Multidisciplinary Journal for Education,
Social and Technological Sciences

http://dx.doi.org/10.4995/muse.2017.6462
EISSN: 2341-2593

Teaching chemistry with sustainability

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Received: 2016-02-12; Accepted: 2016-*06-24*

Abstract

Increased awareness on a critical association between the natural environment and human development gave rise multiple projects, aiming to protect the natural environment and to preserve it for future generations. Chemists must be acquainted with the principles of green chemistry and the need to practice experimental chemistry with cleaner chemical reactions and sustainability. This is a major concern for all the educators forming new professionals within the Chemistry, Pharmacology and Biology curricula in the Faculty for Higher Studies Zaragoza from the National Autonomous University of Mexico. With this in mind, we start our teachings explaining from the very beginning, how important it is to perform microscale techniques and to follow the principles of green chemistry in the Basic Science Laboratory. Furthermore, we have modified, designed and evaluated working procedures related with chemical synthesis, kinetics and calorimetry. By doing this, we managed to greatly reduce the amount of reagents required and residues generated. Some laboratory reagents have been substituted with renewable substances. We have also included in our programme a regular treatment of residues generated during everyday laboratory work. Our goal is to emphasize the importance of minimizing the environmental impact of chemistry and to prepare environmentally concerned professionals who keep sustainability as main priority and perform chemistry procedures with good laboratory practice routines.

Keywords

Education, sustainability, green chemistry, microscale, experimental chemistry.

1. Introduction

To recognize that the environment is a fundamental element for human development has led to create programmes specifically designed to improve the utilization of natural resources and to preserve them for future generations (Matlin et al. 2015). A multidisciplinary approach has to be taken in order to face many environmental challenges already existing. Chemistry, in general, and green chemistry in particular, are key disciplines to achieve these goals with sustainability (Fisher, 2012).

1.1 Sustainability

What does sustainability mean? Why do we hear about it more and more often and why should we be concerned about it? This term emerges from the need to counteract the unsustainability that predominates and characterises many technological, industrial and agriculture procedures occurring nowadays in the world (Watson, 2012). High utilization and irresponsible consumption of every type of natural resources are unsustainable in long-term. Equally unsustainable and unacceptable are the effects on human health, wild life and nature, caused by the high generation of pollutants, increased amount of greenhouse chemicals, accelerated and disorganized expansion of human settlements that go along the logarithmic increase of world population, decreased biodiversity, loss of natural resources and socioeconomic destabilization. Altogether, the mentioned problems and circumstances are indicating a global emergency, mostly caused by human actions. We are the main actors of the Anthropocene, as the Nobel Prize in chemistry Paul Crutzen defined the present era of human influence on earth. As dominant species, we are responsible from the critical situation in which earth has been artificially placed. The remediation of problems already existing and the avoidance of new and bigger problems may hopefully also be in our own hands.

Hans Carl Von Carlowitz used the word “sustainability” for the first time in 1713, in his book “Silvicultura oeconómica”, advocating for the conservation, growing and use of wood in a continuing, stable and sustained manner. He referred to sustainable as not to cut down more trees than those that could be simultaneously planted (Schmithüsen, 2013). Later on, George Perkins Marsh published “Man and Nature”, with a detailed analysis about the environmental impact of human activities. Perkins Marsh made clear that it was very urgent to find the way to stop and prevent the devastating effects that were already caused by human beings (Perkins Marsh, 1864). Rachel Carson, considered as the mother of the ecologist movement, published “Silent spring” in 1962, discussing the risks associated with the widespread application of dichlorodiphenyltrichloroethane (DDT) as pesticide, arguing that DDT caused more damage than benefit and that the negative effects on the environment and the human health were still largely unknown (Carson, 1962). This work raised awareness on the danger caused by environmental pollution with DDT and contributed to the implementation of regulatory measurements taken by governmental agencies in many countries. The impact of “Silent spring” continued with the 1972 report from the ”Club of Rome”, which gathered a global network of independent and renowned thinkers, set out to push the boundaries of thinking on sustainability (Meadows et al., 1972). These publications made evident that the kind of scientific progress that was known until that moment, was not the solution to all problems. On the contrary, science and technology were too often responsible for causing environmental and social problems (Schmithüsen, 2013).

The World Commission on Environment and Development (WCED) from the United Nations (UN) presented a report entitled “Our Common Future”, which is also known as the Bruntdland report. In the first chapter of this report, sustainable development is defined as that which is able to satisfy the needs from the present generation without compromising the capacity from future generations to satisfy their own needs (WCED, UN, 1987).

1.2 Education

Sustainable development must be as integrated and holistic as science and education (Vilches, 2011, 2013). In fact, sustainability is based on education, as it has been discussed in the UN Conference on human environment, in Stockholm, the Intergovernmental

Conference on Environmental Education, in Tbilisi, the UN Conference on Environment and Development (UNCED) and the UN Conference on Sustainable Development that had place during 1972, 1977, 1992 and 2012, respectively. The UN proclamation of the decade of Education for Sustainable Development is the biggest and most recent effort to direct education towards sustainability. The UN declared 2005-2014 as the decade of Education for Sustainable Development in order to confront the global emergency situation that we are living. According to the UN, education alone will not be enough to achieve a more sustainable future. However, sustainability cannot be reached without education. Therefore, the UN attempt to integrate principles, values and practices of sustainable development in every aspect of education, in order to promote changes of behaviour that are necessary to preserve the future integrity of the environment and economy, as well as social justice for present and future generations (DEDS, 2012).

The time for educators and students to look at environmental problems as spectators has passed. We must ask ourselves what can we do in response to these international calls and act accordingly. How can we, by teaching chemistry at the universities, redirect education towards sustainability? At the present moment, we are working with two proposals that may fulfil this purpose at the Faculty for Higher Studies Zaragoza (FES-Z) from the National Autonomous University of Mexico (UNAM): Microscale Chemistry and Green Chemistry.

1.3 Experimental chemistry education

Significant changes are necessary to face the present global emergency. Such kind of changes are indispensable within experimental chemistry, one of the most powerful engines to redirect the present socioeconomic crisis towards sustainability (Bybee, 1991). Accordingly, UNESCO proclaimed 2011 as the international year of chemistry with the motto: “Chemistry-our life, our future”, perfectly stating the strong influence of chemistry on the human society and the opportunities that it may provide to make a transition towards sustainability. Thus, how can we contribute with experimental chemistry education towards sustainability? We decided to work with microscale chemistry and green chemistry, since they are powerful tools that have already been effectively used to achieve this goal (NMCC, 2002; Cannon and Warner, 2011).

1.3.1 Microscale chemistry

Working with microscale means to reduce the amount and utilization of chemical reagents to the minimal levels that are necessary to properly perform the experiments. Microscale also represents a group of environmentally safe methods to accomplish chemical processes, avoiding pollution without compromising the quality standards of the results. The amount of chemical reagents needed for our practical sessions in the Basic Science Laboratory is drastically reduced to a rank of 0.5 - 0.005 g (NMCC, 2015).

Microscale chemistry provides among others, the following benefits:

- Less production and utilization of chemicals
- Less storage space required
- Less working time in the laboratory
- Lower glassware costs
- Lower costs for laboratory work

http://dx.doi.org/10.4995/muse.2017.6462
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- Improved laboratory techniques
- Better air quality and minimal exposure to toxic fumes
- Cleaner and more productive environment
- Safer laboratory work
- Improved awareness of risk for people using chemicals
- Higher awareness of the importance of the environment
- Promotion of the three R principle (Replacement, Reduction, Refinement)

Microscale chemistry is very attractive for educators because it addresses general needs for teaching science without special equipment. Working with microscale appeared as an alternative to make chemistry teaching less laborious and more accessible for a higher number of students. Since these objectives are in line with sustainability, microscale is a valuable tool to facilitate the transition of cumbersome laboratory methods to more sustainable methods, without compromising chemistry education. However, green chemistry is still the best and more complete alternative to reach sustainability.

1.3.2 Green chemistry

Green chemistry is a working philosophy that emerges in response to the need for preserving the environment, with prevention as main objective, instead of remediation (Luque, 2012). According to the American Chemical Society (ACS), green and sustainable chemistry is a distinctive way of thinking, based on a set of principles that when used in the design, development and implementation of chemical products and processes, enables scientists to protect and support the economy, the people and the planet. Green chemistry consists in finding new ways to create and innovate, as well as to reduce waste and energy consumption and to look for replacement for dangerous substances (Anastas and Warner, 1998).

The following table contains the 12 principles of green chemistry, conceived by Paul Anastas and John Warner (1998) as a framework for designing or improving materials, in order to make ”greener” products, processes and systems:

1. Prevention: It is better to prevent waste than to treat or clean up waste after it has been created.

2. Atom economy: Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

3. Less hazardous chemical synthesis: wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. Designing safer chemicals: chemical products should be designed to affect their desired function while minimizing their toxicity.

5. Safer solvents and auxiliaries: the use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary whenever possible and innocuous when used.

6. Design for energy efficiency: energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

7. Use of renewable feedstocks: raw materials or feedstocks should be renewable rather than depleting whenever technically and economically practicable.

8. Reduce derivatives: unnecessary derivatization should be minimized or avoided, because it requires additional reagents and can generate waste.

9. Catalysis: catalytic reagents are superior to stoichiometric reagents.

10. Design for degradation: chemical products should be designed so that at the end of their function they breakdown into innocuous degradation products and do not persist in the environment.

11. Real-time analysis for pollution prevention: analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. Inherently safer chemistry for accident prevention: substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

To adhere ourselves to the 12 principles proposed by Anastas and Warner, we need to have the ability to integrate additional disciplines in order to achieve sustainability. New generations of chemists must be acquainted with green chemistry and sustainability from the very beginning of their professional education in order to be able to prevent pollution and to perform cleaner chemical processes. Therefore, we ask ourselves which actions must be taken for teaching experimental chemistry with sustainability. How may we promote the cultural change required among teachers and students during their experimental chemistry work, while keeping full awareness of their roles as academics, professional and citizens?

This is an important concern for educators involved in teaching experimental chemistry to students following the Chemistry, Pharmacology and Biology (QFB) curricula in the FES-Z from the UNAM. This concern is very much present in the Laboratory for Basic Science (LCB), during the first two semesters of education at professional level and it is the reason why, we have integrated microscale and green chemistry principles in our laboratory work, whereas we keep looking for new designs and evaluate new proposals of experimental work, oriented both to better education and sustainability.

2. Methodology

The QFB curricula and the LCB I and LCB II programmes were examined, focusing on design, needs or easiness for modification and evaluation of experimental chemistry proposals for chemical synthesis, kinetics and calorimetry. An exhaustive review of relevant literature was done to find experimental proposals with low cost, easy access and everyday utilization that could be adapted to microscale and green chemistry. Then, proposals were studied in relation to subjects and objectives included in the curricula and LCB programme. Some proposals were selected, adapted to microscale and green chemistry, evaluated and classified according to the 12 principles of green chemistry by using a Likert-type scale (Morales-Galicia, 2011) to determine how green they were (Figure 1). In addition, proposals were also evaluated according to b) reagents toxicity and c) need for treatment of residues, by means of pictograms and ecologic diagrams, respectively. In this work, only a proposal to study chemistry kinetics will be discussed.

Figure 1. Colour code and Likert- type scale of analysis to evaluate grades of green

This proposal was developed in the laboratory according to the following procedure:

1. Prepare solutions: 1g vitamin C, 0.04 M iodine, 5% cornflour and 3% hydrogen peroxide in 60 mL of water.
2. Fill up insulin syringes (1mL).
3. Transfer solution to beakers of 10 mL.
4. Add H_2O_2, agitate the mixture and start registering time.
5. Stop the time when the iodine-starch complex (deep blue) appears.
6. Test by triplicate, using 5 different H_2O_2 concentrations.
7. Perform statistics analysis: obtain average value, standard deviation (S) and relative standard deviation or coefficient variation (% CV).
8. Plot and obtain empirical equation.

3. Discussion of the proposal and results

Experimental work designed to study a iodine-vitamin C clock reaction (Wright, 2002) by microscale, according to the 12 principles of green chemistry was organized in 4 steps: A, B, C and D, established as follows:

Measurement instrument	Chemical source	
	Laboratory reagents	Everyday use products
Micropipette	A	C
Insulin syringe	B	D

Here, only results of step D are shown. In this case, we used insulin syringes and everyday use products, such as vitamin C tablets, commercial 3 % hydrogen peroxide, cornflour and tincture of iodine. Results are shown in Tables 1, 2 y 3, and Graph 1. Statistics analysis and corresponding equation with an r = 0.9998 indicates that the best function explaining the effect of different hydrogen peroxide concentrations on the speed reaction is potential. The coefficient variation (CV) obtained in repetitions from every assayed concentration was not higher than 2.20 %, suggesting that the variability was minimal. Therefore, systematic experimental error may be considered under control. The proposal was also considered adequate to be performed in LCB to study the speed of a chemical reaction.

		V H_2O_2 (mL)				
		0.20	0.30	0.40	0.60	0.80
#	1	289 s	181 s	124 s	71 s	49 s
	2	295 s	181 s	122 s	69 s	49 s
	3	292 s	182 s	125 s	70 s	48 s
$\bar{y}$		292.00 s	181.33 s	123.67 s	70.33 s	48.66 s
S		3.00	0.54	1.53	1.53	0.58
% CV		1.03	0.32	1.24	2.17	1.19
r (potential)		0.9995				

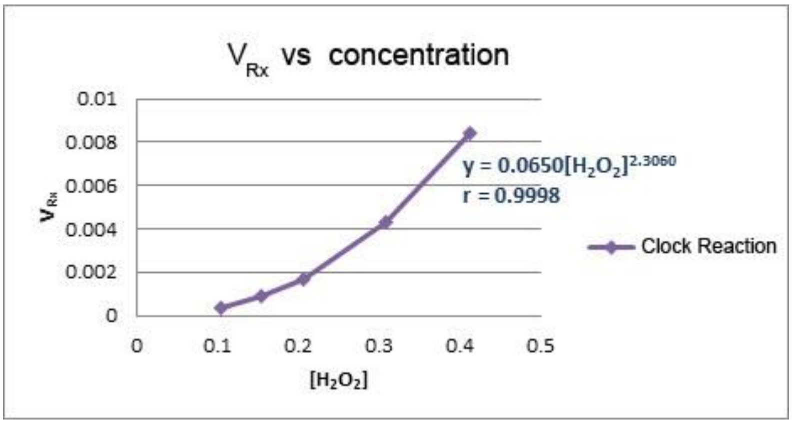
Table 1. Endpoints obtained varying H_2O_2 concentration and function to which data may be adjusted

H_2O_2		Time (s)	V_{Rx} ($[H_2O_2]$ /s)
V (mL)	Molarity (M)		
0.2	0.1029	292.00	3.5239×10^{-4}
0.3	0.1544	181.33	8.5149×10^{-4}
0.4	0.2058	123.66	1.6642×10^{-3}
0.6	0.3088	70.33	4.3907×10^{-3}
0.8	0.4117	48.66	8.4607×10^{-3}

Table 2. Speed of reaction with different H_2O_2 concentrations.

Parameters	Results
Potential equation	$y = bx^m$
y	V_{Rx}
x	$[H_2O_2]$
m	2.3060
b	0.0650
r	0.9998
Empirical equation	$V_{Rx} = 0.0650\ [H_2O_2]^{2.3060}$

Table 3. Minimal square parameters to determine the empirical equation.



Graph 1. Speed of reaction (V_{Rx}) in response to different H_2O_2 concentration.

A flux diagram was elaborated, in order to evaluate how green was the experiment (Figure 2). Safety pictograms are included in this diagram, to facilitate the recognition and handling of dangerous chemicals in every step of the process. Afterwards, a Likert-type scale and a colours' code were used to make a numerical qualitative evaluation of the process in relation with the 12 principles of green chemistry (Stewart et al., 2016). Additional tables were elaborated to show how to obtain the final evaluation (Table 4) and to enlist justification for every step of the process (Table 5).

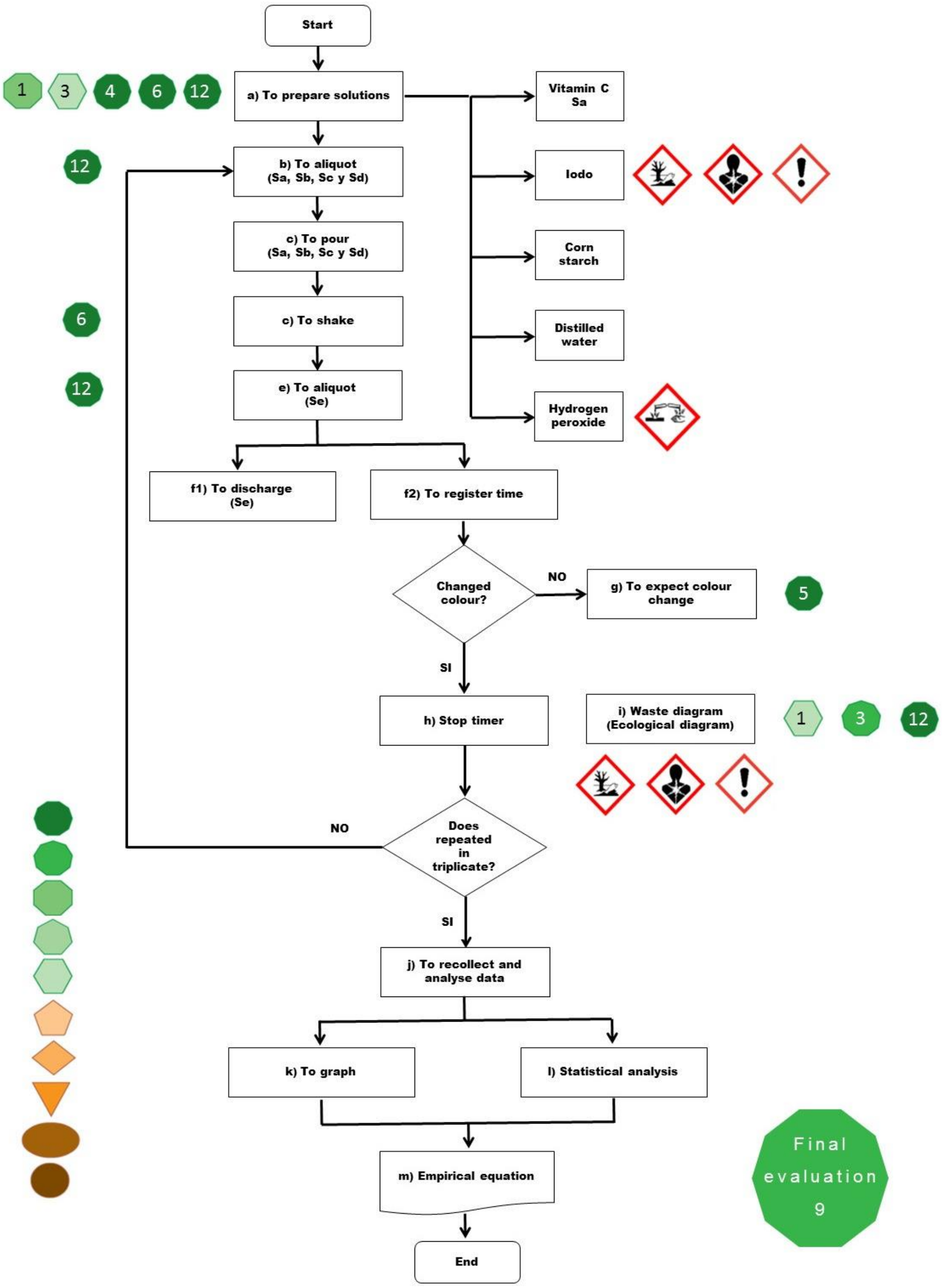


Figure 2. Flux diagram to evaluate an experimental proposal involving the iodine-vitamin C clock reaction. A final numerical score of (9) was assigned.

The process of making a greener experiment starts with a drastic reduction in the amount of reagents. When the amounts of utilized reagents are smaller than 1 mL, residues, risks, environmental damage and costs are also smaller. Costly chemical reagents normally acquired from specialized companies are substituted with low cost, everyday use products. These simple actions take experimental work closer to become green enough for making a transition towards sustainability. An evaluation before and after modifications verifies that these changes actually make the chemical work to become greener.

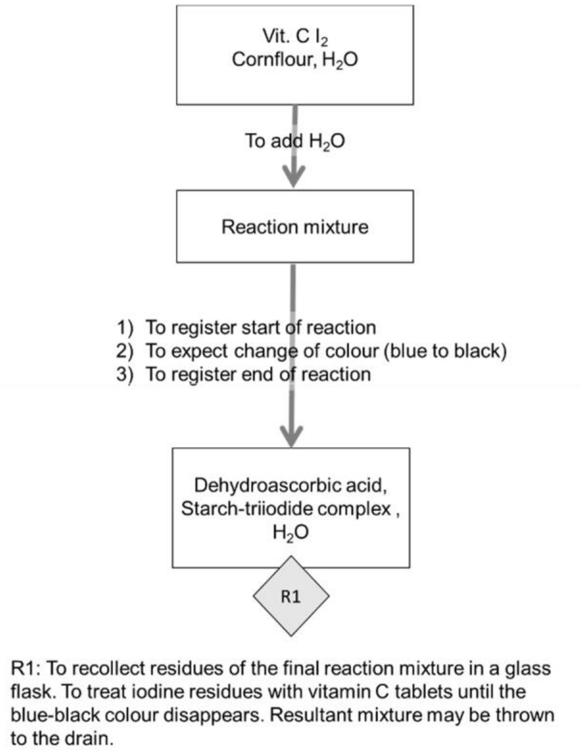
Process step	Principle of Green Chemistry	Likert-type scale	# of evaluation
a)	1 3 4 6 12	(8) (6) (10) (10) (10)	1 2 3 4 5
b)	12	(10)	6
d)	6	(10)	7
e)	12	(10)	8
g)	6	(10)	9
i)	1 3 12	(8) (6) (10)	10 11 12
Total Points (PT)		108	12
Final Evaluation = PT / # E 108 / 12 = (9) value of Likert-type scale The proposal is STRONGLY GREEN			

Table 4. Results of final evaluation procedure of the experimental proposal involving the iodine-vitamin C clock reaction. A final numerical grade of (9) was assigned to this particular experiment.

Step	Principle	Justification
a)	1	Iodine must be still treated prior to disposal. Principle 1 receives a score of 8.
	3	Amounts of reagents utilized and residues generated are greatly reduced. Microscale and every day use products make principle 3 to receive a score of 6
	4	Replacement of reagents by everyday use products makes principle 4 to receive a score of 10.
	6	Microscale drastically reduces costs and energy consumption. Therefore, principle 6 is evaluated with a score of 10.
	12	Principle 12 receives also a score of 10, since very small amounts considerably decrease risk for health and the environment.
b)	12	As above
d)	6	As above
e)	12	As above
g)	5	Using cornflour as indicator makes principle 5 to receive a score of 10.
i)	1, 3, 12	As above

Table 5. Justification for making greener an experimental proposal involving the iodine-vitamin C clock reaction.

An ecologic diagram was also elaborated to show in detail source and handling of residues generated (Figure 3). Students are also involved, as much as possible, in the treatment of residues, to increase their responsibility, environmental culture and participation in reducing the impact of their work in the environment.



R1: To recollect residues of the final reaction mixture in a glass flask. To treat iodine residues with vitamin C tablets until the blue-black colour disappears. Resultant mixture may be thrown to the drain.

Figure 3. Ecologic treatment of residues generated by the iodine-vitamin C clock reaction.

4. Conclusions

Three experimental proposals were adapted to be performed in the LCB from the QFB curricula at FES-Z, UNAM. Here, one of them is discussed as an example from the benefits of incorporating microscale and green chemistry, in search for a transition towards sustainability.

Several goals can be reached applying green chemistry principles and using low-cost, everyday use, easily available materials. Pollution and dangerous residues generated by work in the laboratory during chemistry education are greatly reduced. Increased awareness of the necessity to preserve the environment, the importance of decreasing residues and the responsibility for proper disposal of dangerous chemicals are also key advantages of green chemistry and must be compulsorily incorporated in chemistry education. In the present report, we discuss the evaluation of an experimental proposal in relation with the 12 principles of green chemistry, reagent toxicity and handling of residues. The results of this evaluation indicated a strongly green procedure, with a numerical score of 9, which also indicates that is adequate for teaching experimental chemistry and sustainability. Different teaching methods have been evaluated and chosen within the framework of the European Higher Education Area to be implemented into a Combustion course delivered at the ETSID of the Universitat Politècnica de València. Such methodology is based upon the interaction between the lecturer and the student, and is being applied for groups with large number of students. Among the main results, the high grades obtained by students have to be noted, which are independent of the area that is being evaluated (theoretical lectures, guided work…). In spite of the fact that such an estimator is not definitive to determine the success of the methodology, it can be considered as a first good approximation. However, certain deficiencies have been detected due to the dissemination of information among students when using the evaluation system by means of the UPV digital platform, which questions some of the grades obtained by some students. Such information dissemination has been quantified numerically. When eliminating such results, grades are still high, showing a high degree of comprehension of the concepts by the students.

5. Acknowledgements

This project was supported by UNAM (DGAPA PAPIME PE210815).

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