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Laboratory Experiment

Quantum Dots Synthesis and Application in a Course-Based Undergraduate Research Experience

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ABSTRACT: The course-based undergraduate research experiences (CURE) approach is increasingly being used in undergraduate experimental courses. Here, we describe the implementation of CURE in an upper-level inorganic chemistry course, in which students were assigned different current themes to study. This paper focuses on the theme of quantum dots, highlighting how guidance, inquiry, and research were integrated into the classroom. The quantum dots theme introduced various concepts to students such as electron−hole pairs, band gaps, particle capping, doping, and size effects. A questionnaire distributed among the students revealed that the continuation of their research throughout the semester kept them engaged, and they maintained a high level of interest in the subject. The success of CURE in this course is revealed, as the instructor and professor will maintain this approach in the next semesters.

KEYWORDS: *CURE, Quantum Dots, Inorganic Chemistry, Laboratory Experiment, Laboratory-Based Chemistry Teaching*

■ INTRODUCTION

Upper-level inorganic chemistry courses are designed to provide students with a deeper understanding of chemical research,[1] emphasizing both literature and skill development.[2−4] Recent studies have suggested that inorganic chemistry instructors should incorporate engaging pedagogies to promote intrinsic motivation. These methodologies support student autonomy, competence, and relatedness.[1] Thus, there has been an increase in the search for courses with higher levels of involvement of the students. Among these approaches, the course-based undergraduate research experiences (CURE) approach gained considerable interest for laboratory courses due to its reflection of a more authentic research experience in comparison to traditional methodologies or inquiry-based courses.[5]

The design of CURE involves five basic elements: (i) research practices, (ii) discovery, (iii) relevance, (iv) collaboration, and (v) iteration.[6−8] From these elements, it is easy to notice that the research theme plays a significant role in the success of CURE methodology. For instance, according to Lung, adoption of a theme increases relevancy, focuses on processes, integrates units, and fosters "higher order thinking", reporting improved student attitudes.[9] Similar conclusions were observed in several other reports.[10,11] Thus, it is essential to find relevant topics for students to research in their practices, leading them to discover key aspects of the discipline due to iteration and collaborative work inside a group of students.[12]

In this work, to illustrate the importance of inorganic chemistry research in society, seven different current themes were proposed to the students during one semester of 2023. These themes, also listed in the Supporting Information (SI), included (1) metal−organic framework (MOF) synthesis and applications,[13−15] (2) interaction between inorganic complexes and DNA,[16−18] (3) dye sensitized solar cells,[19−21] (4) silver nanoparticles as catalysts,[22] (5) metalloenzymes and their mimics,[23,24] (6) supramolecular chemistry,[25] and (7) photoluminescence of quantum dots (QDs)[26] and inorganic complexes.[27] This course served as an upper-level experimental inorganic chemistry curriculum at UFSCar (Universidade Federal de São Carlos). It is important to note that although CURE suggests using new and unexplored experiments, the themes were chosen based on the availability of reagents and infrastructure to guide the students effectively. For example, to investigate the main interaction modes between coordination compounds and DNA, students were asked to purify DNA from a fruit[28] instead of using a commercially available human DNA sample. Moreover, to enable the DNA extraction and purification, magnetic nanoparticles were synthesized.[29,30] This approach ensured that CURE provided a consistent topic for students to study throughout the semester, allowing them to explore different aspects of inorganic synthesis, analysis, and applications. In this context, we chose to highlight one of these themes to demonstrate how students were able to engage in research. Specifically, we will focus on the study of quantum

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dots (QDs) to show how students entered the research area through this course, evidencing the success of this approach.

We attribute part of the success of the course due to the relevance of this theme, since in recent decades there has been an increase in research into the photocatalytic properties and applications of various types of small particles, including quantum dots (QDs).[31] QDs are nanoparticles of semiconductor material with typical diameters of 2 to 10 nm, which have optical properties such as bright luminescence, a broad excitation profile, narrow emission peaks, and photostabilizers.[32,33] Due to the size of these materials, the "size-dependent effect" occurs, which corresponds to changes in the physical properties of solids when their size is reduced to nanoscale dimensions.[32,34,35] This effect can be explained by using a simple model of a particle in a box. It is possible to adjust the emission and absorption spectrum of a QDs by changing their size, which can be easily adjusted during their synthesis.[26,33,36] When a nanocrystal increases, the energy of the first excited state decreases, which qualitatively agrees with the behavior of a particle in the box.[37]

One way to demonstrate the size-dependent effect is through solutions of QDs with different diameters, showing that the luminescence depends on the size of the material.[32] Size-dependent photoluminescence (PL) is the most studied phenomenon in chemistry and biology.[31] The advantage that QDs have over typical fluorescent materials is that their fluorescence can be synthetically tuned over a wide wavelength range.[36] Most materials aimed at teaching laboratories that address QDs are based on toxic elements, such as $CsPbCl_3$, PbS, and CdSe.[26,32,33,37−40] A QD that does not contain any toxic elements and requires little material for its synthesis to be carried out is ZnS. Another advantage that these QDs have is the low cost of the reagents used, making their synthesis viable in teaching laboratories that have few resources.

In the QDs CURE, the aim was to show that the material's luminescence is linked to its composition. Hence, students were asked to synthesize three QDs: ZnS, Mn-doped ZnS, and Ni-doped ZnS. Furthermore, the students designed a comparison of the optical properties of the QDs with those of the Zn-salen complex. Noticing the photoluminescence of these materials, they tested them as photocatalysts for degrading organic dyes. The students finished the course familiarized with important concepts in QD synthesis and optical properties, evidencing CURE as a good approach toward a higher level of understanding.

■ EXPERIMENTAL SECTION

Synthesis and Characterization of ZnS QDs

First, 22.5 mL of an aqueous solution of 0.1 M L-cysteine was added to a 22.5 mL solution of 0.1 M zinc nitrate under a nitrogen atmosphere and magnetic stirring for 15 min. Then, 25 mL of a solution of 0.1 M sodium sulfide was added, and the mixture was kept at 50 °C for an additional 20 min.

Synthesis and Characterization of Mn-Doped ZnS QDs

Mn-doped ZnS QDs were obtained by a reaction between 10 mL of 0.1 M zinc acetate, 4 mL of 0.07 M manganese sulfate, and 10 mL of 0.04 M L-cysteine solutions. After stirring the mixture for 30 min, the pH was adjusted to 11 with 1.0 M NaOH. The mixture was kept under a nitrogen atmosphere at room temperature for 15 min, and a solution of 10 mL of 0.1 M sodium sulfide was added. The solution was maintained at 50 °C for an additional 20 min.

Synthesis and Characterization of Ni-doped ZnS QDs

Ni-doped ZnS QDs were obtained via a similar procedure as the Mn-doped ZnS QDs. In a round-bottom flask, 10 mL of 0.1 M zinc acetate, 4 mL of 0.14 M nickel acetate, and 10 mL of 0.04 M L-cysteine solutions were added. After the mixture was stirred for a few minutes, the pH was adjusted to 11 with 1.0 M NaOH, and the mixture was kept under a nitrogen atmosphere for 15 min at room temperature. Then, 10 mL of 0.1 M sodium sulfide was added, and the solution was maintained at 50 °C for an additional 20 min.

The three QDs were characterized by UV−vis spectroscopy and DLS (dynamic light scattering). The UV−vis spectra were recorded on a Hewlett-Packard 8452A diode array or in a Varian Cary 8454″ spectrophotometer using a 1 cm path length quartz cuvette. The size distributions by intensity were determined by dynamic light scattering (DLS) using a Malvern ZetaSizer Nano ZS at a temperature of 25 °C.

Synthesis and Characterization of Zn(Salen)

A 285 mg portion of zinc oxide (3.5 mmol) and 0.25 mL of methanol were added to a mixture containing 1 mL of salicylaldehyde (7 mmol) and 0.23 mL of ethylenediamine (3.5 mmol). The resulting powder was mixed for another 30 min. The solid compound was isolated by filtration, and the crystals were washed with methanol and dried for a week. The Zn-salen complex was characterized by infrared and UV−vis spectroscopies.

Congo Red Reduction Test with ZnS, ZnS:Mn, ZnS:Ni, and Zn(Salen)

The reduction of Congo red was investigated after reaction with ZnS, ZnS:Mn, ZnS:Ni, and Zn(salen) compounds. Fresh stock solutions of 20 mL of Congo red (40 mg L^{-1}) were prepared. Then, 5 mL from the stock solution was added to 4 different tubes containing 1 mL of water, ZnS, ZnS:Mn, and ZnS:Ni, respectively. The samples were placed inside a beaker filled with water to maintain the reactions at the same temperature. The final solutions were irradiated with UV light, and their absorbance was measured using an Epoch microplate spectrophotometer over 2 h (30 min interval) at 500 nm (see Figure 3).

Measurements

FTIR Spectroscopy. Fourier transform infrared (FTIR) spectra were obtained in KBr pellets using a Bomen-Michelson FT spectrometer, model MB-102. All measurements were obtained in the interval of 400 and 4000 cm^{-1}.

Electronic Spectroscopy (UV−Vis). Electronic spectra were recorded in an HP Hewlett-Packard 8452 A spectrophotometer. The samples were analyzed in solution using a quartz cell with a 1 mL maximum volume and an optical path of 1.0 cm. Samples were prepared from stock solutions by dilution in distilled water.

DLS Analysis. Dynamic light scattering analysis was performed using a Zetasizer μV instrument (Malven Instruments, Ltd., Malvern, Worcestershire, UK), using a quartz cuvette ZMV1002-2μL.

Fluorescence Analysis. The luminescence spectra were recorded on a Shimadzu RF-5301PC spectrofluorometer, exciting the samples at 270 nm. All samples were prepared in water by dilution of stock solutions in distilled water.

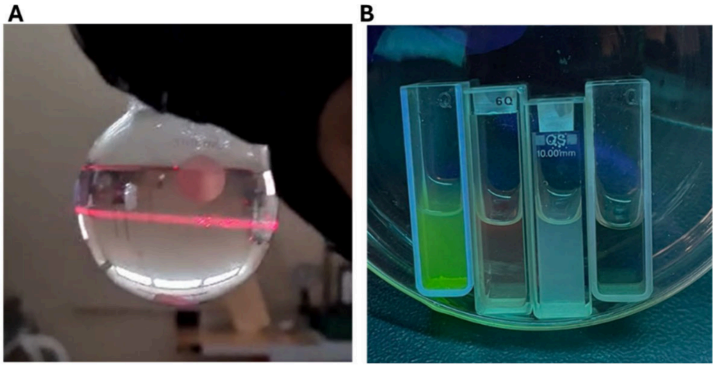

Figure 1. (A) Tyndall effect observed in the ZnS QDs suspension upon irradiation with a red laser and (B) fluorescence observed in the QDs materials upon irradiation with a light at 245 nm, from right to left: ZnS:Ni, ZnS, ZnS:Mn, and Zn(salen).

HAZARDS

All chemicals should be handled with proper personal protective equipment. It is advised to work in fume hoods. Disposal of reactions and chemicals should be performed correctly in a properly labeled disposal container. Exposure to zinc nitrate can cause headaches, dizziness, nausea, and vomiting. Sodium sulfide produces toxic and corrosive gases. Nickel acetate is toxic, an irritant, and presents an acute aquatic toxicity (Category 1). The solution of Na_2S in water is a strong base, reacting violently with acids. Manganese sulfate can cause serious eye irritation and may be harmful if inhaled. Sodium hydroxide produces strong basic solutions and is corrosive. Ethylenediamine is a colorless liquid with an ammonia-like odor and is a corrosive chemical that can cause severe irritation of the skin and eyes.

RESULTS AND DISCUSSION

The semester was structured into 15 weeks, with each week comprising 4 h of instruction. The first week was dedicated to explaining the course structure and allowing students to select their desired project themes. Weeks 8 and 15 were reserved for seminar presentations, where students shared the progress and results of their work. Week 14 was designated as a flexible period for students to refine or repeat experiments that may not have gone as expected. Detailed procedures for each project theme are provided in the Supporting Information (SI). In addition, students received original research papers corresponding to their experimental procedures to deepen their understanding and study for their projects. All of the procedures given to the students of each theme can be found in the SI.

The instructor was available throughout the course to answer student queries, with common questions including, “What is the goal of this experiment?” and “What should we expect to observe?” For this reason, the instructor needed to be thoroughly familiar with all of the project themes. It should also be noted that the guidelines in the SI were not always strictly followed, as modifications were made to setups or experiments were reattempted when initial attempts failed.

Thus, to enhance the course’s effectiveness, it is recommended that the instructor begins each class by discussing with the students their plans for the week, enabling joint decisions on how to arrange glassware or handle certain chemicals, thereby minimizing errors and disruptions to the schedule. Managing seven concurrent projects can be challenging, and in our case, the instructor was supported by a graduate student and a technician who assisted the students alongside the instructor.

Case Study: QDs CURE

The class was composed of 20 students, and they were separated into seven different groups. At the beginning of the course, students were given a text containing explanations to seven main themes (see the Supporting Information). They were asked to carefully read and choose one of them, as they were expected to work with this theme during the whole semester. Thus, each set of students was responsible for a different topic. More information regarding each topic can be found in the SI. All groups showed a certain degree of involvement with the topic and some level of investigation. Here, we are highlighting only the QDs results due to their higher involvement with the theme, demonstrating a success case.

The group responsible for the QDs theme was composed of three students. During the next few weeks, they synthesized ZnS QDs with and without doping (either with Mn^{2+} or Ni^{2+}). The students decided on their own to resynthesize some of the material once they verified issues with the synthesis or analysis. Originally, the instruction indicated that the QDs needed to be synthesized with thioglycolic acid as a capping agent, but after noticing the unavailability of this reagent, the students employed L-cysteine, using a procedure already reported in the literature.[41,42] Their nanomaterials presented fluorescence upon UV irradiation, and they observed the Tyndall effect[43] (Figure 1).

The choice of the percentage of metal for the doping procedure was arbitrary, choosing 4%. The UV−vis spectra revealed alterations in the number of bands for ZnS nanoparticles before and after doping with either Mn^{2+} or Ni^{2+}. Whereas ZnS nanoparticles presented only one band at 280 nm, ZnS:Ni presented bands at 273 and 313 nm, which is similar to what was observed for ZnS:Mn at 266 and 296 nm. These findings reveal that doping changed the electronic properties of our material. During class, n and p doping was explained to the students to guide them to evidence the band gap changes with their experimental results. Thus, using their UV−vis plots, they were able to obtain a Tauc plot and the corresponding band gaps of their materials. For instance, doping with nickel and manganese decreased the band gap from 3.94 to 3.40 eV (ZnS:Ni) and 3.23 eV (ZnS:Mn). Using FTIR spectroscopy, the students verified the presence of a band around 1603 cm^{-1}, which was assigned to L-cysteine as a capping agent (Figure 2A). Photoluminescence of these

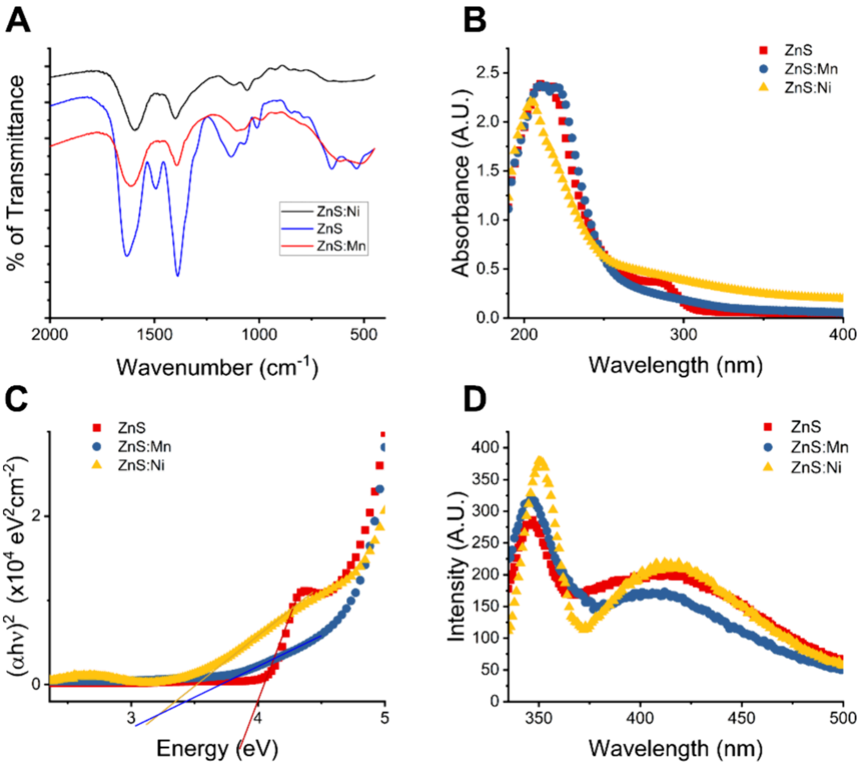

Figure 2. QDs spectroscopy study performed by the students. (A) Solid FTIR spectra performed at 10% w/w KBr; (B) UV−vis electronic spectra of aqueous solutions; (C) Tauc plots obtained from UV−vis; and (D) fluorescence of QDs excited at 270 nm of aqueous solutions. Samples were prepared by diluting stock solutions of the quantum dots in distilled water until they reached similar absorptions at the band around 200 nm.

materials was verified, and the students observed that they had a close maximum, but doping shifted the photoluminescence to lower wavelengths.

The photoluminescence spectra are useful to disclose the efficiency of migration, charge carrier trapping, and transfer and to understand the fate of electron−hole pairs in metal oxide nanoparticles since photoluminescence emission results from the recombination of free carriers (Figure 2).

These materials were employed as photocatalysts to degrade Congo red dye. Students used a UV light chamber for TLC visualization as a reactor. The UV light used had a power of 4 mW and λ_{max} at 254 nm. A 96-well plate was used to perform the degradation study, in triplicate, and methylene blue (lines A−D) and Congo red (lines E−H) dyes were used. As illustrated in Figure 3 (left), 50 μL of the nanoparticles ZnS:Ni (column 1−3), ZnS (column 5−7), and ZnS:Mn (column 9−11) was added to each well. Further, 100 μL of the dye was added to each well at different concentrations: 0.1148 mM (A and E), 0.0574 mM (B and F), 0.0287 mM (C and G), and 0.0143 mM (D and H). For a control, in columns 4, 8, and 12, only the dyes were added.

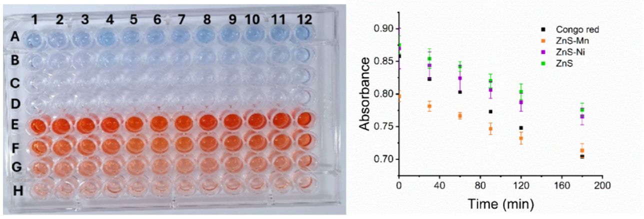

Figure 3. Degradation experiment: 96-well plate used in the experiments (left) and absorbance of Congo red dye over time upon irradiation at 254 nm (power = 4 W) in the presence or absence of the QDs (right).

Prior to their use in the photodegradation experiment, the absorbance of all nanoparticles was adjusted to have the same absorptivity at 254 nm. The students analyzed the absorption of the dye after 30, 60, 90, and 120 min of exposure. The results for Congo red are presented in Figure 3 (right). Upon analyzing the photodegradation over time, they observed that ZnS and ZnS:Ni had protective effects over the degradation of Congo red, whereas ZnS:Mn degraded Congo red to a higher extent than natural photodegradation. As ZnS particles are normally employed as photocatalysts, the protective effect was a surprising factor,[44,45] specially in the use of dye degradation.[46,47]

However, it generated an opportunity for students to study photon efficiency due to electron−hole recombination. The reduction in the efficiency of the photocatalytic activity by absorbed protons caused by this process was hypothesized to be two main reasons: either (i) the capping agent was inhibiting the use of the hole to oxidize the dye[48] or (ii) the size of the nanoparticles was causing such effects due to volume recombination.[49] Thus, students found in the literature that the L-cysteine layer is beneficial to the separation and transfer of photogenerated electrons and holes at the surface of QDs[50,51] and concluded that it was more likely the second hypothesis was the reason for the low photodegradation of their QDs. DLS (dynamic light scattering) measurements performed by the students revealed a mean diameter of 92 nm for both ZnS and ZnS:Ni, which is in agreement with photocatalysis experiments (Figure 4). Interestingly, smaller particles were obtained for ZnS:Mn (32 nm), and these

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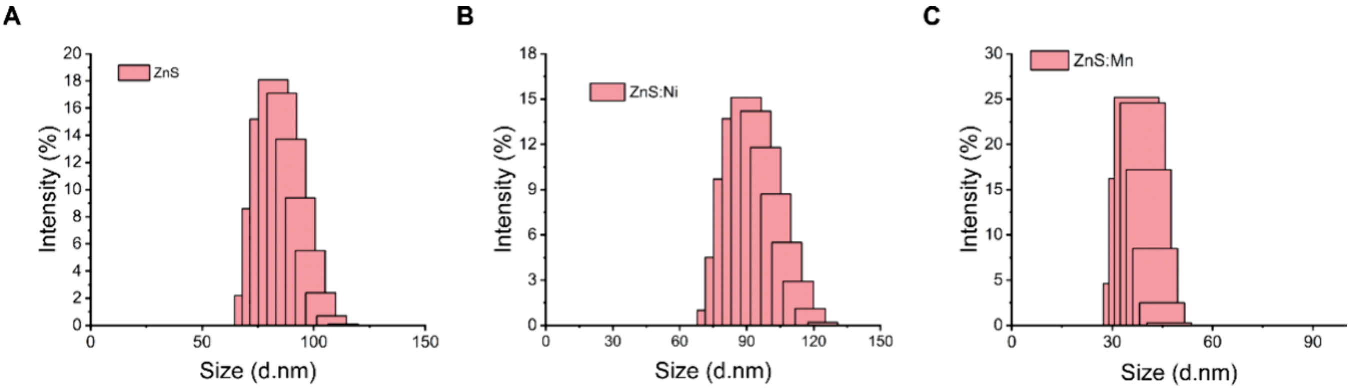

Figure 4. Dynamic light scattering results of the synthesized nanomaterials: (A) ZnS, (B) ZnS:Ni and (C) ZnS:Mn.

particles were the most active as photodegradation catalysts. Their conclusion was that smaller particles should be synthesized, and the next CURE semester will be responsible for that task.

One of the objectives of the inorganic experimental class is to synthesize, purify, and characterize metallic complexes. Therefore, we added into their experiments the synthesis of Zn(salen) as a photoluminescent complex so that the students could verify that the QDs were more efficient in a photodegradation experiment than the inorganic complex. In fact, as the salen ligand has strong absorption at 245 nm and fluorescence emission at 504 nm, the dye was not photodegraded in the presence of Zn(salen).

Evaluation of the Instructor

In typical classes, students are guided to synthesize inorganic complexes to observe their spectroscopic properties, isomerism, and reactivity. However, the experiments performed in these classes are not connected to each other, and the results are typically discarded. In contrast, the CURE methodology enabled a broader field of study in the classroom. Students engaged in research-based studies, observing real-life applications of their experiments. They were exposed to techniques not usually employed in the classroom, such as DLS and fluorescence spectroscopy, which increased their knowledge of the department's available equipment.

Each group studied different themes and presented their results to the class, introducing students to many other applied-based research areas and broadening their knowledge of inorganic experiments. To better utilize the CURE methodology, it would be beneficial to have more equipment available in the laboratory. However, we managed this limitation by seeking departmental support for the use of NMR, DLS, fluorescence, and microanalysis.

During the first semester of 2024, this methodology was applied to a different class, with a new instructor who had not designed the course or the experiments. Some challenges emerged under this new leadership. For instance, the diversity of project themes significantly increased the instructor's workload, as managing multiple simultaneous projects proved demanding. Additionally, since the course focused on cutting-edge and contemporary topics, there were difficulties in sourcing certain reagents and laboratory equipment, particularly in institutions with limited access to resources. This necessitated support from other researchers in the department. The new instructor also noticed that the experiments were generally more complex than the traditional ones, resulting in a higher likelihood of failure, which in turn led to increased frustration among students. Another issue was the limited interaction between student groups due to the specificity of each project, despite the intention of students to explore various topics within inorganic chemistry. To make seminar discussions more productive, it may be beneficial to reduce the number of themes and focus on more interrelated projects.

The learning outcomes of this course are as follows: (1) synthesize and purify coordination and organometallic compounds containing transition metals; (2) characterize these compounds using spectroscopic techniques such as UV–vis and infrared (IR) spectroscopy; (3) study the structural aspects of coordination and organometallic compounds; (4) measure the conductivity and coordination points of coordination compounds; and (5) relate the properties of these compounds to the theoretical frameworks that describe them. Therefore, the use of course-based undergraduate research experiences (CURE) must encompass all of these aspects to meet the course objectives. To evaluate whether students achieved these goals, both the reports and the seminars in weeks 8 and 15 were used as assessments. These evaluated students' understanding and application of knowledge in addressing their assigned topics. For example, all groups, including those focusing on nanotechnology, were required to synthesize coordination compounds and characterize them using at least FTIR and UV–vis spectroscopy. In their reports, students were expected to connect these spectroscopic results to theoretical concepts, such as symmetry and Tanabe–Sugano diagrams, as a means of correlating the properties of their complexes to the underlying theories.

Both the 2023 and 2024 instructors agreed that the central topics and goals of the course were achieved. They also concurred that two seminars and two reports were sufficient to engage students and help them reflect on their experiences. Overall, the course format was found to be interesting and generally well-received by students. The continuous nature of the projects fostered greater engagement in the practical work, making the semester more dynamic and bringing students closer to the experience of real research and laboratory work.

We believe that the CURE methodology is a good approach to improving the quality of teaching experimental inorganic chemistry. In the coming semesters, we plan to continue applying this methodology, with some themes adjusted due to issues observed in the experiments. Most themes were retained and improved as a continuation of the first semester. For instance, the group dedicated to QDs synthesis in the second semester will focus on improving the synthesis procedure to obtain smaller particles for better photocatalytic yields.

CURE of All Topics

During 15 weeks, students were guided on a specific topic. To help them during the semester, the instructor marked their notebooks, explaining what they should include in the explanation of their observations. Students wrote two reports during the course: one in the middle of the semester and the other at the end. A seminar accompanied the report, in order to guide the students toward errors and expectations. At the end of the semester, a questionnaire composed of 11 multiple choice questions and one open ended question was sent to them, evaluating their feeling about the methodology. The class was composed of 20 students, and the questionnaire answers were plotted in a heat map, as shown in Figure 5. The questions were answered on a scale of 1 to 5, where (1) indicated no, (2) a little, (3) moderately, (4) highly, and (5) yes.

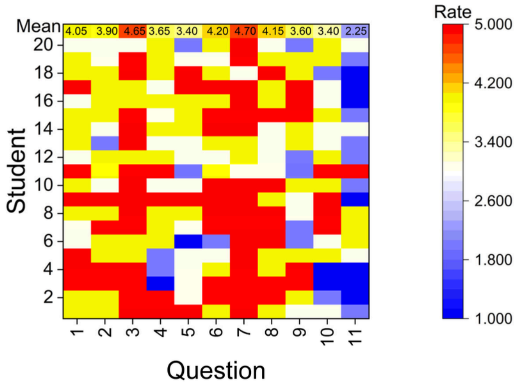

Figure 5. Heat map of the questionnaire filled in by the students. Briefly, the questions were as follows. (Q1) Do you think you learned how to synthesize and purify transition metal complexes and inorganic compounds? (Q2) Do you think you learned how to characterize transition metal complexes and inorganic compounds? (Q3) Do you believe you were able to see the importance of inorganic chemistry in current topics? (Q4) Did you feel frustrated when the experiments did not work? (Q5) Do you believe you learned more when experiments failed? (Q6) Do you think that having experiments fail can help you learn to deal with frustrations? (Q7) Do you think that having a specific goal in the semester helped in learning? (Q8) At the beginning of the semester, when you heard about how the classes would be, did you get excited about the subject? (Q9) Knowing how the CURE methodology is, would you take another class using the same teaching methodology? (Q10) The traditional methodology has previously established protocols. Considering that, would you have liked to have used previously tested experiments? (Q11) Would you have liked to have a course in this discipline with the traditional methodology?

Students rated a mean of 4.05 ± 0.75 in response to whether they believed they learned how to purify and synthesize inorganic compounds (Question 1). A similar mean rating of 3.90 ± 0.78 was given for learning to characterize inorganic compounds (Question 2). Interestingly, 70% of students indicated that they could see the importance of inorganic chemistry in new themes (Question 3), with a mean rating of 4.65 ± 0.58. Despite some experiments not working, the degree of frustration was moderate with a mean rating of 3.65 ± 1.08 (Question 4). They believed they learned moderately from failed experiments (3.40 ± 1.09, Question 5) but agreed that experiencing failed experiments improved their understanding of dealing with frustration (4.20 ± 0.89, Question 6).

A high degree of acceptance was achieved when asked if topic-based chemistry helped in the learning process, with a mean rating of 4.70 ± 0.65 (Question 7). Most students were highly enthusiastic about the course when they learned about the CURE methodology at the beginning (4.15 ± 0.81, Question 8). However, after the course, their interest in the CURE methodology declined to moderate levels (3.60 ± 1.14, Question 9). When asked if they would prefer a course that has previously tested experiments, they gave a similar rating (3.40 ± 1.23, Question 10). Despite similar ratings regarding their interest in the previously known experiments and CURE methodologies, students gave a significantly lower rating (2.25 ± 1.25) when asked if they would prefer to have taken the course using the traditional methodology (Question 11). Therefore, the CURE methodology seems to improve students' interest in taking the course, which is mainly due to their feeling about having learned something useful and current in the inorganic chemistry field.

■ CONCLUSIONS

The CURE methodology has proven to be a significant step in fostering students' interest in inorganic chemistry and, more importantly, in research. Students experienced firsthand how research is conducted in laboratories, including dealing with failed experiments and developing hypotheses, with the guidance of instructors and professors. This approach resulted in a lower generation of waste, as students reused their experimental results in subsequent classes.

The selected theme of quantum dots synthesis utilized available equipment in the department, allowing students to engage with tools they would not typically use in a traditional course. Moreover, the focus on quantum dots facilitated the continuation of their research-based approach into subsequent semesters, positively impacting their self-esteem as they contributed to producing something both useful and current. Overall, students, professors, and instructors reported higher satisfaction using this methodology. We anticipate that some of these CURE themes could even lead to research articles with undergraduate students as the primary researchers.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.4c00869.

The instructions given to the students in all seven topics, along with the experimental protocols (PDF, DOCX)

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