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Incorporating Course-Based Undergraduate Research Experiences into Analytical Chemistry Laboratory Curricula

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ABSTRACT: A continuous effort within an undergraduate university setting is to improve students' learning outcomes and thus improve students' attitudes about a particular field of study. This is undoubtedly relevant within a chemistry laboratory. This paper reports the results of an effort to introduce a problem-based learning strategy into the analytical chemistry laboratory curricula at North Carolina Central University. This study involved a total of 48 science major students who were taking two analytical chemistry courses, namely Quantitative Chemical Analysis and Instrumental Analysis, spanning Fall 2011 to Spring 2015. Course-based undergraduate research experiences or CUREs have been systematically incorporated into the laboratory components of these two consecutive analytical courses in Fall 2014 and Spring 2015 semesters. Each CUREs project involved identifying a problem, locating an appropriate method via literature search, designing a study, collecting samples, measuring variables, analyzing data, and presenting the results in a formal report and an oral presentation. Our evaluation of the preliminary impacts of CUREs integration shows that the majority of students became more excited about careers in chemistry, and science in general, as an outcome of this exercise. This is evidenced by overwhelmingly positive feedback received from the student participants, as well as increased retention of upper-level science major students.

KEYWORDS: *Upper-Division Undergraduate, Analytical Chemistry, Inquiry-Based/Discovery Learning, Applications of Chemistry*

Course-based undergraduate research experiences (CUREs), primarily in biology and chemistry, are garnering increasing attention as one of the desirable pedagogical strategies to facilitate science learning in college.[1−5] The CUREs approach challenges students to frame "real-life" practical research questions and design viable approaches to acquire meaningful data. This could enable them to make informed decisions. Several reports have indicated that the integration of authentic research experiences into introductory science courses greatly enhanced undergraduate students' preparation and interest in science careers.[6−12]

Numerous chemistry-specific pedagogy initiatives exist for promoting innovations in college chemistry teaching. These include a variety of the Process Oriented Guided Inquiry Learning (POGIL) activities, as well as hundreds of others described in presentations made at conferences and workshops, including the Gordon Research Conference on "Chemistry Education: Research & Practice," Biennial Conference on Chemical Education (BCCE), and The Chemistry Collaborations, Workshops and Communities of Scholars (cCWCS), to name just a few. CUREs share much of the same merits with pedagogy initiatives such as POGIL and problem-based learning (PBL) as they all involve student-centered, guided, inquiry-based research projects. However, CUREs are distinctively different from other initiatives. A CURE project requires the students to address a research question or problem using a course-specific approach, and the expected outcome is unknown to both the students and the instructor. Students are expected to initiate and perform a complete set of investigations and report the findings within a short period of time. Four to five weeks is a typical time frame for chemistry CUREs exercises, which would translate into 12−20 h of lab work.

The greatest opportunity for influencing and encouraging students' interests in seeking a career in chemistry, or any other of the STEM disciplines, is during their first years at a university.[3] However, a large student body and high costs associated with multiple sessions of general chemistry laboratories necessitate that a pilot test be initiated on a smaller scale. Analytical chemistry courses were used as a pilot test because the CUREs project implementation was limited to a small population of students and took only a few weeks. The integration of CUREs into analytical chemistry courses could be a starting point in overhauling the introductory chemistry laboratory curriculum. At a very preliminary level, this study was designed to address the following research issues: (1) what is the potential of CURES to enhance students' motivation to learn Quantitative Chemical Analysis, and (2) how will the introduction of forensic-themed CURES affect students' learning in an Instrumental Analysis laboratory course. The integration of CUREs into science courses is a scalable pedagogy. While there is much similarity between CUREs topics explored in this study and research topics being pursued in existing literature under the name of special projects or independent projects, two distinct CURE models have emerged as possible ways of expanding its implementation in large classroom settings: the local model, where an individual faculty designs a CURE stemming from his or her own research interests; and the national model, where a CURE is developed by an individual faculty, and then is adopted and implemented by a network of faculty who teach the same subject course. We intend for this paper to help start brainstorming new CUREs ideas that can be systematically incorporated into undergraduate analytical chemistry laboratory curricula. By further understanding of the impacts of these

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strategies, there is a hope to be more effective in stimulating students' learning effectiveness and overall interest in chemistry.

ANALYTICAL LABORATORY COURSES

Analytical Chemistry is a subdiscipline of Chemistry which deals with the identification and assay of materials and their composition. At North Carolina Central University (NCCU), the combination of Analytical Chemistry I—Quantitative Chemical Analysis (ACI) and Analytical Chemistry II—Instrumental Analysis (ACII) offers an integrated view of theories, chemical methods, and instrumental techniques. These courses allow for students to solve a variety of real-world problems in areas such as environmental monitoring, medical diagnostics, and forensic investigation. Currently, ACI satisfies one of the natural science course requirements for students in the Departments of Chemistry, Biology, and Pharmaceutical Science at NCCU. Only Chemistry major students are required to take ACII. The enrollment numbers for both courses have ranged from 5 to 20 in recent years.

The laboratory sections for both ACI and ACII courses meet once per week for 3 h, with the instrumental room available during the week so that students may come at any time to complete their measurements. Students work in pairs during the regular lab activities for part of the semester, but conduct the CUREs projects individually. Each section is limited to 16 students. The general outlines of the experiments and schedules for ACI and ACII are shown in Tables 1 and 2, respectively.

Table 1. General Lab Schedule for ACI, Fall 2014

Week	General Lab Activity	Independent Activity
1	Check-in, use of automatic and/or volumetric pipets, flasks, and burets	Description of real-life samples and project format
2	Statistical analysis of data, making standard solutions, unit conversions and dilutions	Assignment of groups, literature review of potential research topics
3	Experiment: pH measurements and acid/base titration	Project title and description due
4	Experiment: EDTA titration	Presentation literature review
5	Experiment: Redox titration	Collection and preparation of samples
6−10	Group rotation of experiments	Determination of analytical methods, preparation of standard solution, group discussion
11−15		CUREs (research and oral presentation)

For the first few weeks of each semester, students are systematically trained on relevant laboratory techniques and various instrumental methods. Ideally, the students would then be able to choose a method with which to conduct their research. It is imperative that the overall planning and preparation of CUREs be introduced in the first weeks of each semester so students can develop a better understanding of the underlying purpose of their individual CURE projects.[7] However, the amount of time spent on the relevant discussions about CURE projects will be limited, so as not to interfere with the regular instruction of standard labs. With careful planning and frequent brief discussions throughout the first 10 weeks of the course, each student shall be able to come up with some concrete ideas about their own research topics, which can be investigated with the suitable tool and technique covered in the course.

Develop and Implement CURE Project ACI, "Real-Life" Sample

ACI is concerned with determining the amount of the constituents present in the material in question. The objectives of ACI are to teach fundamental aspects of acid/base chemistry, chemical equilibrium, and electrochemistry. Another objective is to acquaint the student with a variety of techniques and tools of chemical quantitative analysis. The students are exposed to the contribution these aspects of chemistry have on a diverse range of fields, such as medical diagnostics, agriculture and food processing, and environmental monitoring. The specific experiments, as well as the progress expected on the CUREs, are outlined in Table 1.

Develop and Implement CURE Project ACII, "Real-Life" Sample

ACII presents a survey of modern instrumental methods of chemical analysis. This course focuses on fundamental principles in spectroscopic and chromatographic techniques, as well as their realization in modern instrumentation for chemical analysis. By the end of the semester, students should develop an understanding of the capabilities of the above-mentioned analytical techniques and be able to suggest suitable methods for particular analytical problems. Because forensic investigations serve as excellent examples of how science can explain past events by careful observation and analysis of present evidence, these investigative techniques were incorporated into the course.[13] The specific experiments, as well as the progress expected on the CUREs, are outlined in Table 2.

RESULTS AND DISCUSSION

During the first week of both courses, students were given specific instructions on how to write a formal report, how to give an oral technical presentation, and the grading rubrics for both were provided. The instructor provided several examples of potential avenues the students could pursue, guidance on how to further develop an appropriate CUREs project, and guidance on how to find a corresponding technique via

Table 2. General Lab Schedule for ACII, Spring 2015

Week	General Lab Activity	Independent Project Activity
1	Check-in, lab note-books, general laboratory practices	Description of forensic evidence and project format
2	Statistical analysis of data, practice sample preparation techniques	Assignment of groups, literature review of potential forensic-themed topics
3	Experiment: Analysis of caffeine and benzoic acid by UV−vis, and Analysis of riboflavin by fluorescence	Project title and description due
4	Experiment: Analysis of iron by AAS, and Analysis of polymers by IR	Presentation literature review
5	Experiment: Analysis of ethanol by GC and Raman, and Analysis of caffeine by HPLC	Collection and preparation of samples
6−10	Group rotation of experiments	Determination of analytical methods, preparation of standard solution, group discussion
11−15	-	CUREs (research and oral presentation)

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literature search. To complete the CUREs project effectively, the students used the literature to guide them in collecting samples, measuring variables, and analyzing the resulting data. At the end of the semester, the students gave an oral presentation on their findings, as well as submitted a written report. Included in the written report was a student survey. This was given to help assess the impacts of the CUREs projects on the student perceptions of learning outcomes. The CUREs decided upon by the students are listed in Table 3.

Table 3. ACI and ACII CUREs Projects 2014−2015

ACI: "Real-Life" Sample	ACII: Forensic Theme
Determination of Vitamin C Concentration in Orange Juice by Titration	Description of Bisphenol-A in Samples of Water Using UV Detection
Determination of Calcium Concentration in Powdered and 2% Milk	Spectroscopic Detection of Gun Powder
Determination of Iron in Soap	Spectroscopic Analysis od Dextromethorphan (DM) in Over-The-Counter Cough Syrups
Finding Concentration of Ascorbic Acid in Vitamin C Tablets	Rapid and Sensitive Detection of Melamine in Milk with Gold Nanoparticles by Raman Scattering
Determining Molarity and Percent Mass of Acetic Acid in Vinegar	Development and Optical Characterization of Latent Fingerprints
Determination of Chlorogenic Acid in Coffee	-
The Analysis of Caffeine in Coffee	-
Determination of Free Chlorine in Water Sources	-

Assessment of Student Learning Effectiveness

At the end of the semester in which the CUREs were implemented, each student was asked to prepare and submit a formal report describing their project. This provided them with an opportunity to gain experience with the format of a technical paper and to work on their technical writing skills. The use of an oral presentation and submission of a final report by each student also ensured individual accountability. One benefit to these activities was to allow students to see how much they had learned and to share their success with their peers.

For the ACI course, students were encouraged to enhance their learning process by suggesting ideas for new approaches or course improvements. The students' responses are outlined in Box 1. The results of this general inquiry suggest that the CUREs implementation was positively received by most of the students. The inquiry results included encouraging outcomes, such as increased confidence and an increase in problem-solving abilities.

Box 1. ACI Student Responses to a General Request for Feedback on the Implementation of CUREs.

- *I have gained a lot from this process. The experiment has allowed me to learn independent work.*
- *I think that the independent lab project was a great idea.*
- *I was able to use a new instrument, teach someone else, and also make solutions.*
- *I did like doing a self-experiment. This lesson was able to show us that everything does not all go to plan when it comes to lab preparation, and that we as students have to be able to be scientist and change things first hand.*
- *The independent project was a very great idea, ... I gained so much confidence that kept me going till the completion of the experiment.*
- *Personally the "cookbook-labs" are just as fun, informative and easier.*

At the end of the ACII course, students were again asked to evaluate how well course objectives were achieved and areas where improvement could be made. Also, a more quantitative attitudinal survey questionnaire was added. This questionnaire asked the students to rank their reactions, whether positive or negative, to questions in regards to perceived growth on certain aspects of the CUREs project. The format and questions asked in the questionnaire were partially inspired by a similar project implementation done at Winston-Salem State University.[14] The survey questions and the results are shown in Table 4.

Table 4. ACII, Spring 2015 Student Attitudinal Survey

Survey Items[a]	Strongly Disagree, %[b]	Disagree, %[b]	Neutral, %[b]	Agree, %[b]	Strongly Agree, %[b]
CUREs project was interesting and exciting			20	20	60
Related to real-world problems		20			80
Made me more likely to get involved in research activities		20	40	20	20
Enhances my critical thinking ability	20	20		40	20
Improves my written and verbal communication skills	20		40	40	
Prefer CUREs over traditional lab			20	40	40
Want to participate in future CUREs in other laboratory courses			20	60	20
Overall, experience useful		20		60	20

[a]Representative free-response comments included: " The independent experiment helps me to better understand how to make different solutions." "I feel as I did something extremely useful and I enjoyed doing it." "A little more structure for research would have helped." [b]$N = 5$.

A majority of the students responded that their CURES projects were interesting and exciting. The same percentage of the students preferred CUREs over traditional cook-type labs, wanted to participate in future CURES in other laboratory courses, and found the overall experience useful. The results of the evaluation of this part of the study were largely skewed by the negative responses from one single student, who did not actively participate in the exercise.

To put our study in perspective, we compared student performance with respect to the overall retention rate in the CUREs cohorts relative to the performance of those in the traditional instruction settings. As shown in Figure 1, the implementation of CUREs in both ACI and ACII courses had a positive effect on the overall retention rate of each participating student cohort. The retention rate of the Fall 2014 ACI class in which CUREs were implemented leaped almost 30% from the Fall 2011 ACI class. A similar improvement was seen when one compared the retention rate of the Spring 2015 ACII class with those of two previous ACII classes offered in Spring 2013 and Spring 2014. The pass rate of each class was provided in Figure 1; however, these numbers are potentially more subjective as the final grade of each course depended on instructor

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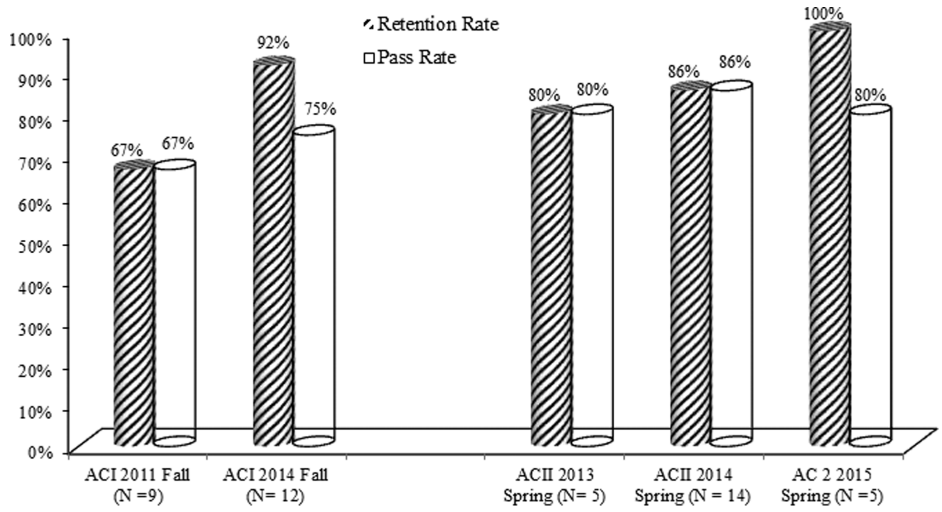

Figure 1. Retention rates and the pass rates of cohort students who participated in the CUREs in Fall 2014 and Spring 2015 semesters vs those who did not in Fall 2011, Spring 2013, and Spring 2014 semesters

input rather than just individual student effort. No direct correlation can be found between the retention rate and the passing rate of each student cohort under study.

■ LIMITATIONS OF THIS STUDY

This was a small-scale study that took place at NCCU, a primarily undergraduate institution (PUI). Comparison of results and improved performance was based on the same instructor's previous experience teaching the same courses for five semesters, spanning Fall 2011 to Spring 2015. The class size of both the study groups and the controlled groups was relatively small. Despite these limitations, we feel that our report captures the distinct characteristics of the integration of CUREs into analytical chemistry courses, and discusses ways in which the student learning gains can be systematically evaluated. These CUREs type projects, when considered individually, are not unique to small classes at PUIs, they could easily be adapted to the larger classes found at non-PUIs.

■ CONCLUSIONS AND FUTURE WORK

It has been demonstrated that by incorporating CUREs into our analytical chemistry laboratory curricula, we were able to induce positive effects on students' motivation to learn both Quantitative Chemical Analysis and Instrumental Analysis. Three different approaches on assessing the use of CUREs on the students' learning outcome were explored. The first one was qualitative in nature, which consisted of a compilation of students' general feedback on the implementation of CUREs. Most students spoke highly of the exercise. The second one focused on students' own perceptions of the learning experience and the science-related skills they develop from participating in a CURE. The majority of students reported increased confidence in their lab skills, including technical skills, analytical skills, and communication skills. The third one was semi-quantitative, which offered a direct comparison of the study groups and the control groups with respect to the overall retention rate of each student cohort, spanning Fall 2011 to Spring 2015. Significant improvements were found for those student cohorts in both analytical courses where CUREs were systematically implemented. We plan to continue this effort in future semesters when these two analytical chemistry courses will be offered. We hope that our report draws attention to the advantages of implementing CUREs not only at PUIs (where the course size is generally small), but also for the larger classes found at non-PUIs. We also hope that by expanding the incorporation of CUREs into the laboratory components of all levels of chemistry courses at NCCU, we will be able to retain more students as science majors and encourage them to consider future careers in STEM disciplines.

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Notes

The authors declare no competing financial interest.

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