Learning Circular Economy by Hands-on Experiments: A Case-Study on Phosphorus Recovering from Wastewater at School

Ornella Francioso[1], Alberto Zanelli[2], Mauro Murgia[3], Lorenzo Forini[4], Armida Torreggiani[2]

Dipartimento di Scienze e Tecnologie Agro-Alimentari, Università di Bologna, Italy[1]
Consiglio Nazionale delle Ricerche (CNR), Istituto per la Sintesi Organica e la Fotoreattività, Italy[2]
CNR, Istituto per lo Studio dei Materiali Nanostrutturati, Italy[3]
Gamification External Consultant, Italy[4]

Abstract

Circular economy (CE) is now gaining attention in academia and industry as an emerging model for minimizing primary resource depletion, waste and greenhouse gas emissions. In the present work, we present a learning pathway, designed for high schools, useful to introduce some basic concepts of CE among youngsters by starting from a laboratory experience.

The path was developed in the framework of the European project Raw Matters Ambassadors at Schools (RM@Schools), an innovative program to make science education attractive for youngsters which and to promote a wide dissemination action on raw material-related themes in Schools and Society. In this context, lab experiments to approach raw materials (RMs) considered critical by EU and the necessity of their recovery were set up for high school students.

Phosphate rock (P) is one of the critical RMs for EU, and it is primarily used in agriculture. After 2033 Iit is expected a huge decline in P extraction and consequently, a dramatic decrease in fertilizers, food and feed.

The goal of the lab experience presented here is to educate students that P can be recovered from secondary resources such as urine, a component of wastewater. The laboratory activities are planned in a theoretical training under the teacher guidance and another practice where students become the main protagonists of all phases of the work (from design to evaluation). The laboratory activity is composed by three experiments with various levels of difficult. By using the material created for this learning path, students become familiar with the concept of biogeochemical cycles and specifically nitrogen and phosphorous cycling, and learn that in CE end-of-life products are considered as resources for another cycle. In addition, consideration must be given to the interactions between materials to determine the best circular solution. Students can be aware of the benefits of closing material loops in a simple and engaging way.

Keywords: *P recycling, Struvite, hydroponics, circular economy, raw materials, learning-by-doing*

1. Introduction

In the learning paths for undergraduate students that are the next generation of professionals, it is important to integrate a participatory vision on sustainability [1]. In fact, education is the most important tool to reshape worldviews and values and has enormous potential to address the sustainability challenges facing humanity [2].

The raw material value chain has been identified by Europe as a sector requiring education of highly skilled professionals because the supply of a certain group of raw materials (RMs) is a major concern for the growth of the European industry [3]. Phosphorus (P) is one of them. P is a life essential element, and its availability is of great relevance to global food security, as it is a major component of mineral fertilizers [4]. The increased mining of phosphate rocks, exacerbated by population growth and increased biofuel production, has caused anthropogenic alteration of the P cycle beyond its natural biogeochemical rate. There is a great disparity in the geographic distribution of P reserves in the world: Morocco and the Western Sahara account for 71.5% of all P reserves [5] and other countries, USA and China, are limiting the production or exports [6]. Moreover, 80% of inorganic P is lost from the mine to the fork [7] and only 10% of fertilizers are used by humans [8]. Over half of the soil-to-fork fertilizer application losses are in runoff from agricultural soil. Thus, the European Commission has listed P in its critical RM list in 2014 [9] because of a variety of multiple-faceted reasons, and not just a question of deficiency. Price volatility and geopolitical P factors are important factors for the EU to include this essential element in the list. Some EU member states have also adopted national strategies for recovering P from wastewater and reusing it in agriculture [10]. Consequently, the best path for P management is to set up a recovery system that closes the P cycle, minimize losses and

optimize the waste value [11]. As the majority of consumed P ends up in municipal wastewater, a sustainable and rational wastewater management pathway for P recovery is becoming workable. P may be recovered from wastewater in the form of struvite or calcium phosphate and used as a slow-release fertiliser in agriculture.
A learning path, targeted for students of 15-18 years old and focused on the P recovery was set up in the framework of Raw Matters Ambassadors at Schools (RM@Schools) [12-14], a European project, which aims at raising awareness on the sustainable use of raw materials as well as increasing the interest for STEM disciplines, able to allow the future transition towards a low carbon society. By using a combination of approaches such as open discussion, learning by doing, and implementing i.e. waste reduction and recycling at schools, students are involved in an experiential learning process to develop critical thinking and to increase their awareness about sustainability development.

2. Activity Structure

The pathway begins by introducing students to relevant content knowledge about the P cycle and its importance for agriculture, as well as some solutions offered by the research focused on the P recovery. Then, students, in groups of 4-5, are engaged in hands-on activities to support or extend their learning and their inquiry skills.

2.1 Experimental design

Phosphorus can be recovered from wastewater in crystal form of magnesium ammonium phosphate ($MgNH_4PO_4\ 6H_2O$), also known as struvite which is also considered an environment-friendly fertilizer.
The laboratory activity included three experiments designed at different levels of difficulty under highly controlled conditions: i) production of synthetic urine from which struvite is extracted; ii) test the fertilizer property of struvite on basil plants in hydroponics; iii) to build a simple reactor to recovery struvite [12].

2.2 Struvite preparation

Urine, a product of human excretion, is a component of urban wastewaters. Urine is one of the richest and most accessible sources of phosphorus and nitrogen to make struvite. Struvite can be obtained by a precipitation reaction at basic pH from synthetic urine, helped by magnesium addition, as follows:

$$\mathbf{Mg^{2+} + NH_4^+ + H_2PO_4^- \rightarrow MgNH_4PO_4{\cdot}6H_2O \downarrow + 2H^+}$$

The struvite precipitates after about 3 hours in the form of white powder. The yielded struvite can be used to fertilize garden or potted plants.
The teacher's role is to explain theoretically the chemical reaction, and the effect of all reagents, including pH. Each group takes part in preparing the struvite. By the end of the experiment, the groups are asked to quantify the struvite to be used in the hydroponics (2.3 section). The present laboratory practice assists pupils in developing skills for proper and safe use of scientific equipment (e.g., balance, pH meter), making observations, performing measurements, and well-defined scientific procedures (e.g., writing a lab protocol). A special focus concerns students' ability to cooperate effectively with others in performing complex tasks.

2.3 Hydroponics

The struvite recovered through the precipitation reaction (see 2.2 section) is a valuable mineral fertilizer. The teacher's role in this trial is marginal as he/she has to give instructions on how the basil plants should be treated for hydroponics. Groups have different roles at different times. For example, one group is responsible for preparing the basil plants to be flared. After that, the plants need to be acclimated with the nutrient solution. Another group is involved in collecting plastic bottles obtained from the recycling at school or home. This procedure, in addition to reducing the cost of growing basil plants, reinforces the concept of a circular economy. A third group is responsible for monitoring nutrient solution parameters, sun exposure and basil plants growth until the test is complete.
Furthermore, pupils learn a key concept in many biological disciplines: the dose-response relationship of a treatment. The evidence for a dose-response relationship proves that the observed effects support a causal relationship between struvite concentration and the effects on basil plant. In this experiment, in order to evaluate the efficacy of struvite, a dosage of 10 and 100 mg/L is given to hydroponic cultures (Fig.1). All doses compared to the untreated basil plants. After a period of cultivation, about 3 weeks, the plants are removed by the hydroponic system and the fresh and dray weights of each treated plants are measured. Hydroponics develops a variety of interdisciplinary and

practical skills in the disciplines of plant biology, ecology and sustainability, chemistry, nutrition, water, alternative energy, technology, and mathematics. Students can also practice important soft skills like teamwork, critical thinking, and responsibility as they work together to grow plants.

Figure 1. Basil plants in hydroponics at different doses of struvite. The trial was performed in the laboratory of high school.

2.4 Reactor to recovery struvite

Building a simple reactor for extracting struvite from synthetic wastewater and evaluating its operation (Fig. 2) is an important test of this educational pathway. Teacher assistance is necessary because pupils have to handle some dangerous equipment (e.g., hair dryer and hacksaw). In this trial, all groups are involved in building the reactor. The aim of this experience is to demonstrate that the struvite recovery can be obtained from synthetic wastewaters (see 2.2 section) by using very common materials available in hobbyist warehouse.

This experience requires manual ability and at the same time, basic knowledge of plumbing. The highest level of difficulty is to achieve an efficient hydraulics system. Pupils become aware of the P recycling from wastewaters to reduce the exploitation of natural resources. Finally, laboratory experience may develop skills in using scientific equipment correctly and safely, making observations and carrying out well-defined scientific procedures.

Figure 2. The picture on the left illustrates the individual components of the reactor: A) lid; B) central body; C) funnel; and D) Tap. The image on the right displays the mounted reactor

3. Conclusion

The lab experience, set up as part of the RM@Schools project, can give students the opportunity to use tools, data collection techniques, and theories of science. Lab experiences are particularly useful in preparing the next generation of scientists and engineers by helping students achieve a variety of educational goals.

In particular, from this experience, students, involved in the test of this activity, realized that they needed to arrive at a common goal, helping each other and feeling co-responsible for the work. Thus, when students share ideas, they also learn to build stronger arguments. It was also interesting to observe that active learning helps students be more creative, and through cooperation, better and more innovative project ideas and solutions were developed, such as building a reactor to produce struvite.

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