Green Chemistry

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# Teaching Lab Report Writing through Inquiry: A Green Chemistry Stoichiometry Experiment for General Chemistry

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We present a novel experiment suitable for advanced placement high school chemistry or first-year undergraduate chemistry. This experiment has four key features: students utilize stoichiometry, learn and apply principles of green chemistry, engage in authentic scientific inquiry that promotes optimal science learning, and discover why each part of a scientific lab report is necessary. Stoichiometry, the study of amounts of reactants and products in chemical reactions, is an important topic in general chemistry. It is standard practice to include a stoichiometry experiment in general chemistry laboratory programs. Many excellent stoichiometry experiments have previously been described *(1–6)*; however, none in the literature combine all of the features present in this experiment.

Green chemistry emphasizes the reduction of hazards to human health and the larger environment as well as resource conservation through informed design of chemicals and chemical processes. It offers a morally and ethically responsible way to do chemistry, and in addition it greatly reduces costs associated with the acquisition, use, and disposal of hazardous substances. Green chemistry has undergone tremendous growth in a short period of time. Its tenets now influence synthetic chemistry in the industrial and academic research sectors and are beginning to have an impact on other areas of chemistry. This experiment utilizes green chemistry and provides an opportunity for students to apply three of its twelve principles *(7),* those of waste prevention, atom economy, and safer chemicals. When green chemistry is included in a university curriculum, it is typically introduced in the organic chemistry laboratory course. There are a handful of published classroom exercises that introduce green chemistry principles to general chemistry students *(8, 9),* but laboratory experiments that explicitly teach green chemistry to first-year university or high school students are lacking in the literature. Introducing green chemistry to students in general chemistry is worthwhile because green chemistry is of growing importance within our larger society and because anecdotal evidence indicates it motivates students who value environmental protection and resource conservation to view chemistry positively and to pursue chemistry at a more advanced level *(10, 11).*

This experiment is designed in accordance with the latest research findings on how students learn science most effectively *(12).* These findings indicate that science curricular materials and instruction need to address prior student conceptions before a new learning experience, engage students in authentic scientific inquiry, and provide students with opportunities to practice metacognitive processing. Prior student conceptions include the knowledge and experience that students bring to bear when they begin thinking about a new task or problem. Often these conceptions include inaccuracies and naïve mental models that must be addressed directly before students can construct new, more accurate understandings. This experiment addresses prior student conceptions about how to solve stoichiometry problems involving a mixture of substances through prelab questions given to students the week before they attempt the hands-on work in the laboratory. The opportunity to address and correct preexisting student deficiencies helps to ensure that all students benefit from the new learning experience in the laboratory.

Inquiry can be defined as a set of interrelated processes by which scientists and students pose questions about and investigate phenomena in the natural world *(13).* This experiment is an example of inquiry because students have to think about and plan laboratory procedures to use in order to investigate a scientific question and then justify their choices in writing. It is authentic inquiry because students attempt to verify results of a written report, as scientists attempt to replicate and extend the work of others. By contrast, traditional experiments taught in undergraduate courses are often referred to as “cookbook labs” because students follow a step-by-step procedure as one follows a recipe. The difference is pedagogically meaningful because significant evidence indicates that students learn science best when learning is inquiry-oriented *(14–16),* and while this pedagogy is widespread (to varying degrees) in K–12 science education, it is still rare in university science courses *(17).*

Metacognitive processing is thinking about and consciously directing one’s own thinking while attempting to solve a problem or address a question. This experiment forces students to apply stoichiometric principles to authentic use, requiring them to make decisions about a starting point for calculations, appropriate mathematical steps, and the desired answer. Typical stoichiometry problems assigned as student homework do not require metacognitive processing; rather, such problems ordinarily require students to remember and apply a simple algorithm.

Written scientific communication adheres to generally agreed upon standards in format and content to enable scientists to attempt to replicate or validate others’ results. Students are usually required to write lab reports that approximate these standards after they conduct laboratory experiments. However, they rarely understand the true purpose of the lab report structure. In particular, the students are generally unaware of the perspective afforded by considering what information another scientist would need to replicate an experiment to verify or refute findings. While our strategy for achieving student understanding of the reasons for standard lab report format is unique, other strategies have been reported that also achieve this goal. These include asking students to read journal articles and imitate specific sections in their own reports *(18)* and utilizing the Science Writing Heuristic alternative lab report structure for inquiry-based experiments *(19).* The strategy we present motivates the need for scientific communication by asking students to carry out an experiment based only on a previous student's written report. That written report lacks at least one significant section of a scientific report, and this deficiency creates cognitive dissonance (thereby addressing prior conceptions) by causing students difficulty in the laboratory. The task requires students to think about and ultimately invent the need for each section of the report in order for the true purpose of the communication to be accomplished.

## Materials and Methods

Several days before the scheduled laboratory period, students are provided a prelab assignment containing background information on green chemistry. The prelab questions ask students to determine the composition of a mixture similar to the one they will analyze in the laboratory.

Upon arriving to lab, pairs of students are each given one of three sample lab reports. Each of the three sample reports includes a different problem—one is missing materials and methods, another contains widely discrepant results in two different experimental trials, and the third lacks a meaningful discussion of results. Students are told they may discuss the experiment with others but may not show each other their lab reports. Available in the laboratory for students are crucibles, Bunsen burners, analytical balances, and a mixture of solid sodium carbonate and sodium bicarbonate. The mixture is about 80% (by mass) sodium bicarbonate so that a significant mass change occurs upon heating. Students are instructed to replicate the experiment described in the lab report they were given to confirm or refute its findings. The experiment requires heating multiple samples of the solid mixture to constant mass. At the conclusion of the lab, students are instructed to place solid product waste in one container (waste #1) and unused (or insufficiently heated) solid in another container (waste #2). These solid wastes are reused (waste #2 is heated to completion first) when preparing the sample provided to students the following semester. Hence, no solid waste is discarded.

Rather than writing a full lab report, students are asked to answer a series of questions about their results, including the composition of the mixture they were provided, how the quality of the lab report they were given affected their work, how they communicated with other groups in the lab, and how this laboratory work relates to green chemistry principles of atom economy, low toxicity, and minimal waste. Depending on the level of student lab experience, the instructor's goals, and the quantity of time given to complete the work, this ending assignment could be modified in several ways. Students could be asked to write a full lab report, to write only the sections of the lab report that were deficient in the original report provided, or to write other sections of a lab report selected by the instructor.

## Hazards

None of the materials used in this lab are hazardous. 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 simultaneously work in large numbers in a laboratory, so the risk of accidents or spillage is high.

## Results and Discussion

Field tests of this experiment were conducted with a small group ($n$ = 8) of advanced placement (AP) chemistry students in a high school and with a larger ($n$ = 96) group of general chemistry students at a university. Students had difficulty with the prelab assignment, primarily because they did not recognize that only one component of the sodium bicarbonate/sodium carbonate mixture undergoes a chemical reaction.

During the laboratory period, students consulted with each other many times as they tried to determine an appropriate procedure, to comprehend the data and analysis of results in the sample report they received, and to understand the data they collected. Some expressed frustration with the lack of detail and explanation in various sections of the sample reports they received; they recognized that the report they received was inadequate as a template when another person needed to conduct the same experiment to verify the results. Several students remarked that now they understood why lab reports had to contain so much information and why the information had to be organized in similar format in all reports. Other student comments indicated curiosity about and enthusiasm for green chemistry; a number noted that previous experiments conducted in the course definitely did not meet the criteria for green chemistry. Many students reported thinking far more during this experiment than during previous cookbook-type experiments (a typical comment was, "My brain hurts after thinking for three hours."). Teaching assistants and instructors in the different laboratory sections noted more student–student interaction and that students spent more time considering and formulating written responses to the questions than is typical during a general chemistry lab session. Students were able to successfully complete the experiment and the written assignment in a three-hour lab period; most students needed the full three hours to finish.

Students' written work indicated that the majority of students in both settings were able to determine the correct procedure, carry out the experiment, and successfully calculate the composition of the mixture. Most students recognized glaring inadequacies in the written reports they worked with and made reasonable suggestions for improvement. Also, most students were able to identify why the experiment qualified as green chemistry. Many students did not correctly calculate the atom economy of the experiment, indicating that elaboration of that concept is necessary after the experiment.

Teaching assistants (TAs) at the university typically have little or no prior experience with inquiry experiments. We found it helpful to provide TAs with a written teaching guide. The instructor also met with the TAs before students did this lab to clarify goals for learning by students and to provide an explanation of some of the theory behind approaching learning in this manner. Many students also have no experience with inquiry-oriented approaches to laboratory science; a brief introduction to the purpose and structure of this type of experiment during the lecture or discussion meetings beforehand helped prevent students from feeling overwhelmed or confused during the laboratory period.

## Conclusion

This stoichiometry experiment utilizes an inquiry format to introduce students to green chemistry, involves students in two of the core principles of green chemistry, and promotes student understanding of the purpose of oral and written scientific communication. The experiment is appropriate for an undergraduate general chemistry course or a high school AP chemistry course.

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## [W]Supplemental Material

Instructions for the students, three sets of the sample lab, and notes for the instructor are available in this issue of *JCE Online*.

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