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How to Prepare Didactic Experiments Related to Chemical Properties for Primary, Secondary and High School

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Abstract: *The article shows didactic experiments related to chemical properties which could be easily adapted to any educational level, from primary to high school. Moreover, through of these experiments, teachers could introduce diverse relevant concepts which are normally included in the curriculum of chemistry subject depend on the educational level. Furthermore, each of these didactic experiments is included in one of the three fundamental blocks of chemistry subject in Spain: 1) matter and its states, 2) acid-base reactions and 3) redox process. In addition, most of the experiments, which are described here, could be performed in school laboratories because they only need basic lab equipment and common chemical compounds. The main aim of the authors is to encourage school teachers to use educational practices, such as didactic experiments, as pedagogical tools to consolidate and integrate the knowledge that students receive in theoretical classes.*

Keywords: *Didactic experiments, educational tool, chemical knowledge consolidation, soft skill development.*

1. Introduction

Every day people are continuously in contact with chemical substances independently if they live in a city or in the countryside because the backyard, the kitchen, and other areas around home provide natural "laboratories" for everybody. Each chemical substance intrinsically possesses a serial of properties which can be used to our advantage, as teachers and as a society. These properties could be classified in state (solid, liquid and gas), acidity or basicity, oxidative or reductive power, shape, density, and so on. Students find chemistry subject really difficult to understand for them, therefore they are not enough motivated and consequently some chemical concepts are not easy to explain to them [1-4]. Moreover, students (ages 6-18) define chemistry as one of the more complex and boring subjects in primary, secondary and even high school [5-7].

For these reasons, the key to success in teaching chemistry is capture their attention and give them the basic vocabulary in order that they could interpret and discuss chemical phenomena at both adequate and acceptable level [8-10]. An effective way to capture their attention is that school science teachers perform experiments, adequate to the educational level, because students could observe the chemical properties by themselves, and even doing these didactic experiments in groups in order to discuss them in a pleasant atmosphere [11-12]. Furthermore, working in groups also helps students to learn how to communicate their ideas and doubts with other members of the group, focus on solving questions and develop social skills such as teamwork, tolerance and respect for the opinion of others [13-15]. Our teaching experiences suggest that a wide and profound theoretical knowledge base is not essential for school students and didactic experiments are an effective pedagogical tool to offer evidence-based science instruction to students from primary to high school. On top of that, the experiments presented in this work demand both basic and common material resources so a broad spectrum of science teachers and academic institutions could perform them in school laboratories. Additionally, most scientist and science educators are interested to include active learning approaches, such as practical lessons or laboratory experiments, which allow school students to appreciate how primary evidence is used to construct scientific knowledge [16-17].

2. Objectives

The aim of the present contribution is to describe some laboratory experiments related to chemical properties using common chemical substances in order to offer teaching tools to school science teachers that allow them to introduce their students, from all educational levels, into the world of chemistry and increase their interest in this science.

On one hand, the didactic experiments, which are described herein, present a high versatility because each didactic experiment can be adapted perfectly to either primary, secondary or high school curriculum depend on the depth of the concepts and explanation given to students and the chemicals used to performed the practicals. On the other hand, each experiment is about one of the three main blocks of the Spanish chemistry subject at pre-university level: matter and state change, acidity-basicity and oxidation-reduction reaction [18]. More concretely, these didactic experiments are related to:

- State change and density of gases (CO_2, N_2 and He).
- Acidity-basicity of daily chemical substances and measurement of their pH values.
- Trapping gases (NO_2/N_2O_4 and H_2).

3. Experimental

3.1. Apparatus, Materials and Chemicals

For the experiment titled "Appearance changes": digital balance, Erlenmeyer flasks, blunt-nosed thumb forceps, balloons, Dewar flask or polystyrene box, dry ice (CO_2), liquid nitrogen and helium gas.

For the experiment titled "pH in our lives": hot plate stirrer, stirring rods, glass beakers, Erlenmeyer flasks, funnels, tubes, pipettes, red cabbage, distilled water, ethanol, lemon juice, vinegar, anti-calc, fruit milk drink, milk, soap, toothpaste, detergent, antacid tablets and bleach.

For the experiment titled "Trapping gases": glass beakers, Erlenmeyer flasks, tubes, assorted rubber stoppers, graduate cylinders, pipettes, spatula, blunt-nosed thumb forceps, copper coins, zinc powder, 1M hydrochloric acid (HCl) and 0.1 M nitric acid (HNO_3).

3.2. Hazards

HCl and HNO_3 are strong acids and therefore are corrosive. They are also strong oxidizing agents and when in contact with organic matter are heat-, shock, friction-, and impact-sensitive. HCl and HNO3 react with many metals to produce hydrogen (H_2), a flammable and explosive gas, and several nitrogen oxides (NO_x), toxic gases, respectively. Sodium hydroxide is a strong base and, consequently, is corrosive.

Dry ice is cold and quickly sublimates into carbon dioxide gas because its sublimation temperature is -78ºC at the atmospheric pressure. Carbon dioxide (CO_2) is not toxic but it can build up pressure or displace normal air and could cause asphyxia. Liquid nitrogen (N_2) is extremely cold and, at atmospheric pressure, boils at -196ºC. Liquid nitrogen rapidly vaporizes to gas with about 700 times the liquid volume. By displacing air, the gas may kill by asphyxiation. Helium gas (He) is not toxic but in principle it could asphyxiate through denying the body access to oxygen (O_2). Air is composed of approximately 21% oxygen, 78% nitrogen and other trace components. The addition of any gas, except oxygen, to air reduces the oxygen concentration through displacement and dilution. Breathing as little as one or two breaths of air containing from 19% to 10% of oxygen can have serious and immediate effects such as poor judgment and coordination, as well as, increased pulse and breathing rate. But, when the oxygen concentration in air is less than 10%, a person can become unconscious without any warning symptoms [19].

It is important to point out that even the simplest activities with the most basic of materials can be harmful or dangerous, so personal protective equipment, information on substance safe handling, teacher supervision and guidance are critical in all experiments.

4. Procedures and Results

In this article, the authors describe three didactic experiments that could be performed by students from primary, secondary and high school.

4.1. Appearance Changes

Every day, people observe how a material will change from one state or phase to another at specific combinations of temperature and surrounding pressure. At the atmospheric pressure, temperature is the determining factor in the change of state in most cases, for instance, if ice (solid water) is heated it melts to liquid water and if that liquid water is heated it boils to vapor (gas water). These changes are called physical changes of matter state. Among the most important physical ones are state changes and volume changes. Usually, the matter could be presented in solid, liquid and gas state.

Two types of state changes can be distinguish due to the influence of heat: progressive and regressive changes. Progressive changes occur when heat is applied to the matter such as melting, evaporation and sublimation. While regressive changes are produced by the cooling of the matter like freezing, condensation and inverse sublimation.

A classic example of sublimation is dry ice, which is composed solely of solid carbon dioxide (Figure 1A). CO_2 at atmospheric pressure and room temperature is a gas, but at high pressure and low temperature CO_2 gas changes to its solid state without passing through the liquid state (inverse sublimation). Dry ice is widely used in the world of science, but particularly in medicine, to transport cells, tissues and even organs at an optimum temperature to avoid their degradation.

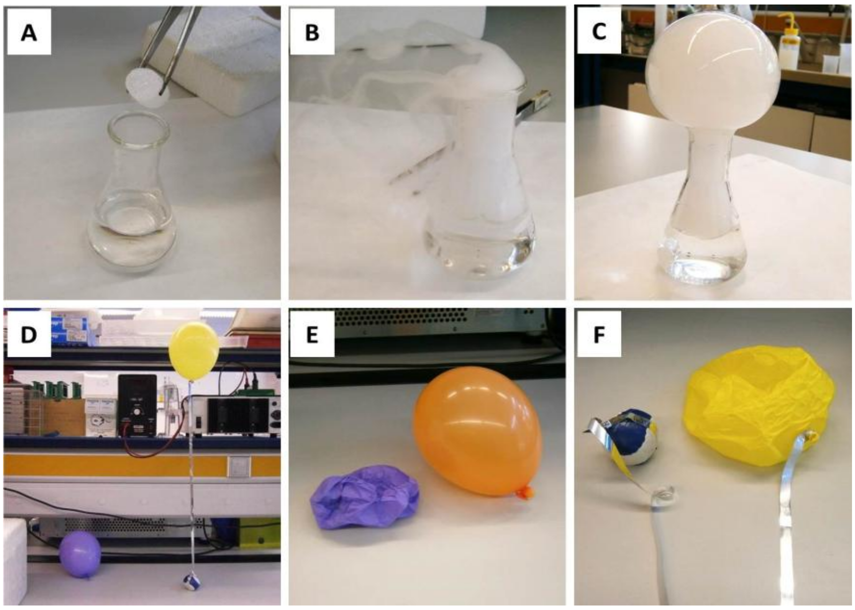

Fig1. (A) *Dry ice is composed solely of solid carbon dioxide. (B) Dry ice is added in an Erlenmeyer flask that is half filled with water, generating a strong detachment of bubbles of carbon dioxide. (C) The mouth of the Erlenmeyer flask has shower gel so as to form bubbles filled with carbon dioxide. (D) Purple balloon inflated with air and yellow balloon inflated with helium. (E) Purple balloon, inflated with air, after placing in a polystyrene box containing liquid nitrogen. The air inside the balloon contracts and the balloon is deflated. (F) Yellow balloon, inflated with helium, after dipping in the liquid nitrogen. Due to the reduction of gas volume, its density increases, so that the helium balloon, out of the polystyrene box, falls to the ground.*

Dry ice at room temperature starts to slowly sublimate. In order to speed up this change of state, dry ice (solid carbon dioxide) could be added in an Erlenmeyer flask with water, observing a strong detachment of bubbles of carbon dioxide (Fig. 1B). In fact, carbon dioxide reacts with water forming carbonic acid, an unstable weak acid, which quickly decomposes into water and carbon dioxide. The experience could be funnier if the mouth of the Erlenmeyer flask has shower gel because of the formation of bubbles filled with carbon dioxide (Fig. 1C).

Volume changes are related to changes in the space occupied by the matter. For instance, a material increases in volume if the space that occupied increases, and, in contrary, if the material decreases in volume mean that decreases the occupied space. There are two changes: shrinkage and dilatation. Shrinkage is the volume decrease that undergoes the matter upon cooling. While dilatation is the volume increase experienced by the matter when is heated [20]. In other words, most matter increases in volume when is heated and, therefore, its density decreases. This happens because the mass of the matter stays the same, but its volume increases. The other way around, most matter decreases in volume when is cooled down and, consequently, its density increases.

A visual experiment is to shrink the volume of a gas using liquid nitrogen. A balloon is inflated blowing. Once inflated, the balloon is placed in a Dewar flask or polystyrene box containing liquid nitrogen. The gas inside the balloon contracts and the balloon is deflated (Fig. 1D). When the balloon is removed from the Dewar, the temperature rises, the gas expands again and the balloon returns to its initial size. This is a qualitative demonstration of the Charles' law: at constant pressure, a linear relation exists between the volume of a fixed amount of gas and the temperature thereof.

Another experiment consists into inflate a balloon with helium gas. The density of helium is less than that of air so it will try to rise. In that case, the balloon must be tied in order to prevent escape (Fig. 1D). Then, the balloon is dipped in the liquid nitrogen. As before, the balloon is deflated. Due to the contraction of the gas inside the balloon, its density increases; so that the helium balloon, out of the Dewar, tends to fall to the ground (Fig. 1F). When the temperature increases, the volume of gas increases again, thereby decreasing its density and the balloon rises again in the air.

On one hand, school science teachers, doing these experiments, could introduce to their primary school students the concepts of matter, matter states (solid, liquid and gas) and changing matter states (solidification, fusion, evaporation, condensation and sublimation). On the other hand, secondary school teachers could explain, through these laboratory practicals, concepts as states of aggregation and materials are formed by particles that are attracted amount them for electrical strength. Finally, high school teachers could instruct their students about the structure of matter (protons, neutrons, electrons, atomic number, atomic mass), kinetic energy of the particles related to matter states, solid state (crystal and amorphous solid), liquid state (vapor pressure, volatility, viscosity, superficial tension, capillarity, etc.), gas state (gas pressure, gas density, Boyle's-Mariotte's law, Charles-Gay-Lussac's law, Avogadro's law, ideal gas law and Dalton's law).

4.2. pH in Our Lives

Many chemical products that we normally use in our daily lives possess an either acidity or basicity grade that is dangerous for human bodies, especially for the skin and mucosa. The only way to be aware about their dangers is measuring their pH values. Some time ago, scientists desired to measure the grade of acidity of the substance so they developed the concept of pH, in other words, the pH is a scale that scientists use for measuring if a substance is more acid than others. The pH scale ranges from 0 to 14 in water. The letters pH stand for "power of hydrogen" and the numerical value is defined as the negative base 10 logarithm of the molar concentration of hydrogen ions (Eq. 1), in other words, pH represents the acidity, or hydrogen ion (H_3O^+) concentration, of a solution [21-22].

$$pH = -\log[H_3O^+] \qquad (1)$$

Pure water, which is neutral, has a pH of 7. With a higher the concentration of hydrogen ions, a solution is more acidic and has a lower pH. Acids have a pH less than 7, and the strongest acids have a pH close to zero. On the other hand, bases have a pH greater than 7, and the strongest bases have a pH close to 14. It is important to realize that the pH scale is based on powers of ten. For example, a solution with a pH of 8 is 10 times more basic than a solution with a pH of 7, and a solution with a pH of 9 is 100 times more basic than a solution with a pH of 7. In the other way around, a solution with a pH of 4 is 1,000 times more acid than a solution with a pH of 7.

The pH of wet human skin is around 5.5, therefore, creams or soaps with a less or greater pH values may cause damages to the skin such as burns or irritation including rash, redness and swelling. Any substance with a pH great than 10 (e. g. bleach) or less than 3 (e. g. hydrochloric acid) could dissolve skin causing dangerous damage. Knowing the pH of the substances is very important for our security. For that reason, in the next experiment we explain how to obtain a pH indicator from red cabbage.

Firstly, darker leaves of cabbage are cut and cook in a container with a small amount of water for a few minutes. Later, the extract is allowed to cool and then is filtered reserving the liquid and discarding the leaves that have discolored. It is also possible to extract red cabbage pigment with ethanol at room temperature. The aqueous red cabbage extract is purple (Fig. 2B top left); meanwhile, the respective alcoholic extract is pinkish-purple (Fig. 2B top right). The aqueous extraction solution, a part of the pigment, has enzymes and salts; whereas, the alcoholic extraction only has the pigment. Therefore, the main difference between the two red cabbage extracts is the stability because the aqueous extract is easily degraded by bacteria and fungi. Hence, the aqueous extraction should be kept in the fridge and only is stable during one week. However, the alcoholic extraction could be kept at room temperature during one year due to bacteria and fungi do not grown in ethanol. Both red cabbage extracts obtained will use to identify acids and bases.

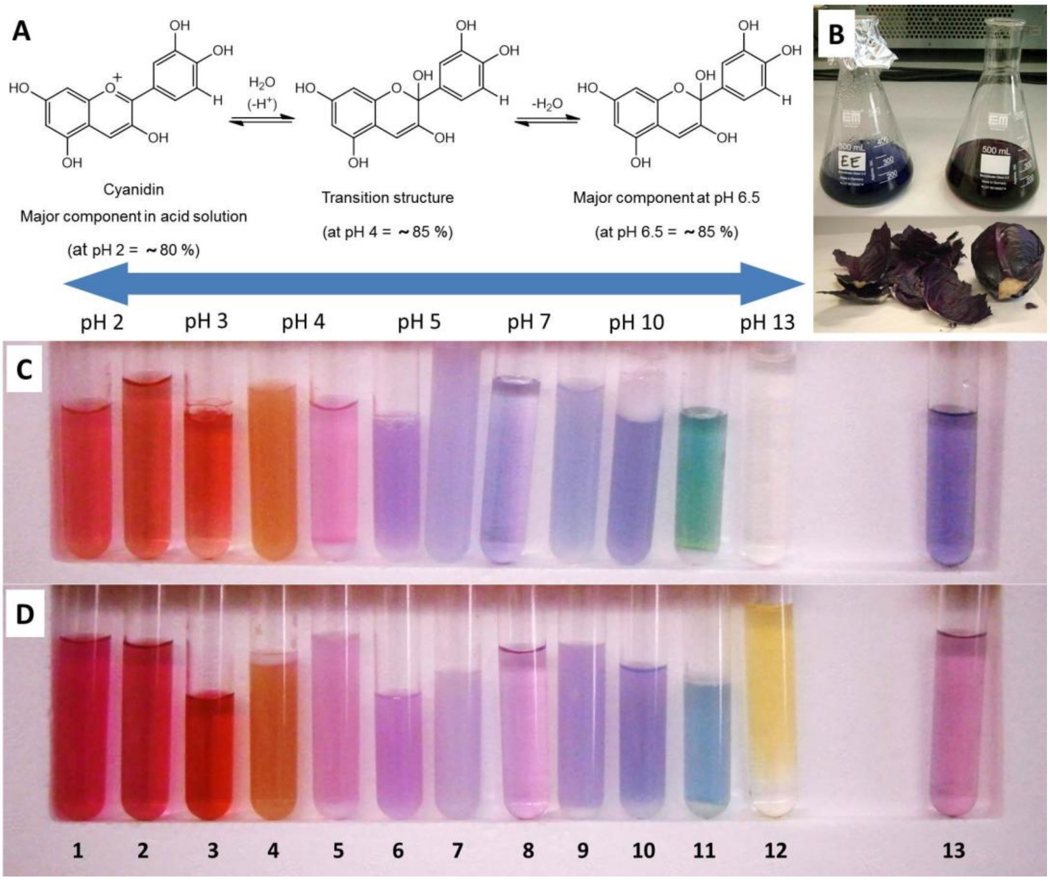

Fig2. *(A) Chemical structures of cyanidin depending on the pH. (B) Aqueous extract (top left) and alcoholic extract (top right) of red cabbage. Darker leaves of cabbage are used to obtain a natural pH indicator (bottom). (C) Aqueous extract and (D) alcoholic extract of red cabbage change their color according to the pH of medium, from red (acid substance) to yellow color (basic substance). The pH of the following substance were checked: (1) lemon juice, (2) vinegar, (3) anti-calc, (4) fruit milk drink, (5) yogurt, (6) soap, (7) milk, (8) water, (9) toothpaste, (10) detergent, (11) calcium carbonate (antacid tablet) and (12) bleach; (13c) aqueous red cabbage extract and (13d) alcoholic red cabbage extract*.

pH indicators are those substances that change their color depending on if they are in an acidic or basic environment. Some vegetables like strawberry, cherry, red cabbage and red onion have a substance (anthocyanin) that is very sensitive to pH changes. Concretely, red cabbage has cyanidin, which is an excellent natural indicator (Fig. 2A). Red cabbage extract changes its color according to the medium: acquires red color in acidic medium [lemon juice (1), vinegar (2), anti-calc (3), fruit milk drink (4) and yogurt (5)], blue color in neutral medium [soap (6), milk (7), water (8), toothpaste (9)], greenish-blue in basic medium [detergent (10), calcium carbonate (antacid tablet) (11)] and yellow color in strong basic medium [bleach (12)] (Fig. 2C and 2D).

It should point out that bleach, as a potent oxidizing agent, quickly degrade the pigment of the red cabbage extract. After adding aqueous extract, bleach has a strong yellow color (Fig. 3B). But 2 minutes later, bleach solution has a light yellow color (Fig. 3C); and after 10 minutes, bleach solution is completely colorless (Fig. 3D). However, bleach degrades the pigment of red cabbage of the alcoholic solution slower than the aqueous one (Fig. 2D, tube 12).

Primary school teachers doing these experiments could show to their students that food, hygiene products, household cleaners and laundry products could be classified as acid, basic or neutral substances. Science teachers from primary schools could also describe the properties of an indicator and introduce the concept of pH. Furthermore, secondary school teachers could use these didactic experiments to teach the chemical definition of acids and bases (protons and hydroxide ions), pH concept, neutralization and ion exchange. On the other hand, high school science teachers could introduce Arrhenius theory, Brönsted-Lowry theory, acid-base pairs, relative strength of acids and bases, autoprotolysis of water, constants of conjugated acid-base pairs, pH formula, hydrolysis, buffers, acid-base indicators, neutralization reaction and acid-base valorations.

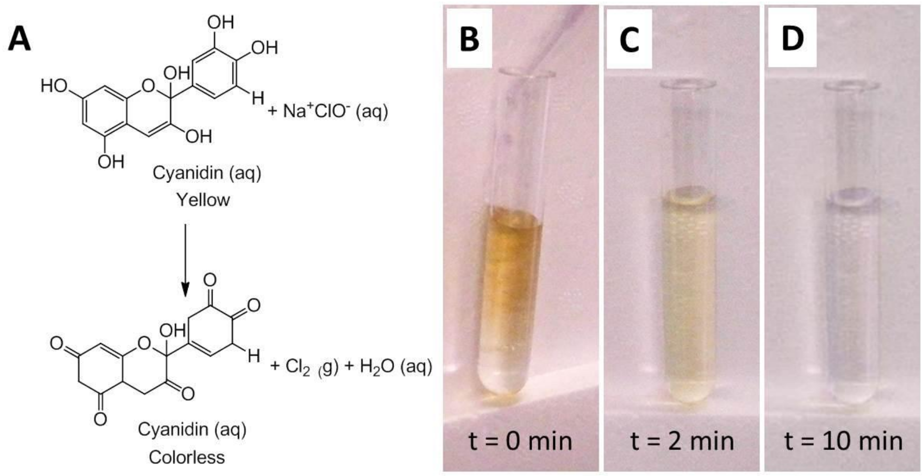

Fig3. *(A) The pigment of the red cabbage extract cyanidin is quickly degraded by bleach due to be a strong oxidizing agent. Addition of aqueous red cabbage extract into bleach at time zero (B), 2 min (C) and 10 min (D).*

4.3. Trapping Gases

Alchemists, the first chemists, did not dispose of adequate material to handle gases and study them properly. But in the fifteenth century, the manufacture of blown glass vessels was widely extended and, unlike normal glass, blown glass could be heated and, late, cooled without cracking and breaking. Then, scientists began to deepen their studies about gases [23-25].

Gases are slippery substances, heavy to study in the laboratory and hard to catch. Consequently, it is easy to avoid doing practical about obtaining and manipulating gases. However, we encourage school science teachers to incorporate the following experiments in their teaching laboratory classes. One experiment is for obtaining nitrogen dioxide, which is more dense than air, and, therefore, easy to manipulate. In another experiment, we explain how to generate hydrogen, which is less dense than air, and the way to trap it easily [26-28]. We also describe another experiment to obtain CO_2 gas, which is less dangerous that nitrogen dioxide and hydrogen. This last experiment is more appropriate for performing in front of primary school students.

4.3.1. Obtainment of Nitrogen Dioxide

For generating nitrogen dioxide, a few drops of nitric acid (0.1 M) are added on copper coins (Fig. 4A). It is easy to observe a rapid release of brown fumes that are oxides of nitrogen, NO_x, but mostly are nitrogen dioxide (Eq. 2). This experiment is strongly recommended to do in a laboratory fume hood due to the high toxicity of NO_x gases.

$$Cu\ (s) + 4\ HNO_3\ (aq) \rightarrow Cu(NO_3)_2\ (aq) + 2\ H_2O + 2\ NO_2\ (g)\uparrow \qquad (2)$$

Nitrogen dioxide is a red-brown gas heavier than air which facilitates its handling such as its transfer into another flask (Fig. 4B). In addition, nitrogen dioxide at low temperature is condensed to dinitrogen tetraoxide (Eq. 3), a colorless gas. Therefore, if the flask is cooled down, its color decreases. Conversely, when the flask is heated, its color increases (Fig. 4C).

$$2\ NO_2\ (g) \leftrightarrow N_2O_4\ (g) \qquad (3)$$

4.3.2. Obtainment of Hydrogen

On the other hand, confining hydrogen gas is relatively easy because it is only necessary an Erlenmeyer flask, tube, assorted rubber stopper, graduated cylinder and beaker. Zinc powder is introduced in the Erlenmeyer flask, then, carefully 5-6 drops of hydrochloric acid (1M) are also added (Fig. 4D and 4E). Zinc metal is oxidized to zinc (II) by the action of hydrochloric acid forming zinc chloride and shedding hydrogen gas (Eq. 4).

$$Zn\ (s) + HCl\ (aq) \rightarrow ZnCl_2\ (aq) + H_2\ (g)\uparrow \qquad (4)$$

It is possible to trap and study the generated hydrogen bubbling up the gas into the graduated cylinder full of water (Fig. 4F). The hydrogen gas displaces the water of the graduated cylinder, which goes into the beaker, and, consequently, hydrogen gas is collected in the cylinder (Fig. 4G). But this, of course, only works if the gas, such as hydrogen, is insoluble in water.

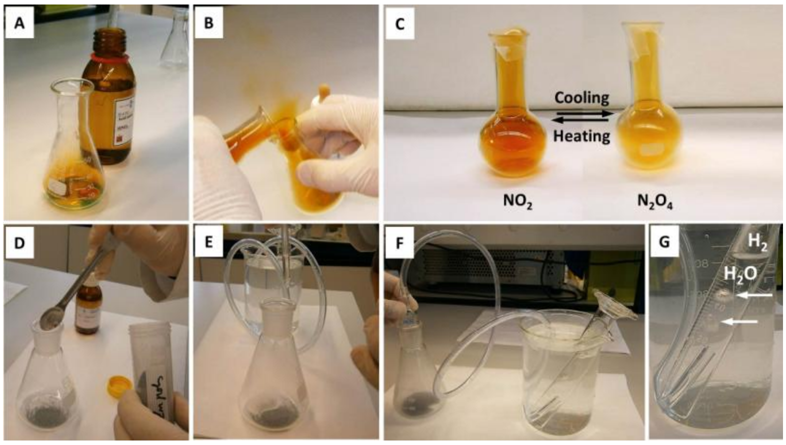

Fig4. *(A) Dioxide nitrogen was obtained adding few drops of nitric acid (0.1M) on copper coins. (B) Dioxide nitrogen gas is heavier than air which facilitates its handling such as its transfer into another container. (C) At room temperature, Erlenmeyer flask is full basically with dioxide nitrogen (left), but al low temperature is condensed to dinitrogen tetraoxide, a colorless gas. After cooling during 30 min, the recipient contains a mixture of dinitrogen tetraoxide and dioxide nitrogen (right), turning into a yellow-brown color. (D) Zinc powder is added in the Erlenmeyer flask. (E) 5-6 drops of hydrochloric acid (1M) are also added. (F) Generated hydrogen could be trapped bubbling it up into the graduated cylinder. (G) The hydrogen gas displaces the water of the graduated cylinder, which goes into the beaker, and, consequently, hydrogen gas is collected.*

4.3.3. Obtainment of CO_2

CO_2 gas could be formed by dropping lemon juice on a marble surface or vinegar in a piece of chalk. These simple experiences are specially appropriated for primary school students because of their high degree of safety and, at the same time, they could study chemical reactions.

Moreover, through the experiments of obtainment gases, primary school teachers could introduce the properties of acids and bases to their students. Furthermore, secondary school teachers could demonstrate not only the properties of acids and their reactivity with metals, but also oxidation and reduction reaction, oxidizing and reducing agent, electron transference, redox process and even combustion. Additionally, high school science teachers could explain several concepts related to redox reactions such as number of oxidation, balancing redox reaction, redox valoration, electrolysis, galvanic cell and battery.

5. CONCLUSIONS

The benefits of using practical experiments as didactic tools are diverse. When science teacher explain experiments and help students to perform it, not only do students gain confidence in their ability, but also improve their understanding of theoretical knowledge through experimentation [29-31]. School science teachers could also show students how to identify hypotheses from the educational practices, explore the experimental methodologies used and analyze the data. Besides, each experiment becomes clear for students because scientific concepts and techniques are gradually introduced by their teachers. By the end of practical lessons, school students are capable of discussing the experiments logically and critically, generating valid conclusions, and also applying the scientific methods and techniques they learn to hypothetical situations involving scientific research. Additionally, if school teachers do experiments in groups, students could develop soft skills such as problem solving, teamwork and communications, which are very important skills in the students' future [32-34]. Moreover, through these practicals, science teachers could demonstrate to students the importance of using safety personnel equipment and useful information on substance safe handling.

Furthermore, most of these experiments can be done using both basic equipment and chemicals found in a normal laboratory, helping science teachers perform experiments that have all the characteristics of excellent classroom demonstrations because of their high degree of safety, ready availability of materials, visual interest and relative simplicity. Moreover, these experiments can be related, according to educational level, with: the study of the properties of materials, the study of the acidity/basicity, the study of states of matter, the study from the general laws of gases to the perfect gas law and, finally, the study of speed reaction. But more concretely, each of these didactic experiments is related with one of the three main blocks of the chemistry subject at pre-university level: matter and state change, acid-base reaction and reduction-oxidation reaction.

Theoretically lessons essentially test the ability to memorize facts; however, educational practices test the capability to formulate new hypotheses, suggest experiments and propose future directions for the research [35]. On the other hand, a way that science teachers have to increase knowledge of chemistry among school students is to include educational practice in their routine.

Authors strongly defend that a good chemistry education provides school students with not only valuable theoretical and experimental concepts but also life skills and career options.

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