

# Connecting Solubility, Equilibrium, and Periodicity in a Green, Inquiry Experiment for the General Chemistry Laboratory

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We present a novel experiment suitable for advanced placement high school chemistry or undergraduate first-year chemistry. The experiment connects several important general chemistry concepts, including chemical equilibrium, solubility, and chemical periodicity. In keeping with the structure of other experiments we have been developing for a research study of student learning in the general chemistry laboratory, this experiment has two additional key features: students learn and apply principles of green chemistry and engage in authentic scientific inquiry that promotes optimal science learning. The chemistry content and key features of the experiment are explained in more detail below.

Chemical equilibrium, the dynamic balance between competing chemical and physical processes in a system, is a critically important topic in general chemistry. A firm grasp of chemical equilibrium is necessary to understand many common types of chemical reactions and pathways, including aqueous weak acid–base and oxidation–reduction processes. It is well-established in the literature that students often struggle to understand chemical equilibrium and have numerous, persistent misconceptions in this area (1, 2). For these reasons, it is standard practice to include an equilibrium experiment in general chemistry laboratory programs. Simple solubility equilibria of sparingly soluble salts, such as calcium hydroxide, present an excellent opportunity to study chemical equilibrium quantitatively in the introductory laboratory for both practical and pedagogical reasons. Practically, many of these salts are inexpensive to obtain and easy to work with in the laboratory. Pedagogically, compared to many other equilibrium systems, they contain a small number of species, which simplifies the calculation of the equilibrium constant.

For these reasons, a large number of excellent solubility equilibrium experiments for the introductory laboratory have previously been developed and described in the literature. These experiments use a variety of different laboratory techniques to measure the concentration of species in solution, including gravimetric analysis (3, 4), titration (5–9), spectroscopy (10–12), electrical conductivity (13–15), and radioactive labeling (16), as well as a number of different methods to analyze data and arrive at a value for the equilibrium constant. However, none of these experiments incorporates chemical periodicity concepts. In fact, experiments of any kind that study chemical periodicity explicitly are rare; a search of this *Journal's* archives revealed no such experiments at the introductory level. Furthermore, none of the existing experiments explicitly include green chemistry philosophy, and few use pedagogical strategies that promote student inquiry in the laboratory.

Chemical periodicity describes the cyclical trends in many properties of the elements that are observed when the elements are arranged in order of increasing atomic number; this phenomenon accounts for the similarities in properties seen among members of the same column or group of the periodic table and for trends in properties within groups. A grasp of periodicity, which can be simply understood in terms of Coulomb's law, is fundamental to an understanding of chemical reactivity, and thus this concept is universally taught in general chemistry courses. This experiment asks students to identify the trend in solubility in their laboratory results, connect this trend to the periodic table, and to use the identified trend to predict the relative solubility of similar compounds that were not analyzed in the laboratory. These hands-on experiences with periodicity concepts provide reinforcement of similar material taught in the general chemistry lecture course.

Green chemistry (17) is a philosophy of how to do chemistry in such a way that hazards to human health and the larger environment are minimized or avoided entirely and resources are conserved to the greatest extent possible. Green chemistry is both ethically responsible and cost-effective as it greatly reduces the enormous costs associated with using hazardous substances and disposing of toxic wastes. Green chemistry now influences the design of many educational laboratory curricula in organic chemistry, and some organic chemistry laboratory courses explicitly teach green chemistry as well (18). Conversely, few green general chemistry laboratory curricular materials exist in the literature. The experiment presented here is green because students determine the  $K_{sp}$  of three substances—magnesium, calcium, and strontium hydroxides—of relatively low toxicity, then apply their findings to approximate the solubility of two much more toxic substances—barium hydroxide and beryllium hydroxide—without actually working with those toxic substances. Thus they are able to accomplish one of the stated goals of the experiment, to determine the solubility of each of the group 2 metals, while minimizing risks. A short description of green chemistry is included in the materials provided to students in advance of the laboratory session, and at the conclusion of the experiment, students are asked to explain why the experiment they did is greener than a similar experiment that required titration of all five group 2 metal hydroxides.

Research on how students learn science best indicates that students need to construct their own knowledge through activities that promote inquiry and discovery rather than simply following a prescribed procedure to replicate a known finding (19, 20). However, both practical and pedagogical considerations make completely open-ended experiments undesirable

for the general chemistry laboratory. This experiment utilizes an unusual format that promotes student inquiry by requiring students to plan and carry out their own experiment based on a somewhat incomplete sample lab report instead of following a step-by-step procedure. Current research (21–23) also shows that students learn and retain new material best when they integrate new and pre-existing knowledge and when they are given opportunities to apply new knowledge to solve problems. This experiment asks students to integrate several disparate chemistry concepts—solubility, periodicity, and equilibrium—that are typically taught at different points during the two-semester general chemistry sequence. Then students must use their findings to understand and explain how their work is consistent with the green chemistry philosophy.

## Materials and Methods

Before the laboratory period, students are given a written handout with general information about solubility equilibria, chemical periodicity, and green chemistry. The accompanying prelab assignment requires calculations similar to those required to complete the experiment. At the beginning of the laboratory period, each pair of students is provided with one of three different sample lab reports to use as a template for designing and conducting their own similar experiment. Students are asked to attempt to replicate the findings reported in the sample they receive. Each of the three sample lab reports is deficient in some way: #1 has a poor calculations section, #2 lacks a detailed procedure, and #3 does not list the materials needed. Students are instructed that while they are strongly encouraged to talk with other student pairs, they may not show each other their sample lab reports. Prohibiting students from simply giving each other their reports promotes student discussion and collaboration during the experiment.

The experiment begins with the titration of saturated solutions of magnesium, calcium, and strontium hydroxides to a phenolphthalein endpoint using standardized hydrochloric acid solution, followed by the calculation of the solubility product of each compound. Instead of writing a standard lab report, students answer a series of questions that ask them to use their results to determine a periodic trend in the solubility of the group 2 compounds they titrated, apply the trend to predict the solubility of other, toxic group 2 hydroxides, and examine the value of the experiment within the context of a green chemistry philosophy. This experiment does not focus on comparing data obtained in the laboratory to literature values for the  $K_{sp}$ 's for several reasons, including difficulties in obtaining reliable literature values, and the effect of ionic activity on equilibrium constants, which is not accounted for in this first-year-level experiment. However, it is worth noting that the trend in  $K_{sp}$  values determined in this experiment is the same as that found in literature values. Literature values are further discussed in the online supplement.

This experiment can easily be expanded to include complexometric titration by asking students to titrate the solutions using EDTA in place of or in addition to hydrochloric acid. Using two different titrants to arrive at the same conclusion about the periodic trend in  $K_{sp}$  provides powerful validation of the experimental results and this extension is worthwhile if time allows.

## Hazards

The experiment minimizes hazards through the use of dilute solutions in small quantities. All three of the analyte solutions used in the experiment are basic; however, only strontium hydroxide ionizes to a significant extent ( $\text{pH} = 12.8$ ), and less than 1 mL of this solution is used per student group. All group 2 hydroxides cause irritation to skin, eyes, and respiratory tract. The titrant solution is 2.00 mM hydrochloric acid. Hydrochloric acid is corrosive and causes severe burns to all body tissue. It may be fatal if swallowed or inhaled and inhalation may cause lung damage. Normal laboratory precautions including protective eyewear are sufficient to work with these chemicals. At the conclusion of the experiment the waste solutions can be neutralized and disposed of using standard laboratory protocols.

The minimal hazards posed by this experiment are noteworthy because many of the previously published solubility experiments for general chemistry use significant amounts of toxic substances including lead (7, 15), barium (8), and silver (9, 13) salts. These heavy metals expose students and instructors to health hazards and also present a long-term environmental hazard if not disposed of properly. One of the significant benefits of green chemistry is that the materials used are less hazardous than materials traditionally used for a particular application. This improvement is particularly significant in educational settings, where large numbers of inexperienced students generate significant waste and also work in large numbers in a laboratory simultaneously so the risk of accidents or spillage is high.

## Results and Discussion

This experiment was successfully pilot-tested several times with small groups of second-year students who had completed general chemistry, and then field-tested with one laboratory section of undergraduate general chemistry students ( $n = 30$ ). The field test was led by graduate student teaching assistants not involved in the designing of the experiment using the instructor's guide for the experiment. One of the authors also met with the instructors prior to the session to help explain the rationale for the unusual format, clarify learning goals for students, and answer questions.

Nearly all of the students were able to correctly complete the prelab assignment, which required writing equilibrium expressions and calculating  $K_{sp}$  values from given concentrations. When students arrived in the laboratory, their laboratory stations were set up with titration apparatus and glassware, and titrant and analyte solutions were at a central location. At the beginning of the laboratory session, students initially struggled to figure out exactly how to carry out the experiment based on the sample lab report they received, because in previous sessions they had been given a step-by-step procedure to follow. A few students seemed frustrated by the different format and the deficiencies in the lab report they received, which they readily pointed out. However, after several minutes of discussion between partners and then among members of different lab groups, students began carrying out the necessary titrations. Most students set up and carried out the titrations successfully on their first try, but two lab groups made errors—one group did not add indicator to the analyte and the other forgot to read the starting volume on the buret—that required them to repeat their

first titration. The instructor did not intervene when she saw the students making these errors, and the students recognized their mistakes on their own and avoided them in future trials. Students' titration endpoint volumes all fell within the acceptable range specified in the instructors' guide.

The calculations required to determine  $K_{sp}$  values from titration data presented a challenge for many of the students. About half of the students initially protested that they could not figure out how to do the calculations or made significant errors on their first try. However, with encouragement from the instructor, they used their sample lab reports and discussions with other students to ultimately successfully carry out the calculations. All of the student groups readily identified the correct periodic trend in  $K_{sp}$  values and applied the trend to the two group 2 hydroxide salts they did not titrate, barium and beryllium. Most students were able to clearly explain why the experiment they conducted was greener than an experiment in which all five group 2 hydroxide salts were titrated. In response to other postlab questions, all but two students identified deficiencies in the sample lab report they received and made reasonable suggestions for improvement.

The graduate student instructor reported observing far more student–student interaction during this session than during previous laboratory sessions where students conducted more traditional, scripted experiments. Many student comments indicated that this experiment required more thinking and work than previous experiments, and several students made positive comments about green chemistry and noted that previous experiments were not green (e.g., heating barium chloride hydrate to determine its stoichiometry). The time required for the entire laboratory session was slightly less than three hours.

## Conclusion

This experiment connects equilibrium, solubility, and periodicity concepts and employs an unusual format that promotes development of student experimental design and data analysis skills. It also adheres to the green chemistry philosophy and introduces students to green chemistry principles. The experiment is appropriate for an undergraduate general chemistry course or a high school advanced placement chemistry course.

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