, environmental sciences, or similar areas. To tackle the project, students must have a basic knowledge of electrochemistry, inorganic chemistry, and analytical chemistry (in particular, complexometric titrations and quantitative UV−vis spectroscopy) as well as the ability to handle data and present their experimental results.

■ STEP 1. INTRODUCTORY ACTIVITIES

The instructor can make an introductory presentation (2 h) on the recycling of spent batteries in a preparatory lesson. To help the instructor, exhaustive information about batteries is reported in several educational publications from different points of view.[20] Moreover, essential concepts that can be helpful to introduce students to the topic are available as online resources and can be discussed by the teacher during the lesson or given as individual homework assignments (see Instructor's Notes for further details).

To evaluate the efficacy of the preliminary lesson, as well as to promote collaboration, creativity, and communication skills among the students, the teacher can propose the self-production of a short video with smartphones. (Note: an example can be found at https://youtu.be/cY7OZnEu3YY?si=QseYtZwYAiXE-dJ0; this video is in Italian, but English subtitles are available.) The purpose of the plot is to test the awareness of their companions and to sensitize the school community.

In a second preparatory presentation (2 h), the instructor can select some significant scientific articles on the topic[6,17,21] and briefly instruct the students on different procedures to extract and evaluate the metals. Following this preliminary step, students can be grouped into small teams (e.g., of three or four people) for collaboration in the classroom or as an out-of-school activity. In this phase, the separated groups can examine the scientific literature on the extraction and quantitative analysis of Zn and Mn, either suggested by the teacher or found for themselves. As the final output of this phase, each

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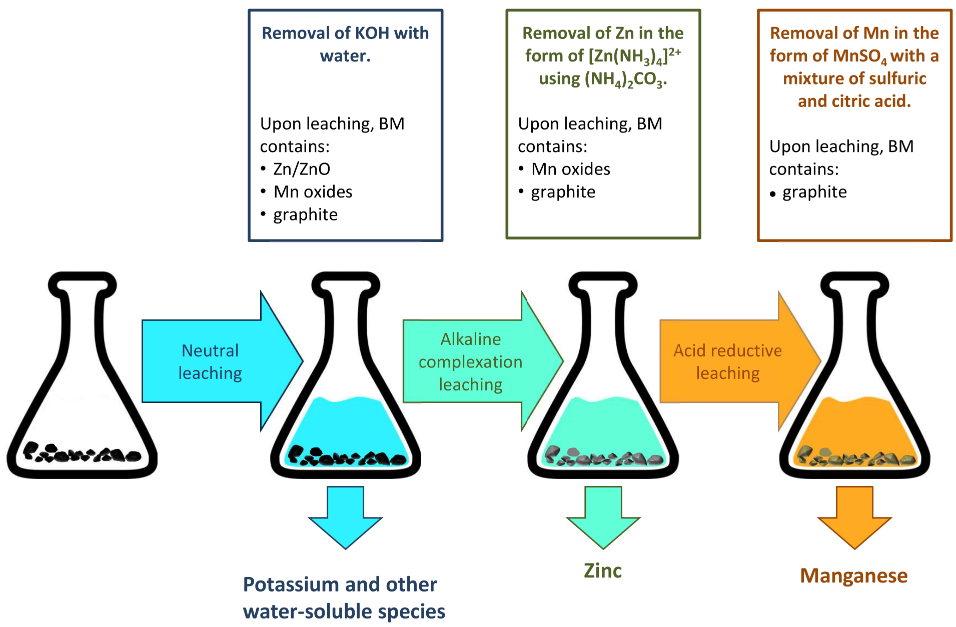
Scheme 1. Summary of the Lab Procedures Proposed in the Present Work



team should produce a broad outline of the laboratory work procedures.

In a third preparatory session (1–2 h), the different groups can discuss together their ideas under the supervision of the teacher and then decide together on a protocol for the experiments to be carried out.

Teamwork improves the collaboration between group members, whereby the necessary negotiation and decision-making skills are needed to obtain the expected results. Project-based learning also requires students to defend their own ideas during discussions and to show the results of their work in a multimedia presentation. Hands-on training in laboratory practice allows students to achieve a deeper understanding of chemical concepts and increases their interest in STEM disciplines by leveraging their curiosity. However, the whole process requires at least 5–6 h with the instructor and many hours of independent teamwork. For this reason, the project can be limited to two preparatory sessions, one dedicated to the batteries and the importance of recycling and the other to the description of the protocols to be used in the laboratory.

The final procedure developed and adopted by the students who participated in the project coordinated by the authors of the present paper is summarized in Scheme 1 and thoroughly explained in the different documents that make up the Supporting Information. In particular, Laboratory Procedures describe the experiments to be followed by the students, whereas Instructors' Notes include detailed information on all the individual steps that will be briefly described in the following sections. Finally, experimental data are also available for simple processing and virtual activities.

■ SAFETY NOTES

Safety glasses, gloves, and lab coats, as well as working in a fume hood, are mandatory during the entire procedure to avoid accidental contact with chemicals. As stated in every article, the alkaline batteries should not be opened. Exposure to the ingredients contained within (e.g., concentrated KOH) could be harmful. However, if necessary to obtain the black mass (BM), open the batteries very carefully, as reported elsewhere.[12] Full details are available in the Supporting Information.

■ STEP 2. LABORATORY ACTIVITY

This step is highly modular, being based on four distinct subtasks, starting from sourcing the BM up to determination of the recovered metals. It can be followed by all the groups of students; alternatively, the teacher can assign a single or different substeps to different groups.

Step 2.1. Preparation of Black Mass (BM)

After the protocol was planned, the students began laboratory activities on the BM using spent alkaline batteries. In our case, it was supplied by RAEE.MAN (Sale, Alessandria, Italy), a company specializing in the collection, processing, and treatment of technological waste. The sample, obtained during daily factory procedures from unselected sources, contained 288 ± 3 mg Mn, 52 ± 3 mg K and 162 ± 10 mg Zn per gram BM, as determined by SEM–EDX analysis (Scanning Electron Microscopy with Energy Dispersive X-ray analysis).

In the absence of this starting material, BM can be obtained by very carefully opening spent alkaline batteries as reported elsewhere[12] or by preparing a model black mass by mixing potassium hydroxide graphite, zinc oxide, and different manganese oxides. The latter method has the advantage of knowing exactly the metal content of the sample. Roughly, a model BM can be prepared with about 30% graphite, 8% KOH, and 22% ZnO and the remaining part can be distributed between different manganese oxides (e.g., 20% Mn_2O_3 and 20% Mn_3O_4).

Whatever the source, the BM should be dried at 60 °C for 24 h before further treatment.

Step 2.2. Removal of Potassium: Neutral Leaching

The next step when investigating BM is the removal of potassium (mainly as KOH) and other soluble components simply by washing with neutral water (Scheme 1).

After several attempts, the best balance among time, temperature, and volumes employed to solubilize K^+ was

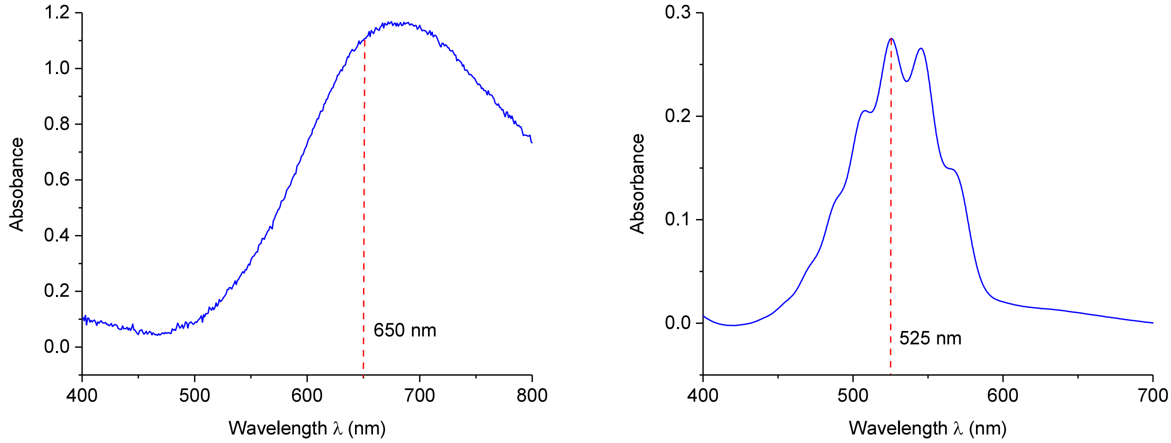


Figure 2. Absorption spectrum of Prussian blue (left) and permanganate ions (right) in water.

obtained. The procedure developed was the following: 5 g of dried BM were suspended in deionized water (50 mL), the resulting mixture was stirred at 50 °C for 30 min, and the solid residue was recovered by filtration. This procedure was repeated three times, taking about 2 h to complete. Finally, the solid residue was dried at 60 °C for 24 h to be ready for the subsequent characterization and recovery of other metals.

Step 2.3. Recovery of Zinc: Alkaline Complexation Leaching and Analysis of Zinc Content

Acid leaching usually results in the simultaneous extraction of both zinc and manganese, thus requiring a further step of separation (e.g., fractional precipitation). In contrast, alkaline complexation leaching allows the recovery of most of the zinc (>80%) with only trace quantities of manganese (<0.1%).[21]

The dried BM from the previous step (approximately 4 g) was treated with 250 mL of 2 M $(NH_4)_2CO_3$ at 50 °C for 30 min, while stirring the mixture, and the leachate was separated from the solid residue by vacuum filtration (Scheme 1). The most probable reaction that occurs between Zn(II), present mainly in the BM in the form of zinc oxide, and ammonium carbonate is as follows:[22]

$$ZnO + 2(NH_4)_2CO_3 \rightarrow [Zn(NH_3)_4]CO_3 + CO_2 + 2H_2O \quad (4)$$

After appropriate dilutions, the zinc content in the extract was determined by complexometric titration, using a 0.01 M solution of ethylenediaminetetraacetic acid (EDTA) and Eriochrome Black T (EBT) as an indicator.

Zinc was also measured using a UV–vis spectrophotometer to confirm the titration data. In this case, the reaction of Zn^{2+} with hexacyanoferrate(II) ions, $[Fe(CN)_6]^{4-}$, in an acid solution leads to the formation of the analogue of Prussian blue $K_2Zn_3[Fe(CN)_6]_2$:[23]

$$3Zn^{2+} + 2K_4[Fe(CN)_6] \rightarrow K_2Zn_3[Fe(CN)_6]_2 + 6K^+ \quad (5)$$

The latter complex, generated in the presence of traces of sulfite,[24] gives rise to a bluish solution that can be measured spectrophotometrically at 650 nm (similarly to Prussian blue in Figure 2).

The results of the analyses confirm the zinc extraction yield reported in the literature (≥80%).[21]

Full details of the analytical methods are available in the Supporting Information. Teachers wishing to propose this work project to their classes can choose which analytical methods to apply, depending on their laboratory equipment. As an estimate of the execution time, note that the extraction and filtration operations take about 1 h, and the complexometric determination about 2 h, if each group repeats the titration three times. Spectrophotometric determination takes about 4 h, including preparation of the reagents.

Examples of the data obtained are reported in the Results section and in the Supporting Information. If the school does not have the opportunity to perform the experimental part, then it could still carry out the data processing (stoichiometric calculations, determination of calibration curve equations, calculation of R^2, etc.).

Step 2.4. Recovery of Manganese: Acid Reductive Leaching and Analysis of Manganese Content

Manganese can be recovered with different types of acid leaching,[6] and most procedures require the use of sulfuric acid. However, the dissolution of manganese oxides such as Mn_2O_3 and Mn_3O_4 is only partial because MnO_2, produced in their reaction with H_2SO_4 (see Instructor notes) or derived from unreacted cathodic material, is insoluble. Therefore, an additional reducing agent, such as citric acid $C_6H_8O_7$, is necessary to solubilize the Mn(IV) species according to the following reaction:[25]

$$9MnO_2 + 9H_2SO_4 + C_6H_8O_7 \rightarrow 9MnSO_4 + 6CO_2 + 13H_2O \quad (6)$$

After removal of KOH and extraction of zinc, the residual BM, weighing approximately 3 g, was leached with sulfuric acid and citric acid (each 0.05 M), at 40 °C, while stirring the resulting mixture for 1 h (Scheme 1). The separation of the extract from the solid residue (approximately 2 g) was carried out by vacuum filtration, and the obtained reddish orange solution was subjected to quantitative analysis.

After the manganese content of the extract was measured (see below), the rather low yield prompted the students to proceed with multiple extractions, thus repeating the procedure (i.e., adding additional solvent aliquots to the residue and repeating the separation). In industrial leaching processes, often a single stage is not enough, and multistage extraction is used. The same method can also be applied for zinc extraction to improve yield and to remove zinc completely.

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The analysis of the manganese content for each extraction step was carried out by spectrophotometry. For this purpose, the leached manganese species were oxidized to permanganate with persulfate, a necessary criterion since it is necessary to have the Mn in a single oxidation state, thereby producing a colored solution.[26] Because of their intense violet coloration, the absorbance of permanganate ions was measured at 525 nm (Figure 2).

■ STEP 3. DATA ANALYSIS AND POST-LAB ACTIVITY

After laboratory analyses, the teams independently processed the collected data, making the appropriate stoichiometric calculations to determine the metal content in the leachates, and all the results were then discussed during a 2 h debriefing.

Table 1 contains an example of the results for the zinc complexometric titration obtained by one of the classes (6 teams).

Table 1. Zinc Complexometric Titration Results

Teams	BM initial mass (mg)	Zn present in the BM[a] (mg)	Zn leached (mg)	Zn leached (%)
1	5005	810	696	85.9
2	5000	809	669	82.6
3	5000	809	621	76.8
4	5027	813	763	93.8
5	5003	809	649	80.1
6	5002	809	687	84.8
mean ± SD	5006 ± 10	810 ± 2	681 ± 48	84.0 ± 5.8

[a]Data obtained by SEM−EDX (Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis).

The percentage of zinc extracted by alkaline complexation leaching was in agreement with the data reported in literature (83%).[21]

The results of the different teams were compared to assess their reliability. In particular, the students were asked if they considered the extreme values obtained acceptable. By applying Dixon's Q test, which is used for the identification and rejection of outliers, they concluded that all values could be accepted for the calculation of the mean.

To confirm the results obtained by volumetric titration, some samples were also analyzed spectrophotometrically, and the teams could evaluate the data. Figure 3 shows an example of the calibration curve, and Table 2 contains the data of three selected teams of students.

Table 2. Zinc Spectrophotometric Analysis Results

Teams	BM initial mass (mg)	Zn present in the BM[a] (mg)	Zn leached (mg)	Zn leached (%)
1	5005	810	616	76.0
3	5000	809	646	79.9
6	5002	809	618	76.4
mean ± SD	5002 ± 2	809 ± 1	627 ± 17	77.4 ± 2.1

[a]Data obtained by SEM−EDX (Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis).

The results obtained by using instrumentation were lower than those obtained by volumetric methods. During the debriefing and class debate, the difference in the results obtained with different methods was discussed. In our case, the students were asked which method they considered most suitable. In their opinion, the preferred procedure is the complexometric titration, which can be attributed to the difficulties encountered in the construction of a satisfactory calibration curve. Analyzing the spectrophotometric method, they observed that the colloidal form of the colored compound can lead to deviations from the linearity of the Beer−Lambert law. However, it was emphasized that volumetric determination is very simple and inexpensive and can be carried out even in a poorly equipped laboratory, giving good results. Some of the students suggested that the percentage of zinc extracted could be increased by multiple extractions.

For manganese, after UV−vis calibration with permanganate standard solutions (Figure 4), the Mn content of the leachates was calculated. Table 3 shows the data obtained by a class (4 teams out of 6).

In the first version of the process, a single extraction step was performed, as in the case of zinc. However, the students calculated a disappointingly low recovery yield (approximately 21%). For this reason, they decided to increase the number of extractions, and some selected groups analyzed each leachate (Table 4).

The mean recovery of manganese in the four steps was 21%, then 18%, 15% and finally 10%. For this reason, the students decided to stop the procedure at the fourth passage, thereby saving time and reagents. This number of extractions was introduced in the final procedure. The mean total percentage of manganese extracted by acid leaching over the entire procedure is approximately 64%.

To confirm the analytical results, ICP-MS (inductively coupled plasma mass spectrometry) was used on a selected set of samples. In our case, it was found that a simple

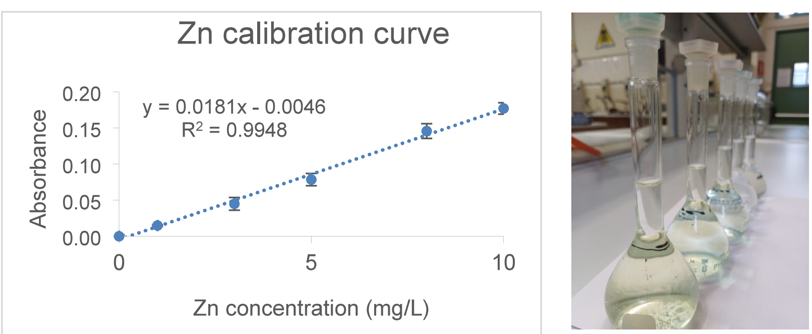

Figure 3. Example of a calibration curve for the spectrophotometric determination of zinc and standard solutions.

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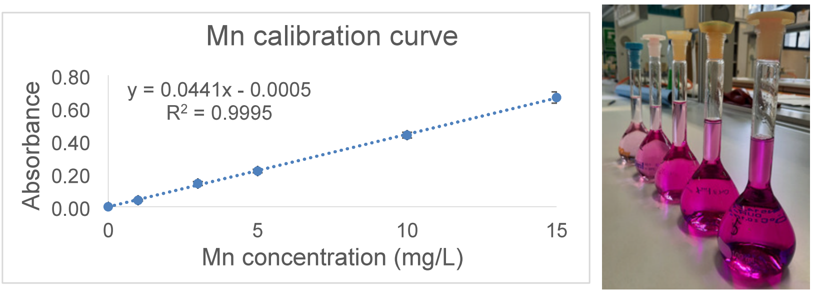

Figure 4. Example of a calibration curve for the spectrophotometric determination of manganese and permanganate standard solutions.

Table 3. Manganese Spectrophotometric Analysis Results (Total Extraction)

Teams	BM initial mass (mg)[a]	Mn present in the BM[a] (mg)	Mn leached (mg)	Mn leached (%)
1	5005	1441	853	59.18
2	5000	1440	924	64.17
3	5000	1440	938	65.14
4	5027	1448	864	59.68
mean ± SD	5008 ± 13	1442 ± 4	895 ± 43	62.0 ± 3.0

[a]Data obtained by SEM−EDX (Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis).

spectrophotometric method can give an acceptable assessment of the manganese content in the leachate.

Finally, the instructor, at her discretion, closes out the project with a summary of the results and a collective discussion of the key steps.

Figure 5 shows different moments of the whole project.

■ ADDITIONS AND VARIATIONS

An additional interesting final step of the work is the precipitation of zinc and manganese compounds from the corresponding leachates (see Laboratory Procedures and Instructor's Notes).

The dropwise addition of HCl to the basic leachate gradually lowers the pH value of the solution, thus favoring the precipitation of zinc carbonate, likely in different forms, from the monoamine complex of zinc carbonate[27] to basic zinc carbonate.[28] This procedure was implemented by some of the teams that participated in the present project obtaining a precipitate containing 48 ± 5% of Zn. Instructors interested in purer products should consider other methods. For example, zinc precipitation from Zn-ammonia solutions can be achieved by adding gaseous CO_2.[29] Alternatively, zinc precipitation can be favored by adding oxalic acid[30] or citric acid upon leaching with a solution of citric-sulfuric acid, as reported here for manganese alone.[25]

Concerning the manganese leachate, the stepwise addition of 1 M NaOH to the acid solution containing manganese led to the formation of manganese(II) hydroxide (provided that all manganese is in the +2 oxidation state). However, the initially white precipitate rapidly became dark brown MnO_2, as expected with exposure to air at high pH values. This residue is not soluble and, therefore, is not suitable for the previous kind of analysis, but its formation represents a simple confirmation of the presence of manganese in solution. Among the alternatives, leachate can be treated with citrate to precipitate manganese citrate[25] or oxalate.[30]

Furthermore, in the absence of a spectrophotometer or in addition to it, digital image colorimetry on a smartphone may represent a fast and inexpensive substitute method for measuring an analyte through the color of images acquired by the integrated camera.[31] Such an approach has been already proposed in various articles with both research[32] and didactic aims,[33] also for remote activities.[34] Moreover, it may also have the advantage of efficiently involving and stimulating the interest of the students.

Finally, those involved in this project were invited to produce an educational multimedia presentation for the City Authorities and the Companies that collaborate with the high school. In our view, this activity represented the crowning achievement of the project and helped the students increase their communication skills.

■ CONCLUSION

In this project, the students developed extraction protocols for Zn and Mn from spent alkaline batteries and simple analytical techniques by testing them. Throughout the work, they had to reflect on the results obtained, rationalizing failures so as to improve the procedures, as defined by themselves, lesson by lesson. They also had the opportunity to approach an environmental and industrial problem in an interdisciplinary way, making use of (or increasing) the knowledge acquired in

Table 4. Manganese Spectrophotometric Analysis Results (From Different Leaching Stages)

Teams	BM initial mass (mg)	Mn present in the BM[a] (mg)	mg (and %) Mn first extraction	mg (and %) Mn second extraction	mg (and %) Mn third extraction	mg (and %) Mn fourth extraction
1	5005	1441	311 (21.6%)	292 (20.3%)	248 (17.2%)	149 (10.3%)
2	5000	1440	317 (22.0%)	225 (15.7%)	217 (15.1%)	164 (11.4%)
3	5000	1440	300 (20.9%)	259 (18.0%)	208 (14.4%)	169 (11.7%)
4	5027	1448	302 (21.0%)	271 (18.8%)	171 (11.9%)	119 (8.2%)
mean ± SD	5008 ± 13	1442 ± 4	308 ± 8 (21.3 ± 0.6%)	262 ± 28 (18.1 ± 1.9%)	211 ± 32 (14.6 ± 2.2)	150 ± 22 (10.4 ± 1.6)

[a]Data obtained by SEM−EDX (Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Analysis).

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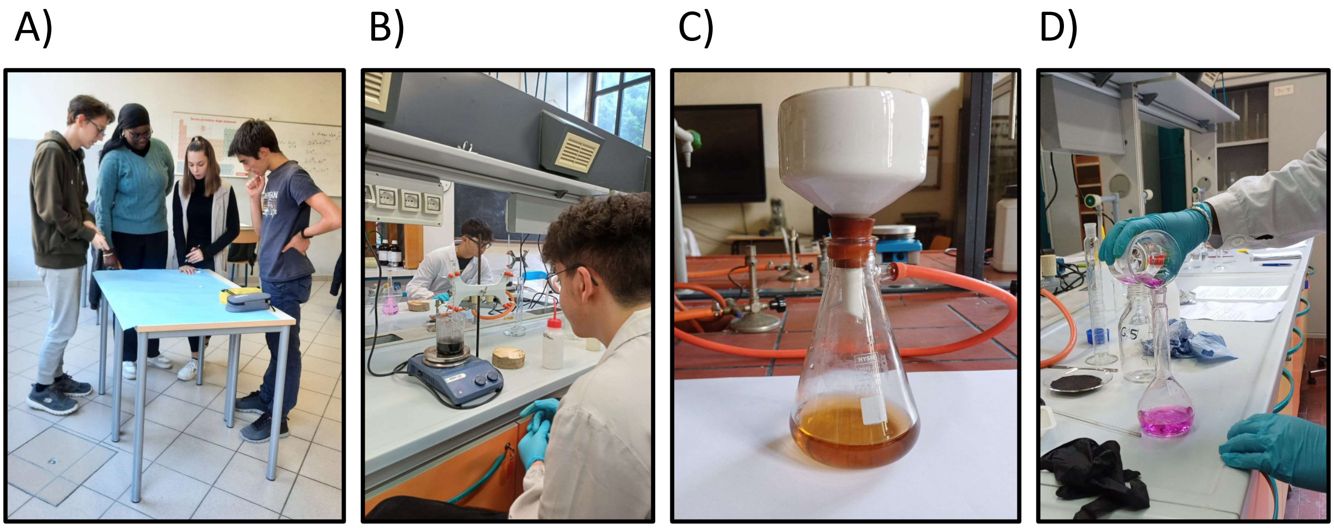

Figure 5. Different moments in the project. Prelab activity: (A) brainstorming and setup of the procedures in the classroom; lab activity: (B) suspension of the BM, (C) filtration upon Mn extraction, (D) preparation of a permanganate solution.

various sectors of chemistry (inorganic, analytical, and industrial).

These activities allowed the students to develop their understanding of the chemistry of batteries and the recovery of critical elements from batteries. The project heightened the awareness that science and technology can provide effective answers to achieve the Sustainable Development Goals proposed by the 2030 Agenda, and that chemists have precise moral duties toward the community.

At the end of the project, the students were asked which soft skills had been enhanced during this work; they answered the following: reading and interpreting articles from the scientific literature, organizing laboratory work themselves within groups, team working, mediating and making shared choices, arguing one's own opinions, listening to others, and, if necessary, changing one's position following confrontation with other people's ideas, public speaking.

These experiments can be tailored to suit the level of students and the availability of laboratory facilities and equipment. The activities described here were performed by high school students but could also be extended to undergraduates, giving them greater opportunities to act independently, by adding ICP-OES or ICP-MS analyses of each leachate and SEM-EDX analyses of the BM at each stage, where possible. More simply, the whole activity part could be used "as is", without the optimization steps as reported in the Laboratory Procedures, within traditional laboratory courses in inorganic, analytical, environmental, or industrial chemistry.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c01535.

Instructors' Notes (PDF, DOCX)

Laboratory Procedures (PDF, DOCX)

Data (XLSX)

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Notes

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