Scientific Activities for the Engagement of Undergraduate Students in the Separation and Recycling of Waste

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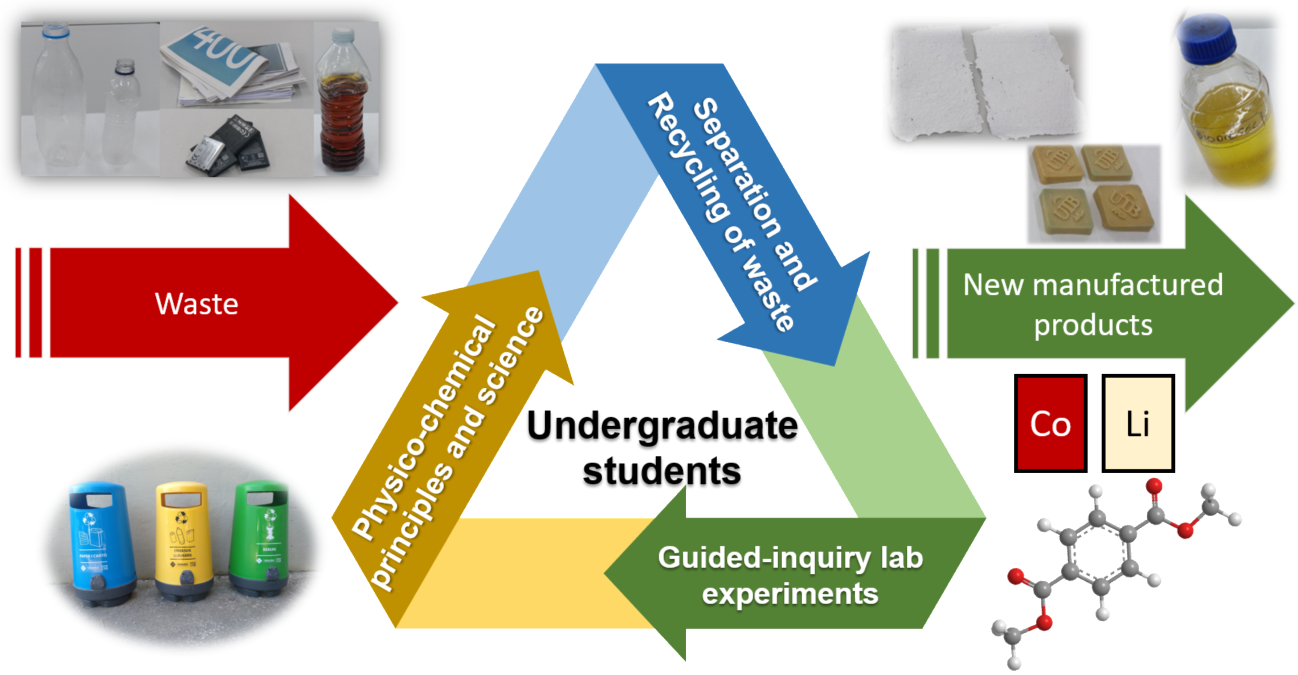
ABSTRACT

Although residues and resource shortages are major problems of modern living, these topics are not usually properly covered in university curricula. To tackle this situation, we have guided undergraduate students through the design of a group of active learning activities, to demonstrate the science behind separation and recycling: trash separation and recycling of paper, plastic, oil and metals (lithium and cobalt available in mobile phone batteries). With a better understanding of the underlying scientific processes and fundamentals, undergraduate students were engaged to undertake and develop adequate physico-chemical procedures for waste separation and recycling. A selection of the activities was presented in a science and technology fair at the University of the Balearic Islands as outreach activities that enrolled undergraduate students acting as teachers for fair visitors. The results showed a good engagement rate of the involved undergraduates as well as a stimulated visitors' interest.

KEYWORDS

First-Year and Sophomore Undergraduate; Multidisciplinary; Public Understanding; Collaborative Learning; Hands-On Learning; Applications of chemistry; Consumer Chemistry; Materials Science; Physical properties; Student-Centered Learning

GRAPHICAL ABSTRACT



INTRODUCTION

In 2015, the United Nations adopted the commonly named 2030 Agenda for Sustainable Development, which included 17 Goals (SDG) to be implemented over a decade.[1] For example, goal 12 is devoted to the responsible production and consumption and, in particular, one of the targets to be achieved from this goal, target 12.5, intends that a substantial reduction of waste generation should be obtained by 2030 through prevention, reduction, recycling and reuse.[2] One of the main pillars to accomplish this target is through a change in the waste disposal habits of the general population, and more specifically those of children and youth. Having the wholehearted conviction that educational institutions must play an important key role in the achievement of these objectives, faculty members of the University of the Balearic Islands (UIB), Spain, designed a program of active learning activities addressed to undergraduate students who take chemistry subjects in the majors of Chemistry and Physics from the Faculty of Science, with the recycling of waste as a common background.

The main goal of these activities was to get insight into the fundamentals and underlying principles of every specific subject, and the key competences of the curriculum through a collaborative and active learning methodology, in which students do not longer play a passive role but they are actively engaged in their own learning process using a formative assessment framework. The idea behind is to gear towards the new paradigm of student-oriented inductive learning against conventional teacher-centered deductive learning. It should be hereby stressed the fact that the chemistry curricula for first year and sophomore undergraduates of any degree at many universities worldwide usually encompass traditional "cookbook" experiments and activities in which students merely follow a lab manual, but no efforts are given towards guided-inquiry lab experiments (GILEs),[3] that will endow students with substantial freedom in the design and execution of the lab experimental workload. Many educators foresee GILEs as a novel pedagogical tool to (i) foster students' self-learning, (ii) improve their critical thinking, (iii) promote teamwork, and (iv) ameliorate students' leadership skills, all in line to cope with student-centered learning environments.

Over the last decade, activities related to recycling have been introduced in the classroom of high-schools and universities. A pioneering work was the paper by Johnson,[4] in which the recycling of classroom chalk residues was proposed as an innovative learning strategy and illustration of re-using of waste. In many other examples the activities presented in the literature are mostly related to the chemical lab residues and how to recycle them,[5,6] but the house trash management and recycling has also become a matter of interest. The activities usually consist of designing recycling plants or processes such as that presented by Harris and Harris[7] in which the students were engaged in designing an automated sorting plant of recyclables based on their physico-chemical properties, or that by Smith[8] involving problem-based learning on the recycling of batteries. In a very recent article in this Journal, Miller et al.[9] proposed a card game to encourage students to take the systems thinking approach on the principles of green chemistry. In addition, practical activities devoted to the recycling of common organic waste and paper have been reported by different authors. For example, in the paper from Venditti[10], an interesting activity related to de-inking of paper by flotation is reported, whereas Bladt[11] and Mascal[12] presented various activities for the generation of motor fuels from different kinds of organic wastes. Also, the production of shear-thinning gels from orange peels[13] and recycling of silicones via depolymerization[14] have been recently reported. In the paper by Subratti *et al.*[15], the construction of a magnetic stirrer from re-used parts is presented to highlight the second life that can be given to e-waste. Unfortunately, most of the educational papers on recycling and green chemistry are only focused on individual activities, which in turn are unable to demonstrate the impact of the circular economy in the handling of waste in a multi- or interdisciplinary framework. To tackle this gap in the literature, the activities presented in this manuscript were planned to provide students a “hands on” exposure to the recycling processes using a holistic framework capitalizing upon the concept of environmental sustainability in the processing and recycling of (i) paper, (ii) various plastic materials, (iii) metal objects (lithium batteries), and (iv) vegetable oil wastes for the fabrication of soap and biodiesel via green chemical methods. In this work, we discuss the different GILE-based activities developed for understanding the fundamentals, physicochemical principles and science behind the recycling of different materials, and how the experiments could be transferred to outreach activities in science fairs.

RESULTS AND DISCUSSION

Sorting and recycling of different waste materials was developed from a multidisciplinary point of view. Two highly effective and widely applied teaching/learning methodologies were used to describe the various chemistry processes involved throughout the recycling of several kinds of materials: project based learning and thematic education.[16]

Undergraduate students from chemistry and physics, tutored by several instructors, carried out a set of experimental activities, summarized in Table 1, all related to the recycling of four different types of waste: paper, vegetable oil (for the production of soap and biodiesel), plastics and metals from mobile phone batteries (see Figure 1). The activities were developed with groups of around 20 students from either chemistry or physics, which were divided into teams of 3-4 students. Usually, at least two supervisors were in charge of a group. The workflow started with the instructor offering a given subject to each team. This was followed by tutorial and inquiry-based learning using both on-line tools and meetings to help students to deliver, in a collaborative team environment, a practical solution for translating a particular type of waste to a new raw material ready to be manufactured. The recycling process delivered should be described in detail along with the proper design and execution of the practical recycling activity, including the materials and chemicals needed. Reviewing and approval of the activity by the instructor was mandatory prior to start the laboratory experiment. Laboratory supervision was organized by faculty members who were also engaged in marking students and approving the final report for oral presentation in class. Although the waste sorting was not performed by any chemical method, GILEs should aware students that inappropriate prior physical separation may jeopardize the success of the subsequent recycling process.

Table 1. Scientific activities carried out to deal with the chemistry and physics involved throughout the recycling of residues

Issue	Activities	Topics
Paper	Paper recycling	Chemical composition, organic polymers, bleaching chemicals, intermolecular forces, physico-chemical properties
Oil	Recycling of vegetable oils for the production of soap and biodiesel	Chemical composition, triglycerides chemistry, saponification and transesterification reactions, micelles
Plastics	Separation of plastics and chemical recycling of PET plastic	Chemical composition, organic polymers, melting, additives, extrusion, depolymerization, physico-chemical properties
Metals	Recovery of metals from electronic waste	Chemical composition, physico-chemical properties, magnetic separation, melting, impurities, alloys, redox chemistry

The instructor’s information and the students’ protocols for every type of material can be found in the supplementary materials (SI). Although many of the practical activities are based on different chemical processes and have their own peculiarities, all of them have a common scheme. Both the correct comprehension of the chemical principles and the adequate development of an experimental protocol are the objectives of the assessment. In the following, the different activities developed are described focusing on the chemistry behind the recycling processes, and the pedagogical benefits of each activity.

Preliminary activities:

First, the students learned about the reasons that prevent the efficient recycling of a mix of all the materials, and how the several categories for material separation are organized from the scientific point of view.[17] With that knowledge, students separated the rubbish from a dump (with the use of mandatory personal protective equipment in a laboratory, such as gloves, goggles and a lab coat) into the distinct colored bins that are common in Spain: yellow (plastic and metal containers), blue (paper and cardboard), green (glass), brown (organic) and black color (mixed, not recyclable). Regarding oil, in Spain, once the cooking oil (animal or vegetable fats, such as olive, sunflower seed oils, etc.) has been used, it must be collected at source and then delivered to the authorized collection systems: at the clean points or in specific containers enabled for it. In particular, the group of students that carried out the activity of soap and that of biodiesel decided to utilize used cooking olive oil for their recycling activities.

Once the separation was done, the students came up with several issues that remained without answer:

1) Why is not the glass material separated by color (at least colorless, green, blue and brown)?
2) Why are plastic and metal containers mixed together in the yellow bin?
3) Why are most kinds of plastic put together while they need actually to be separated for the recycling process?
4) Why are paper and cardboard not collected separately?
5) What does happen with the mixed residues: Tetra Brik® and similar layered packages, aluminum plus tin packages…?

With the knowledge that in the Spanish recycling system most of the metallic and plastic containers are collected together in the same yellow container, reliable separations of the residues can be carried out afterwards. Looking deeply at the possibilities, most of the recycling plants along the country use automatic separation procedures that rely on the shape of the residue (kind of container). Subsequently, even if most of the same kinds of containers are made from the same material (ex.: water bottles are usually made of polyethylene terephthalate (PET) plastic, food trays are usually made of polystyrene (PS)…), this approach is not able to assure a 100% accuracy on separations based on chemical composition. With that in mind, one of the activities proposed in this work was on the physical separation of the different types of plastics and another on the chemical recycling of PET plastic that can be realized after proper identification of plastic materials. Note that these activities were developed with the background of the Spanish recycling system. However, a similar study can be done with the trash-separation system from any other country.

After the separation of residues into distinct waste-bins for recycling, each team of students worked with its own activity: recycling of paper, vegetable oil, plastics and metals.

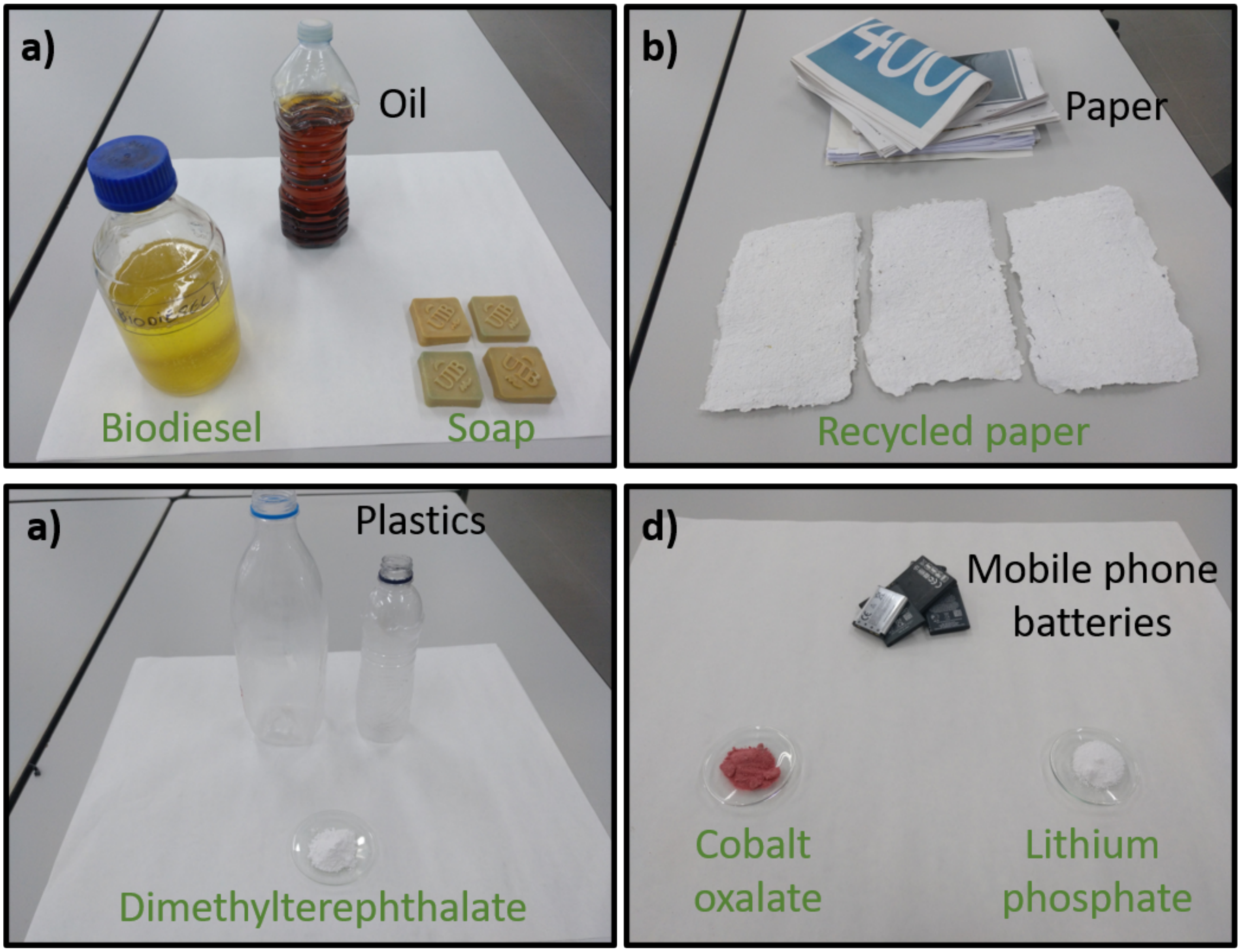


Figure 1. Photographs of the recycling activities: (a) recycling of vegetable oil for the production of soap and biodiesel, (b) paper recycling, (c) chemical recycling of PET plastic, and (d) metals recycling from mobile phone batteries.

The activity of collection and separation of residues was also adapted to the Science and Technology Fair "*Ciència per a tothom*" (Science for Everyone), organized by the University of the Balearic Islands over the last few years.[18] Although the activities to be presented were planned throughout the academic year and organized by faculty members, the main actors are actually the undergraduate students who are trained to give demonstrations for primary and secondary school students, and outreach local public. At the fair, students clarify the reasons for which it is not possible to simply recycle a mix of all the residues, and how the several categories are organized from the scientific point of view. Regarding plastics, they explained to the visitors that in order to recycle plastics (mechanically or chemically), the first thing to do is to separate the different kinds of plastics according to their number classification or class. They showed how the separation of different plastics is possible, thanks to their properties of floatability, as well as their identification by means of their physico-chemical properties. In addition, students demonstrated that metallic cans cannot be separated based on their floating capabilities, a fact which makes aluminum recycling more challenging. Instead, once all the metallic containers were separated from the plastic waste, the magnetic properties of the ferrous ones (made out of tin) allowed separation of aluminum cans that are not stuck to magnets. For the electronic waste, students presented how hand-based separation should be effectively done for isolation of the distinct components, followed by explanations of the different ways for recovery of precious metals available in electronic devices.

Recycling of paper:

To date, paper has become an essential element in our lives. Most paper is formed from wood pulp, whose main component is cellulose. Cellulose is an organic polymer consisting of several glucose units linked together in a manner that gives paper its distinct properties.[19] Currently, a high percentage of the paper produced worldwide contains recycled material because the recycling of paper is significantly easier as compared to that of other materials. The chemistry of polymers and the intermolecular forces together with the chemical washing processes of paper recycling (use of bleaching chemicals) make this a very suitable activity for the laboratory subjects of science majors, and facilitate incorporating transversal learning outcomes.[20,21]

First-year students of the Chemistry major (subject of General Chemistry Lab) prepared a protocol for the recycling of paper (see SI for further details): First, the used paper sheets are cut into small strips. Then, the paper is placed into a container and water is poured on it until covering the paper. The mixture is let soaking for 30 minutes and afterwards the paper is blended with a kitchen blender to obtain a paper pulp. The obtained paper pulp is bleached with different chemicals (such as chlorine, hypochlorite, hydrogen peroxide and peroxyacetic acid). Once the pulp is ready, a mold is introduced into the container to form the paper sheets, removed horizontally and the water is drained out. The obtained paper is placed onto a piece of felt and is pressed. Finally, the paper is air-dried. With the different original materials used and the types of papers prepared, resistance tests were carried out (see SI).

The supervised experimental activity allowed the optimization of the paper recycling methodology that was presented at the scientific dissemination fair “Science for Everyone”. Over the fair days, the undergraduate students carried out the entire paper recycling process for primary and secondary school students, who, in addition to learning all the stages of the process, were able to take home their own sheet of recycled paper. Nevertheless, due to safety issues, the paper was not bleached to avoid the use of hazardous chemicals.

Recycling of oils: soap and biodiesel

Vegetable oils are mixtures of triglycerides, which are esters derived from glycerol and three fatty acids.[22] The carbohydrate chains of the fatty acids can be saturated or unsaturated, the latter being usual in vegetable oils. Spent vegetable cooking oil is a waste that if thrown in the drain has the potential to contaminate 40000 times its volume of water. For this reason, an interesting strategy to recycle cooking oil is the fabrication of other compounds, such as soap and biodiesel by saponification and transesterification reactions, respectively.[23,24] The saponification reaction involves the alkaline hydrolysis of triglycerides, and consists on the reaction of the raw materials to be recycled with a strong mineral base like sodium hydroxide in aqueous medium that generates sodium salts of the hydrolyzed free fatty acids (soap) and glycerol, which serves as a moisturizer. On the other hand, in transesterification, a base-catalyzed chemical reaction involving triglycerides and an alcohol (methanol or ethanol) yields fatty acid alkyl esters (biodiesel) and glycerol, which must be removed for the production of biodiesel. Because of the chemistry behind the production of soap and biodiesel, with processes such as saponification and transesterification reactions; the basic processes of washing and filtering the oil; and the amphipathic characteristics of the soap, the selection of this activity is well aligned with the chemistry curricula in the first subjects of various majors of science.[25]

For this experiment, first-year students of the Chemistry major (subject of General Chemistry Lab) and the Physics major (subject of Chemistry) prepared protocols for the recycling of spent vegetable oil in order to fabricate either soap or biodiesel. The protocols (see also SI) can be summarized as:

Oil conditioning: the spent vegetable oil is filtered to remove solid residues. Free fatty acids are removed from filtered oil by washing with hot water, and subsequently the water is separated by decanting. Finally, the oil is oven dried for 24 hours.

Soap preparation: Mix the clean vegetable oil with a solution of sodium hydroxide and heat to keep the mixture at 50 °C while stirring until a trace residue is observed. At this point, add the desired aromas, colorants and antioxidants, mix and pour into the desired mold to let the soap dry.

Biodiesel preparation: Mix the clean vegetable oil with a solution of sodium hydroxide in methanol and heat to keep the mixture at 50 °C while stirring for 15 minutes. The product is let to stay for 30 minutes, until two phases are observed, the upper golden liquid (biodiesel) and the brownish phase at the bottom containing glycerol and soap. The final biodiesel is obtained by centrifugation.

The educational potential of this laboratory activity, the wide variety of chemical concepts that it deals with, and the simple replication of soap preparation, all contributed to its successful presentation as a demonstration activity in the scientific dissemination fair “Science for Everyone”. For safety reasons, the preparation of biodiesel was not carried out in the fair. During the activity, undergraduate students explained the importance of oil recycling, and the entire workflow for the fabrication of soap using spent vegetable oil.

Separation and chemical recycling of plastics:

In order to recycle plastics (mechanically or chemically), the first thing is to properly separate the different types of plastics according to their classification number or class: 1, polyethylene terephthalate, PET; 2, high-density polyethylene, HDPE; 3, polyvinyl chloride, PVC; 4, low-density polyethylene, LDPE; 5, polypropylene, PP; 6, polystyrene, PS; 7, others, O.[26,27] The students learned how the separation of different plastics is possible due to the floatability in water, glycerin, alcohol and vegetable oil, as well as their identification by means of physico-chemical properties (see SI).[28-30]

The main objective of the activities herein proposed for plastics was to get knowledge on the treatment of the plastic residues, and the mechanical and chemical recycling methods used for their recovery.[31] Students learned that once plastics are separated into their different classes, in order to be mechanically recycled, they have to be washed and crushed into small pieces that are then melted and poured into molds to produce new products. The mechanical recycling of plastics was another activity prepared for the Science and Technology Fair, in which the students demonstrated how plastic pieces can be converted into new plastic products by extrusion (melting and injection). For this purpose, high-density polyethylene plastic (HDPE) was shredded and extruded in bars. The structure of plastics and their physico-chemical properties were also explained to visitors.

To examine the processes behind the chemical recycling of plastics, students studied the depolymerization of PET after learning about its chemical composition. First year chemistry students, after checking the literature, decided to test the alkaline solvolysis reaction for the hydrolytic decomposition of the plastic, in order to fulfill the experimental conditions, mainly being possible to be performed in a single lab session (4 hours).[32]

For the experimental procedure, the students prepared a detailed protocol (see SI), which is summarized as follows: First, empty PET bottles are cleaned and cut into small pieces (ca. 2 × 2 mm). Once dried, the plastic pieces are refluxed for 1.5 hours with potassium hydroxide in pentanol. The mixture is then cooled down slowly and water is added to dissolve the potassium terephthalate. The plastic pieces are filtered off and finally, some hydrochloric acid is added to accelerate the precipitation of terephthalic acid, which is then collected by filtration.

Thanks to this practical activity, students performed a chemical reaction and learned the underlying mechanisms behind it.

Recovery of precious metal ions:

Metals are found in the domestic trash, but most people are not aware of the benefits of waste sorting and recycling. A short inspection of a medium family garbage pail will give us metals like aluminum[33] in the form of beverage cans and food packaging foils; lithium, cobalt, nickel and zinc in batteries; and even silver and gold in electronic devices. Unsorted metals will rust in landfills, hindering the possibility of transforming them back into new products. For the electronic waste (e-waste), students discovered how hand-separation could be done, followed by the study of the different ways for recovery of the precious metals available in e-waste. The proposed activity for the recovery of lithium and cobalt from old mobile phone batteries had two main objectives: the first was to raise the students' awareness of the huge benefits of a correct sorting and recycling of metallic domestic products at the end of their life-cycle, while the second was to assist the learning process of the acquisition of different concepts in chemistry with a particular focus on the redox chemistry. With that in mind, an activity was proposed to the first-year chemistry students as a lab experiment for the subject of General Chemistry Lab. Starting from the vast amount of electronic trash available, we chose to recycle spent lithium batteries from mobile phones.[34]

Students prepared a detailed protocol for the recovery of lithium and cobalt from their old mobile phone batteries (see SI): First, the spent batteries are discharged by soaking them in Na_2SO_4 for 24 hours. Afterwards, the batteries are manually dismantled for direct separation of elements. The copper and aluminum foils are refluxed with N-methyl-2-pirrolidone to dissolve the PVDF binder and remove the lithium, cobalt and carbon powder. To remove the carbon, the obtained black powder is calcined in a muffle furnace at 700 °C for 2 hours. The remaining powder is leached with a mixture of citric acid and hydrogen peroxide for 80 minutes at 70 °C. Subsequently, the cobalt and lithium ions are recovered by fractional precipitation using oxalic acid to precipitate cobalt oxalate and, then phosphoric acid to precipitate lithium phosphate.

As a “proof of concept”, the same project was given to first-year physics students as a part of their general chemistry course using the recycling topic as an engaging stage of instruction of redox chemistry.

Final presentation:

These activities, which were incorporated as formative assessment tools of various compulsory science subjects in chemistry and physics majors, allowed undergraduate students to acquire the knowledge and the scientific basis on which the different processes of recycling of waste are based. Not the least, to raise awareness of the importance of appropriate handling of residues and the need for recycling.

For each recycling activity, the students grouped in teams undertook a literature survey and prepared an experimental protocol for further execution in the laboratory as a practical session; and, finally, the students explained the activity and results to their classmates. For each team, the instructors evaluated the protocol, the execution in the laboratory and the oral presentation.

As already explained, a selection of the activities carried out during the academic year was presented as outreach experiments to an audience of primary and secondary school students as well as external visitors at a science and technology fair organized by the University of the Balearic Islands, excluding those parts of the activities that might be inadequate from the perspective of safety. For example, for the recycling of paper, bleaching chemicals were not used; for the recycling of oil, only soap was produced; for the recycling of plastics, only the mechanical recycling was performed; and for the recycling of electronic waste, students only presented how hand-separation was done, followed by the explanation of the various strategies for precious metal recovery in e-waste.

Regarding the Science and Technology Fair "Science for Everyone", the activity was born in 2014 and takes place yearly for 3 days, at the beginning of May. Although the fair was postponed in its 2020 edition due to the COVID-19, it is already planned for next year thanks to its great success. Since its first edition, one of the main goals of the fair is that visitors receive the scientific explanations from first year students, which have learned about the experiments during the different learning activities along the course. The audience focus is mainly groups of classmates with their teachers from all around the region (mainly Majorca), and also families with children. Year after year, the activity is reaching more students, being more than 5000 visitors in the 2019 edition. Once prepared, the activities were divided according to its level (primary or secondary school) and the students were conducted through the different activities. The accompanying teachers had a short summary of all the activities in advance to be able to prepare the visit with the students.

CONCLUSIONS

Based on the preliminary activities herein proposed and then executed in the laboratory, students came up with five questions (see below) the answers of which indicate that, from a scientific viewpoint, the Spanish rubbish system should be improved in several ways.

1) *Why is not the glass material separated by color (at least colorless, green, blue and brown)?* The collection of glass by color would help minimize the use of additives and would make the recycling of all the glass containers easier.
2) *Why are plastic and metal containers mixed together in the yellow bin?* Regarding the Spanish yellow container, it is obvious that it would be optimal to separate the metallic and the plastic containers or, at least having the aluminum alone, which cannot be magnetically selected.

3) *Why are most kinds of plastic put together while they need actually to be separated for the recycling process?* The separate collection of the whole bunch of plastic materials would make its recycling easier, but it would be not so comfortable to have at least 7 additional rubbish bins.

4) *Why are paper and cardboard not collected separately?* The separate collection of paper and cardboard would help produce a better-quality paper, at least with the paper fraction.

5) *What does happen with the mixed residues: Tetra Brik® and similar layered packages, aluminum plus tin packages…?* The reliable separation of mixed residues is a cumbersome process and so the best approach would be to completely eliminate them from our life.

In parallel to the pure academic development, the purpose of the practical activities described in this paper was to raise students' consciousness about two concepts: The first was to reinforce the reality that waste is no longer an undesirable and unavoidable end product of consumption, but a valuable raw material. The second one was to illustrate that the household trash and waste contain a number of recyclable items that should be sorted out, including: plastic, cardboard, paper, glass and metals from electronic waste, and how, using the proper treatment, waste components can be transformed into new manufactured products. The overall engagement and participation of our students evidenced that these activities helped increase their environmental concern on waste materials, therefore accomplishing our teaching objectives.

In addition, a selection of the recycling activities developed by the students was presented in a Science and Technology Fair, which contributed to student learning at two levels. On the first level, the university students who explained the different activities were more engaged and comprehended the topics better than in a traditional teacher-centered lesson. On another level, the science fair attendees learned from the open-air experiments the science behind recycling and how this helps to promote a more environmentally friendly way of life.

ASSOCIATED CONTENT

Supporting Information

Information for instructors on the prelab, lab, and postlab activities (DOCX).

Information from the students, including the final experimental protocols for the recycling of residues, safety information for all the experiments, and an appendix with hazard and precautionary statements (DOCX).

Adaptation of the activities (except recovery of cobalt and lithium from spent batteries) for hands-on distance learning during COVID-19 (DOCX).

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REFERENCES

1. Sustainable Development Goals Knowledge Platform. https://sustainabledevelopment.un.org/index.php?menu=1300 (accessed 2020-11-07).
2. The Global Goals for Sustainable Development. https://www.globalgoals.org/12-responsible-consumption-and-production (accessed 2020-11-07).
3. Fakayode, S. O. Guided-inquiry laboratory experiments in the analytical chemistry laboratory curriculum, *Anal. Bioanal. Chem.* **2014**, *406* (5), 1267–1271. DOI: 10.1007/s00216-013-7515-8
4. Johnson, L. D. Utilization of a classroom waste product- A project, *J. Chem. Educ.* **1939**, *16* (10), 495–496. DOI: 10.1021/ed016p495

5. Weires, N. A.; Johnston, A.; Warner, D. L.; McCormick, M. M.; Hammond, K.; McDougal, O. M. Recycling of Waste Acetone by Fractional Distillation. *J. Chem. Educ.* **2011**, *88* (12), 1724−1726. DOI: 10.1021/ed2001158
6. Blake Corcoran, K.; Rood, B. E.; Trogden, B. G. Chemical Remediation of Nickel(II) Waste: A Laboratory Experiment for General Chemistry Students. *J. Chem. Educ.* **2011**, *88* (2), 192−194. DOI: 10.1021/ed100519t
7. Harris, M. E.; and Harris, H. H. Sorting Recycled Trash: An Activity for Earth Day. *J. Chem. Educ.* **2007**, *84* (2), 207−210. DOI: 10.1021/ed084p207
8. Smith, M. J.; Gray, F. M. Batteries, from Cradle to Grave. *J. Chem. Educ.* **2010**, *87* (2), 162−167. DOI: 10.1021/ed800053u
9. Miller, J. L.; Wentzel, M. T.; Clark, J. H.; Hurst, G. A. Green Machine: A Card Game Introducing Students to Systems Thinking in Green Chemistry by Strategizing the Creation of a Recycling Plant. *J. Chem. Educ.* **2019**, *96* (12), 3006−3013. DOI: 10.1021/acs.jchemed.9b00278
10. Venditti R. A. A Simple Flotation De-Inking Experiment for the Recycling of Paper. *J. Chem. Educ.* **2004**, *81* (5), 693. DOI: 10.1021/ed081p693
11. Bladt, D.; Murray, S.; Gitch, B.; Trout, H.; Liberko, C. Acid-Catalyzed Preparation of Biodiesel from Waste Vegetable Oil: An Experiment for the Undergraduate Organic Chemistry Laboratory. *J. Chem. Educ.* **2011**, *88* (2), 201−203. DOI:10.1021/ed9000427
12. Mascal, M.; Scown, R. Converting Municipal Waste into Automobile Fuel: Ethanol from Newspaper. *J. Chem. Educ.* **2008**, *85* (4), 546−548. DOI:10.1021/ed085p546
13. 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. DOI: 10.1021/acs.jchemed.8b01009
14. Döhlert, P.; Weidauer, M.; Peifer, R.; Kohl, S.; Enthaler, S. Introducing Students to Feedstock Recycling of End-of-Life Silicones via a Low-Temperature, Iron-Catalyzed Depolymerization Process. *J. Chem. Educ.* **2015**, *92* (4), 703−707. DOI: 10.1021/ed5007579
15. Subratti, A.; Lalgee, L. J.; Jalsa, N. K. Robust, Efficient, and Economical Magnetic Stirrer: A Device Based on Pulsed Width Modulation, Built Using Mainly Recycled Parts. *J. Chem. Educ.* **2020**, *97* (1), 305−307. DOI: 10.1021/acs.jchemed.9b00395
16. Hopkins, T. A.; Samide, M. Using a Thematic Laboratory-Centered Curriculum to Teach General Chemistry. *J. Chem. Educ.* **2013**, *90* (9), 1162–1166. DOI: 10.1021/ed300438t
17. Williams, P. T. *Waste Treatment and Disposal*, 2nd ed.; John Wiley & Sons Ltd: England, 2005. DOI: 10.1002/0470012668
18. University of the Balearic Islands, "*Ciència per a tothom*" project. https://seras.uib.cat/ciencia/ (accessed 2020-11-07).
19. Campbell, J. A. Paper: A modified natural polymer. *J. Chem. Educ.* **1986**, *63* (5), 420–421. DOI: 10.1021/ed063p420

20. JCE staff. New Paper from Newspaper. *J. Chem. Educ.* **2001**, *78* (11), 1512A. DOI: 10.1021/ed078p1512A
21. Carter, H. A. The Chemistry of Paper Preservation: Part 4. Alkaline Paper. *J. Chem. Educ.* **1997**, *74* (5), 508–511. DOI: 10.1021/ed074p508
22. Ullmann, F. *Ullmann's Encyclopedia of Industrial Chemistry*, 7th ed.; Wiley-VCH: Weinheim, Germany, 2011. DOI: 10.1002/14356007
23. Kawentar, W. A.; Budiman, A. Synthesis of Biodiesel from Second-Used Cooking Oil. *Energy Procedia.* **2013**, *32*, 190–199. DOI: 10.1016/j.egypro.2013.05.025
24. Félix, S.; Araújo, J.; Pires, A. M.; Sousa, A. C. Soap production: A green prospective. *Waste Management.* **2017**, *66*, 190–195. DOI: 10.1016/j.wasman.2017.04.036
25. Pohl, N. L. B.; Streff, J. M.; Brokman, S. Evaluating Sustainability: Soap versus Biodiesel Production from Plant Oils. *J. Chem. Educ.* **2012**, *89* (8), 1053–1056. DOI: 10.1021/ed100451d
26. Burmeister, M.; Eilks, I. An example of learning about plastics and their evaluation as a contribution to Education for Sustainable Development in secondary school chemistry teaching. *Chem. Educ. Res. Pract.* **2012**, *13* (2), 93–102. DOI: 10.1039/C1RP90067F
27. Enthaler. S. Illustrating Plastic Production and End-of-Life Plastic Treatment with Interlocking Building Blocks. *J. Chem. Educ.* **2017**, *94* (11), 1746–1751. DOI: 10.1021/acs.jchemed.6b00888
28. Guedens, W. J.; Reynders, M. Identification and Formulation of Polymers: A Challenging Interdisciplinary Undergraduate Chemistry Lab Assignment. *J. Chem. Educ.* **2017**, *94* (11), 1756–1760. DOI: 10.1021/acs.jchemed.7b00284
29. Harris, M. E.; Walker, B. A Novel Simplified Scheme for Plastics Identification. *J. Chem. Educ.* **2010**, *87* (2), 147–149. DOI: 10.1021/ed800055p
30. Hughes, E. A.; Ceretti, H. M.; Zalts, A. Floating plastics: an initial chemistry laboratory experience. *J. Chem. Educ.* **2001**, *78* (4), 522. DOI: 10.1021/ed078p522
31. Precious Plastic Project. https://preciousplastic.com/ (accessed 2020-11-07).
32. Kaufman, D.; Wright, G.; Kroemer, R.; Engel, J. "New" Compounds from Old Plastics: Recycling PET Plastics via Depolymerization. *J. Chem. Educ.* **1999**, *76* (11), 1525–1526. DOI: 10.1021/ed076p1525
33. European Aluminum, "Recycling Aluminum: a pathway to a sustainable economy" 2015. https://www.european-aluminium.eu/ (accessed 2020-11-07).
34. Chen, X.; Luo, C.; Zhang, J.; Kong, J.; Zhou, T. Sustainable Recovery of Metals from Spent Lithium-Ion Batteries: A Green Process. *ACS Sustainable Chem. Eng.* **2015**, *3* (12), 3104–3113. DOI: 10.1021/acssuschemeng.5b01000