JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc

Laboratory Experiment

What Makes a Good Reaction? An Introduction to Green Chemistry in an Undergraduate Practical

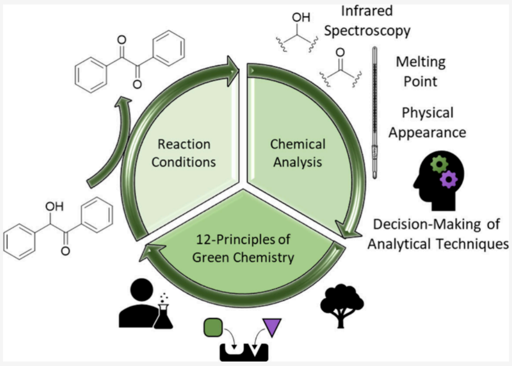
Ewan Forsyth, Craig D. Campbell, and Malcolm I. Stewart*

Cite This: *J. Chem. Educ.* 2026, 103, 2265−2274

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Grounded within the real-world context of sustainability and green chemistry, herein, we present a practical that compares three starkly different methods for the oxidation of benzoin to benzil. To promote student engagement, the different reaction protocols are assessed critically. This decision-making process includes asking the student to consider the success of the reactions by evaluating multiple factors, including yield; purity; experimental conditions; and environmental impact assessed against the 12 principles of green chemistry, as well as using spectroscopy to confirm the reaction product. By doing this, students discover the importance of decision-making while developing evidence-based justification skills. Structured discussion sessions embedded throughout the laboratory session provide opportunities for students to proactively critically evaluate the three different reaction conditions and reagents which result in the same chemical transformation. By integrating their quantitative and qualitative data, students evaluate which of the methods they consider to be the "best oxidation method", as well as discovering what makes a "good" reaction.



KEYWORDS: *First-Year Undergraduate/General, Organic Chemistry, Green Chemistry, 12 Green Principles, Oxidation, Synthesis*

■ INTRODUCTION

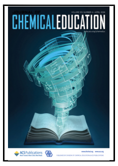
Undergraduate practical chemistry courses traditionally are comprised of laboratory practicals aligned to topics matching lecture concepts.[1] While these links have shown improved performance on lab-relevant exam questions,[2] they can give the impression that this is the optimal methodology to perform such reactions since all students undertake the same procedure. A more authentic representation of practical chemistry involves exposing students to various methodologies to achieve a common goal and comparing the strengths and weaknesses of each approach. Such guided-inquiry approaches are an effective strategy for increasing student engagement, taking ownership of their learning, and developing the critical-thinking skills that are sought beyond the laboratory classroom.[3,4]

Following our spiral-curriculum approach to practical teaching, students are first introduced to skills which are then later revisited but the subsequent practicals develop in theoretical and practical complexity.[5] Careful design of suitable introductory experiments at the requisite level requires full consideration of the variation in students' prior experience and their confidence with practical chemistry: the first exposure to laboratory techniques needs to form a solid foundation to be built upon in subsequent practicals. Selecting familiar functional group interconversions for early undergraduate synthetic practicals can be an important consideration so as to not create an environment of overwhelming cognitive load yet promote deeper theoretical understanding. This approach also provides elements of interest and challenge to the session, helping students feel that the work is worthwhile. Providing authentic context and real-world applications have also been shown to improve students' engagement.[6−8]

Given that the environmental impact of chemistry and the coverage of concepts of sustainability, including the 12 principles of green chemistry,[9] have been introduced in U.K.-based preuniversity courses,[10−15] developing an experiment that deals with this side of chemistry seemed like a good match to improve student engagement. Not only does this fulfill the requirements of accreditation/certification of a degree program to discuss "greenness"[16,17] it also provides students with subject matter that resonates with the wider societal beliefs; i.e., it is an authentic area of research and has real life application.

There are several examples of Green Chemistry undergraduate practicals,[18−24] including comparing of methods for the same reaction,[25−27] and more extensive

Received: December 19, 2025
Revised: February 12, 2026
Accepted: March 10, 2026
Published: March 27, 2026



https://doi.org/10.1021/acs.jchemed.5c01819

synthetic laboratory-based project;[28] however, the majority of reported practicals are aimed at second-year students and above. There are also resources[29] and laboratories[30−33] relevant to preuniversity students. While the prevailing belief that introducing extra degrees of cognitive demand on students at these earlier stages can be challenging,[34] we[5,35−37] and others[38] have shown that, with careful consideration of scaffolding and support, additional elements can significantly enrich the students' experiences and help them develop a sense of confidence and belonging.

The effective expression of one's ideas—oracy—is an important aspect of scientific communication and is a central aspect of our practical course, for example, students discussing aspects of decision-making, data analysis and understanding of chemical concepts in this work.[35,36,39] Indeed, oracy's importance has been recognized at the governmental level in the U.K., where it is set to be introduced to primary and secondary frameworks across the whole national curriculum.[40] This practical also provides an elevated framework for students to self-evaluate synthetic methods through oracy.

What is unique about this work is that we have developed an early on first-year practical that simultaneously explores an organic chemistry reaction, product purification, and decision-making of analytical techniques through the use of oracy in a way that helps students to see how these ideas fit together with a qualitative introduction to green chemistry.

CHOICE OF REACTION

The reaction of benzoin to benzil was chosen because alcohol oxidation reactions are covered in U.K. preuniversity syllabi.[11−15] Multiple synthetic methods for this oxidation have been reported.[41−46] Three of these methods were selected as they covered the same practical skills developments for each student regardless of which method was used, i.e., hot plate heating, temperature monitoring, Büchner filtration, and purification via recrystallization, while the reaction protocols had significant differences for comparison from both a methodological and a sustainability viewpoint (Figure 1). Intentionally, no green-optimized method was provided; thus, advantages and disadvantages of each method can be investigated in an introductory manner. Details of each method are reported in Experimental Procedures.

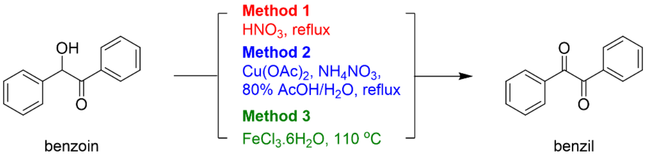


Figure 1. Reaction scheme of benzoin to benzil.

LABORATORY EXPERIMENT

The intended learning outcomes of this practical are

(1) to use appropriate heating and glass handling techniques, to perform an oxidation reaction;

(2) to perform a recrystallization of an organic product;

(3) to develop decision-making skills, including the selection of appropriate analytical techniques;

(4) to use oracy to evaluate critically the advantages and disadvantages of different synthetic methods, both from an operational viewpoint and sustainability perspective.

Although all U.K. university courses are different, studying of any STEM subject usually involves students completing a 3 or 4 year course in that subject, sometimes integrated alongside optional modules, often in STEM subjects. This means students will attend chemistry practicals throughout all years of their course.

The practical is conducted between weeks 4−8 of the students' first term at university and aligns with concurrent lectures on introductory organic chemistry, building upon the functional group interconversions previously introduced at the end of secondary level education in the U.K.[11−15] A year's cohort has roughly 180 students who are split into groups of roughly 12−15 students per practical; this practical is one of a six practical rotation completed over a 4 week block. Logistically, each cohort completing this practical are split into three subgroups, allowing simultaneous completion of the three related methodologies in the session. While the reagents and methodology of each method are different, all students gain the desired practical, decision-making, data analysis and method-evaluation skills, as outlined in the intended learning outcomes.

Working in pairs, the practical lasts for 6 h; however, it could easily be adapted to two 3 h sessions: (i) synthesis and purification; (ii) decision-making and sustainability evaluation. It could easily be altered to institutional requirements; for example, students could investigate all methods, the session could be run in groups of three students each completing one method rather than three pairs of students, and/or it could be adapted to different year groups where more advanced quantitative green chemistry analysis can be implemented. Although the students in this practical did not do a green star matrix analysis, we have provided this to facilitate its inclusion (Supporting Information).

Before completing this practical, students have not had lectures on green chemistry, so no prior knowledge on the topic was assumed; however, some preuniversity courses cover sustainability concepts.[11,13−15] To help students understand the practical, prelaboratory activities include reading through the laboratory manual and completing a short online quiz; this work is expected to take no longer than 30 min. The quiz covers questions focusing on relevant practical techniques and calculation practice; safety/hazard considerations; and understanding of green chemistry; as well as preparing students for the cognitive demands surrounding decision-making and critical evaluation by selecting appropriate analytical techniques in-line with reported best practice (Supporting Information).[47]

A 10 min introductory presentation is conducted at the start of the session (Supporting Information), highlighting key theoretical, sustainability and practical concepts, reviews safety considerations, and brings to the students' attention important factors when planning their reactions as well as helping them to decide which analysis techniques to perform. Scaffolded in-lab discussions provide interactions for students to break from practical work to

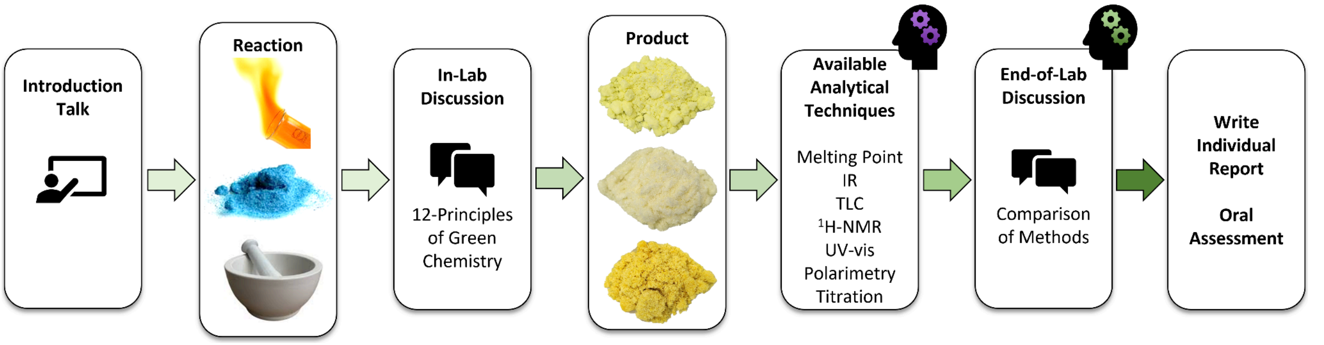


Figure 2. Workflow of the laboratory session with dedicated oracy sessions.

reflect on what they are doing reducing cognitive overload attributed to decision-making.

SAFETY HAZARDS AND PREVENTION MEASURES

Benzoin has no documented hazards. Benzil causes skin and serious eye irritation. Concentrated nitric acid may intensify fire as an oxidizer; causes severe skin burns and serious eye damage; is toxic if inhaled; and is corrosive to metals. Copper(II) acetate is harmful if swallowed; causes severe skin burns and serious eye damage; and is very toxic to aquatic life with long-term effects. Ammonium nitrate may intensify fire as an oxidizer and causes serious eye irritation. Acetic acid (80% (v/v)) in water is a flammable liquid and vapor and causes severe skin burns and eye damage. Iron(III) chloride hexahydrate is harmful if swallowed and causes serious eye damage and skin irritation. Ethanol is a highly flammable liquid and vapor that causes serious eye irritation.

All participants are required to wear appropriate personal protective equipment at all times. All reactions are performed in a well-ventilated fume hood.

EXPERIMENTAL PROCEDURES

To ensure a fair comparison of the different methodologies, the reaction scales for each method and recrystallization conditions were identical. Method 1 uses concentrated nitric acid as the oxidant and solvent. Method 2 involves oxidation of benzoin using catalytic copper(II) acetate, in 80% (v/v) acetic acid–water solution. Method 3 is performed solvent-free as a melt using iron(III) chloride hexahydrate as the oxidant.

Method 1: Concentrated Nitric Acid

Benzoin (4.80 g, 22.6 mmol) in concentrated nitric acid (17 mL) was heated and stirred at reflux for 30 min or until subsidence of the formation of NO_2 gas (maximum 60 min). With continuous stirring, the reaction mixture was cooled in an ice/water bath before the addition of cold distilled water (75 mL) to precipitate the crude product as a yellow solid. The crude product is filtered under reduced pressure and washed with deionized water until washings are pH 7–8. Further purification by recrystallization was performed from hot ethanol (20 mL).

Method 2: Copper(II) Acetate and Ammonium Nitrate

A mixture of benzoin (4.80 g, 22.6 mmol), copper(II) acetate (0.10 g, 0.55 mmol), and ammonium nitrate (4.50 g, 56.2 mmol) in acetic acid/deionized water (80% (v/v), 16 mL) was heated and stirred at reflux (~118 °C) for 60 min. With continuous stirring, the reaction mixture was cooled to room temperature before the addition of distilled water (30 mL) to precipitate the crude product as an off-white solid. The crude product is filtered under reduced pressure and washed with deionized water until washings are pH 7–8. Further purification by recrystallization was performed from hot ethanol (20 mL).

Method 3: Iron(III) Chloride

Benzoin (4.80 g, 22.6 mmol) and iron(III) chloride hexahydrate (18.36 g, 67.9 mmol) were mixed with grinding using a mortar and pestle. The powdered mixture was heated at 110 °C for 60 min, affording a semisolid melt which was stirred periodically with a glass rod. The reaction mixture was cooled (<40 °C) before the addition of distilled water (75 mL) to precipitate the crude product as an orange/brown solid. Further purification by recrystallization was performed from hot ethanol (20 mL).

STUDENT DECISION-MAKING OF ANALYTICAL TECHNIQUES

In this practical, students must consider structural analysis decisions, focused on providing evidence that they have successfully synthesized benzil. The collection of infrared spectroscopy and melting point were selected as mandatory analyses, to relate to preuniversity course material and to provide a consistent simple comparison between the methods. Other analytical techniques that students have previously been introduced to include the following: NMR, UV–vis, TLC, titration, and polarimetry. Students were given the autonomy to decide which, if any, additional data to collect, with the focus on justification of their choices within an argument framework, supported with evidence and rationalization of the data.[48]

The workflow of the practical is shown in Figure 2. Depending on the method completed, the reaction is often remembered by students for producing brown fumes (Method 1), a blue-green color change (Method 2), or using a mortar and pestle (Method 3).

ASSESSMENT

The assessment of this practical comprises several parts;

(1) Prelaboratory quiz.

(2) In-lab practical performance, including decision-making via justification of choices [graduate teaching assistants and senior laboratory teaching staff overseeing the students performing the practical and discussing the various decisions students make, as well as checking their adherence to safety, employment of good experimental technique, teamwork and organization, diligence, and participation during in-lab discussion sessions].

(3) Results [the quality of data that students obtain, i.e., product quality, acquisition and processing of good

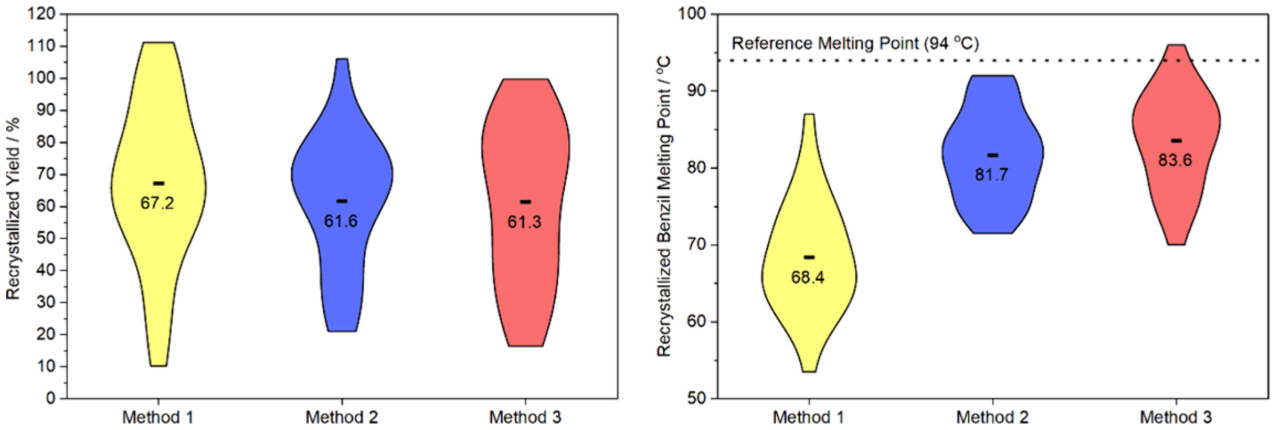


Figure 3. Violin-plot comparison of recrystallized yield and recrystallized benzil melting point compared to reported literature[42] (dotted line at 94 °C) for method 1 (N_{pairs} = 28), method 2 (N_{pairs} = 30), and method 3 (N_{pairs} = 26). In each plot the mean value is reported.

spectral data, and justification of analytical technique selection].

(4) Report and oral assessment [written report, focused on the processing and presentation of data analysis, and a comparison of the three methods; oral assessment conducted as a face-to-face 10 min viva voce discussion with a member of the teaching staff (see Supporting Information for example discussion points)].

RESULTS AND DISCUSSION

Ethical Considerations

Prior to data collection, the University of Oxford Medical Sciences Interdivisional Research Ethics Committee confirmed the data collection methods used in this study were deemed to be educational course evaluation, not requiring formal institutional ethics approval. The study was nevertheless conducted in line with our institutional course evaluation policies and the guidance provided by the ethics board. Participation in pre- and postlaboratory surveys was voluntary and accessed via a link in our Virtual Learning Environment. Responses were limited to one per student; no student details were recorded against the survey responses, and any potentially identifiable information in free-text comments was removed prior to analysis. Students were informed before completing the survey that participation was optional and in no way contributed to grading and were provided information on the nature of the project, the possible use of anonymous responses in publications, and their right to withdraw participation.

Oracy

Within this reported practical, oracy is formalized, with dedicated times within the session to encourage dialogue on method evaluation.[49] An introduction talk and an in-lab discussion focused on experimental methods (e.g., procedural and technical challenges, safety, cost, time), using the 12 principles of green chemistry as metrics and personal opinion of what made a good reaction (e.g., visually interesting, mess generated). Introducing details of the 12 principles of green chemistry once the reactions have begun allows students to consider their method and which of the principles might apply to it without worrying about the setup. This helps to reduce cognitive overload which could be a challenge with an extended introduction at the start of the lab.[3,50] There is also an end-of-lab discussion between the students and staff, focusing on the students' reflections of their decisions and justification of any conclusions.[51]

In-lab and end-of-lab dialogue with students can be split into two categories: (i) how to determine the effectiveness of a generalized reaction and (ii) selection of the appropriate analyses needed to enable characterization of the product in this practical. Active debate on which of the available techniques can yield relevant and useful information were fruitful, with many students focusing on melting point (N_{pairs} = 84) and TLC (N_{pairs} = 59) to aid purity analysis, with IR (N_{pairs} = 84) and ^{1}H NMR (N_{pairs} = 83) spectroscopies identified for structural conformation: (N_{pairs} refers to the number of student pairs). Very few students used UV−vis spectroscopy (N_{pairs} = 3) to see differences between starting material and product; those that justified completion of this technique focused on the quantification of the concentration of benzoin remaining using the visible-wavelength band ($\lambda_{\text{max}}^{\text{EtOH}} \sim 280$ nm), but recognized the difficulty given the overlapping UV-absorption for benzoin and benzil, and concentration effects (see the Supporting Information). Confirmation whether the benzoin starting material was enantiomerically pure or a racemic mixture was determined with polarimetry (N = 1). No students decided to complete titrations to confirm the reaction took place.

After completion of the Experimental Procedures, students are posed the question: "What makes a 'good' reaction?". This initiates a group discussion, where after talking it through, students write factors on an interactive screen, with potential additions made by the instructor if required. The 12 principles of green chemistry are revisited, and students collate their evaluation of the methods. These oracy sessions provide an opportunity for students to gain an understanding of all three methods. Creating time in-lab for these discussions aims to reduce the time needed outside of the lab for analysis for the students and the written report assessment by the staff. Having this as an instructor-led discussion aims to reduce the sensory overload that some students experience from many competing voices.[52]

https://doi.org/10.1021/acs.jchemed.5c01819

Student Analysis

Student analyses of melting point and yield data (N = 168) are reported by student pairs, while best oxidation method selection (N = 143) were collected from assessments conducted in weeks 4−8 of students' first term at university. Discrepancies in sample size (N and N_{pairs}) reflects lab timetabling, data publication, and the optional nature of student surveys.

Every student pair successfully, obtained recrystallized benzil in sufficient quantities to perform analyses. Data for the recrystallized product melting points and yields provides students a common foundation for comparison (Figure 3).

Method 1 provides the widest recrystallized yield distribution and has the highest mean yield of 67.2%. The higher yield, but significantly lower melting point (68.4 °C), is, at least in part, due to residual water or ethanol often being observed in the students' IR spectrum of method 1 product.

The highest melting points are observed for methods 2 and 3 of 81.7 and 83.8 °C, respectively, with literature reporting 94 °C.[42] Student melting points were regularly under-reported as students often do not use a low ramping-rate allowing for temperature-equilibration of sample and thermometer. Students that dried their sample on a Büchner funnel for more than 15 min and used a lower temperature ramping-rate recorded melting points closer to literature. The majority of students used TLC (Supporting Information) and benchtop ^{1}H NMR (60 MHz) of both the starting material and product to confirm the reaction had gone to completion. A common misconception taught preuniversity is that hydrogens on adjacent heteroatoms cannot couple[12,53] and therefore are ignored when applying the "n + 1 rule" to determine splitting patterns. Alongside our previous work,[36] students do observe but often misinterpret the ^{3}J coupling in benzoin between the benzylic and hydroxyl protons.

Within the postlaboratory assessment, the methods are compared initially in table format before drawing conclusions from method comparisons. A quantitative analysis of the 12 principles of green chemistry was not expected in this early undergraduate practical, as this is only one element of the evaluation of "what makes a good reaction?" If this work was being used for a more advanced class or one that focuses more on green chemistry, then this aspect could become explored in greater depth.

Method 1 was often considered least preferred due to the highest reaction temperature, lowest purity assessed by melting point, the use of concentrated nitric acid as the oxidant, and the production of nitrogen dioxide as the most hazardous reagent and byproduct, respectively. Students who chose this as the best method focused on the quicker reaction time and simplicity of reaction to perform.

> *"Method 1 is the best as it can be monitored with the gases being produced and has the shortest reaction time reducing the amount of energy used."*

Where method 2 was selected as the best oxidation method, advantages included its use and regeneration of a catalyst, less harmful solvents, a nontoxic byproduct (N_2), the product spontaneously crystallizing from reaction mixture upon cooling of the reaction, comparable melting point, and yield to method 3. The quantity of reagents involved, the longer reaction time, and concerns on the toxicity of the copper catalyst were noted as disadvantages.

> *"Method 2 is the best in my opinion. It uses lots of reagents including copper(II) acetate which is harmful for aquatic life. However, it produces N_2 as the gas in the reflux which isn't toxic. Method 2 is prettier to look at than method 3 so it made me feel good."*
>
> *"I would consider method 2 to be the best method for oxidation. The first reasons is because it is a method which avoids the use of highly dangerous solvents or reagents, and does not produce any toxic gases. Additionally, method 2 applies several of the principles of green chemistry, some of which are not utilized by the alternative methods. These include the use of a catalyst (with copper(II) acetate), using safer solvents (specifically acetic acid as a solvent compared to using concentrated nitric acid as is the case with method 1). Additional principles of green chemistry used by method 2 were the prevention of waste, as no highly toxic or hazardous waste was produced."*

Advantages of method 3 include a cheap oxidant, the product had the closest average melting point to the literature value, it is solvent-free and has the lowest reaction temperature. However, the use of a melt was also mentioned as a disadvantage as the reaction temperature cannot be lowered significantly to reduce energy consumption, unlike the other methods. Students found the reaction unpleasant to manually stir and look at compared to methods 1 and 2. The isolation and purification of the product from the iron salts proved challenging, which was also deemed a disadvantage.

> *"I found method 3 to be the most consistent with the principles' of green chemistry, reducing waste in terms of solvents and did not require refluxing. It did not produce toxic by-products (NO_2) like method 1."*
>
> *"I had originally thought that method 3 is the best as its purity is the best and it satisfies more of the Principles of Green Chemistry including energy efficiency (lowest reaction temperature) but [method 3] does involve melting $FeCl_3$ compared to dissolving reagents [method 1 and 2]."*

It is notable that often reaction time, temperature, and the energy required to solvate reagents were taken in isolation rather than thought about collectively by the students. After evaluating the advantages and disadvantages of each of the three methods, including evaluation against the 12 principles of green chemistry, students selected which method they consider to be the best (Figure 4). Method 2 was ranked the best overall followed by method 3 and then 1.

In an attempt to introduce students to the idea of scale-up and industrial chemistry, a question was added in to the postlaboratory assessment. Students rarely change their method selection when considering the scalability of the reaction, with temperature, the number of reagents, and the reduction of toxic reagents and products often taking precedent. It was not surprising that students did not consider aspects of heat transfer, the introduction and removal of reagents, changes in priority to cost, atom economy and waste production when deciding on the best oxidation method as they had not received formal teaching about these topics.

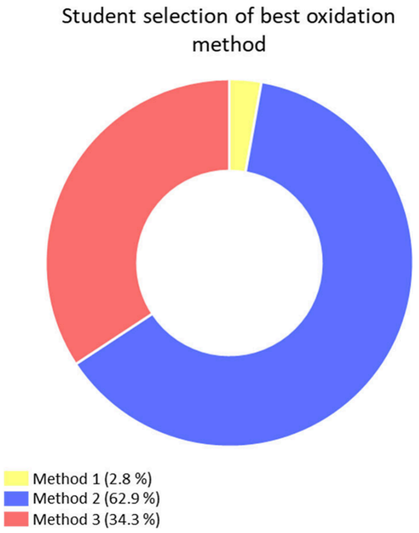


Figure 4. Student selection of the best benzil oxidation method (N = 143).

Evaluation of Decision-Making

Pre- and postlaboratory, students were asked to rank (based on a 5-point Likert scale) the importance of different data/analytical techniques to assess whether the reaction was successful in terms of synthesizing a high-purity product (Figure 5). The pre- and postlaboratory rankings were similar, with students putting more importance on yield and melting point, likely due to persistence of naïve theories from preuniversity.[54] The importance of TLC increased slightly postlaboratory, with students ranking UV−vis spectroscopy, titration, and polarimetry as least important analytical techniques for this reaction. The change in importance-ranking aligned with students' prelaboratory judgment and confirmed in-lab decisions, with those that decreased in importance being the techniques that were least attempted by students.

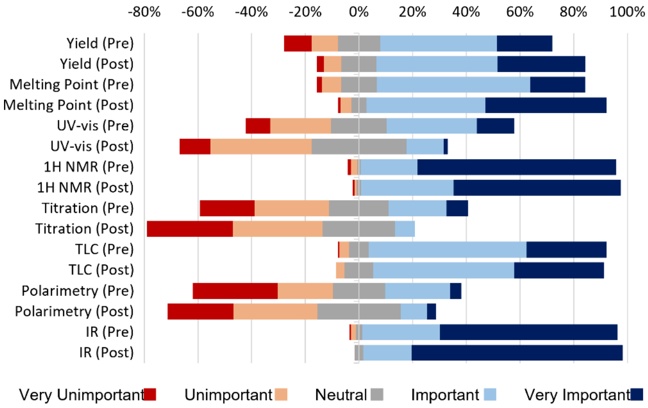


Figure 5. Student ranking of data/analytical techniques in terms of importance to assess pre- and postlaboratory N = 168/122 (Pre/Post).

Good levels of cognitive engagement in the practical were observed, evaluated by an increase in students asking decision-based questions compared to other practicals. Pleasingly, students reported that making decisions as to which data to collect was not "very challenging" (Figure 6a). This aligns with previous reports that students are able to rise to the challenge of making decisions in early stages of an undergraduate practical course.[35−37] Encouragingly, students found that performing the analysis was not particularly challenging (Figure 6b), likely as they had encountered each technique previously in a different practical, our spiral curriculum succeeding. Students were able to apply the skills they had previously encountered to this scenario with limited intervention, thus increasing both competence and confidence within the lab environment.[55−57] The analysis of spectroscopic data was reported as the most challenging part within the laboratory (Figure 6c); this might be because this was completed unsupervised outside of the lab. 89% of students reported that their decision-making skills had improved (Figure 6d). In the prelaboratory survey, 87% of the students classified learning about sustainable chemistry in a practical course as important or very important, with postlaboratory student feedback (free text) illustrating engagement from building in decision-making:

> *"Green chemistry is something I'm very passionate about, and I really liked that I could make more of my own decisions on what analysis to complete, which led to a better understanding of each technique and provided more informed conclusions. I now have more awareness on how I can make greener choices in future labs."*

To understand the perceptions of organic reactions, students were asked to evaluate factors that make a reaction "good" in terms of importance (Figure 7). The pre- and postlaboratory survey results highlight that students' continue to evaluate both yield and purity as important, with product appearance and emotive responses increasing in importance. This is of interest as in many reports, and as was discussed earlier, students noted that method 1 having a high yield is an advantage, despite the lower purity being noted as a disadvantage. Sustainability/environmental factors show a small increase in importance after students have completed the lab, suggesting that students have gained an awareness of how their actions in the laboratory have an environmental impact. Students' emotive response to laboratory experiences is complex and sometimes contradictory, and it is not possible to capture a full understanding of the affective domain within this survey.[58] The survey question "How the reaction makes you feel" aims to encourage students to reflect on their experiences and validate that their experience of enjoyment can be a contributing factor in deciding "What Makes a Good Reaction?"; i.e. enjoyment helps with motivation and leads to students being more engaged in learning.

It is worth noting that while reactions conditions and the three products all look different (Figure 2 and Supporting Information), there are limited differences in spectra. The product appearance and emotive response to the reactions being performed are deemed least important by students overall. However, these considerations show the largest increase in importance after completing the lab (Figure 7). Interestingly, no factors were ranked significantly less important after students had completed the lab.

Student feedback shows that they enjoyed seeing different methods for the same chemical transformation, highlighting that within group settings students can complete different reaction methods and all still meet the intended learning outcomes:

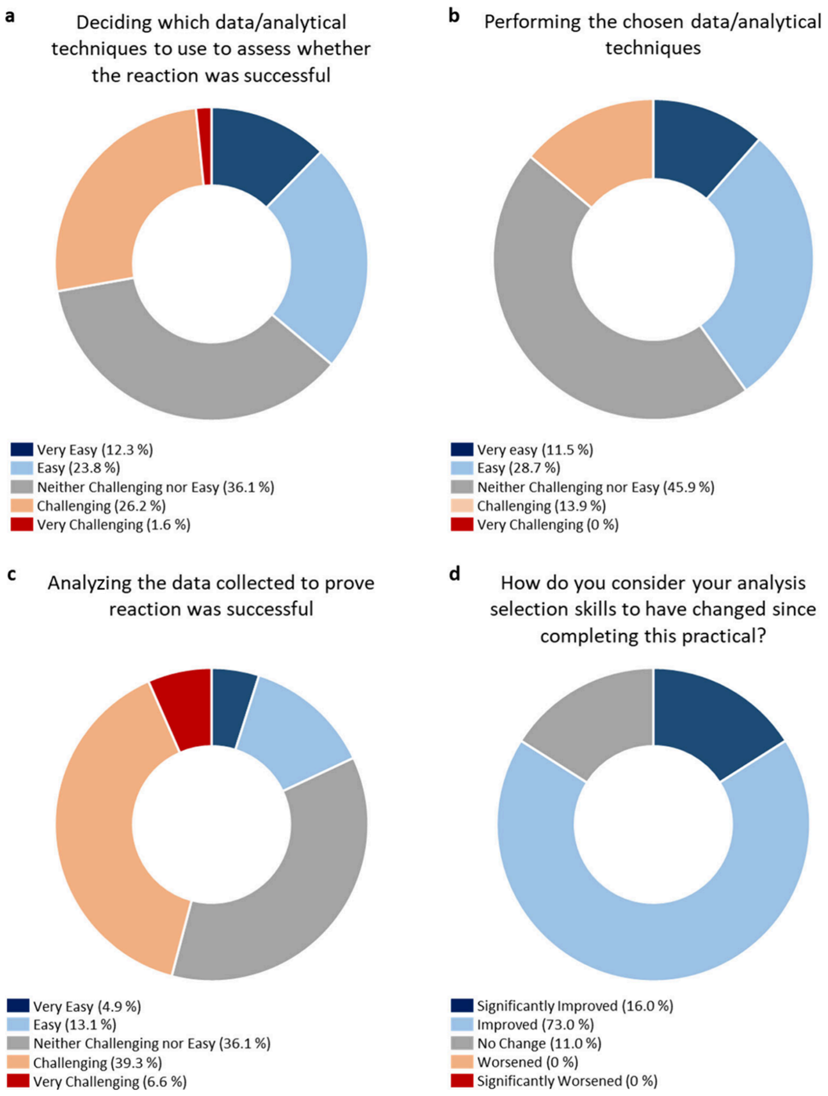


Figure 6. Student postlaboratory survey on analytical technique decision-making (N = 122).

> *"I found the [lab] style of different groups adopting different methods very interesting, as it made you think about the similarities and differences, and therefore felt very connected to 'real' chemistry. I would really like to do more labs similar to this one in the rest of the course."*

■ CONCLUSIONS

We have reported a practical that uses the framework of green chemistry as an authentic scientific context to introduce decision-making of analytical techniques in an undergraduate curriculum. The comparison of the three methods allows for both methodological and analytical comparisons to be made by students. By scheduling dedicated points in the practical for students to use oracy to develop an understanding of the 12 principles of green chemistry and to explore the types of data provided by different analytical techniques, students are supported in developing the confidence to make their own informed choices within a first-term practical.

Students self-reported an improvement in decision-making skills, which was also recognized by instructors, that being first-year students are able to implement skills previously encountered within a spiral-curriculum with minimal intervention. Future work will explore the development of an advanced laboratory practical where the quantification assessment of the 12 principles of green chemistry using the green star metrics[59,60] and E-factor[61] are implemented by students. The impact that this

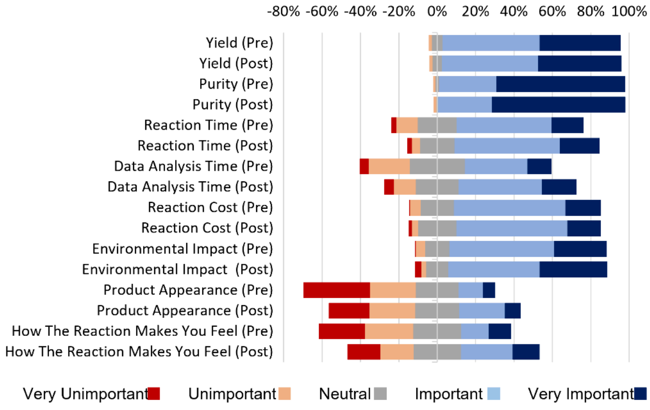


Figure 7. Pre- and postlaboratory student survey results, ranking the following factors that make a "good" reaction in terms of importance to respondents. N = 168/122 (Pre/Post).

practical had on decision-making skills and implementation of green chemistry practices will be monitored within our spiral-curriculum.

ASSOCIATED CONTENT

Data Availability Statement

As this laboratory practical is part of our live course, Supporting Information in alternative editable formats are available to instructors upon request from the Corresponding Author.

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.5c01819.

Supporting Information (PDF)

Introduction, in-lab, and end-of lab presentation slides (PDF)

AUTHOR INFORMATION

Corresponding Author

Malcolm I. Stewart − *Chemistry Teaching Laboratory, Department of Chemistry, University of Oxford, Oxford, United Kingdom OX1 3PS;* orcid.org/0000-0002-5724-9160; Email: malcolm.stewart@chem.ox.ac.uk

Authors

Ewan Forsyth − *Chemistry Teaching Laboratory, Department of Chemistry, University of Oxford, Oxford, United Kingdom OX1 3PS;* orcid.org/0000-0001-6694-1231

Craig D. Campbell − *Chemistry Teaching Laboratory, Department of Chemistry, University of Oxford, Oxford, United Kingdom OX1 3PS;* orcid.org/0000-0002-1082-3508

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.5c01819

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Louise Hewson and Thomas Birkett are gratefully acknowledged for their technical support and assistance in running these practical lab classes. The authors also thank the students who have completed this practical, and the Department of Chemistry at the University of Oxford.

REFERENCES

(1) DiBiase, W. J.; Wagner, E. P. Aligning General Chemistry Laboratory With Lecture at a Large University. *Sch. Sci. Math.* **2002**, *102* (4), 158−171.

(2) Xian, J.; King, D. B. The Effectiveness of General Chemistry Lab Experiments on Student Exam Performance. *J. Lab. Chem. Educ.* **2017**, *5* (5), 95−107.

(3) Burnham, J. A. J. "Developing Student Expertise in Scientiic Inquiry", in Seery, M. K., Mc Donnell, C., Eds. *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*; Creathach Press: Dublin, Ireland, 2019.

(4) Antonio, R. P.; Prudente, M. S. Effects of Inquiry-Based Approaches on Students' Higher-Order Thinking Skills in Science: A Meta-Analysis. *Int. J. Educ. Math. Sci. Technol.* **2023**, *12* (1), 251−281.

(5) Campbell, C. D.; Midson, M. O.; Bergstrom Mann, P. E.; Cahill, S. T.; Green, N. J. B.; Harris, M. T.; Hibble, S. J.; O'Sullivan, S. K. E.; To, T.; Rowlands, L. J.; Smallwood, Z. M.; Vallance, C.; Worrall, A. F.; Stewart, M. I. Developing a Skills-Based Practical Chemistry Programme: An Integrated, Spiral Curriculum Approach. *Chem. Teach. Int.* **2022**, *4* (3), 243−257.

(6) Sokic-Lazic, D.; Throgmorton, J. C.; Snoderly-Foster, L. J. Targeted Chemistry Laboratory Curriculum Enhancements: Transforming Student Perceptions by Integrating Real-World Contexts in Large-Scale Laboratories. *J. Chem. Educ.* **2025**, *102* (8), 3425−3435.

(7) Sristy, S. M. I. H.; Muteti, C. Z.; Vasquez, Y.; Mutambuki, J. M. Integrating Real-World Contexts and Application Cards Activities in the General Chemistry I Course Increases Students' Achievement Scores and Perceptions of Chemistry Relevance. *J. Chem. Educ.* **2023**, *100* (12), 4608−4618.

(8) Ablin, L. Engaging Students with the Real World in a Green Organic Chemistry Laboratory Group Project: A Presentation and Writing Assignment in a Laboratory Class. *J. Chem. Educ.* **2018**, *95* (5), 817−822.

(9) Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press, 2000. DOI: 10.1093/oso/9780198506980.001.0001.

(10) AQA. AQA GCSE Chemistry Specifications 2016, Version 1.1 04; October 2019. https://cdn.sanity.io/files/p28bar15/green/9e1579c8cdada254bf7726b794379cf4c1a56036.pdf?_gl=1*hyxoih*_gcl_au*MTM4MDE2NjYwNy4xNzY0MzM2NDcw (accessed 2025-11-29).

(11) Scottish Qualifications Authority. *SQA Higher Course Specification 2019*, Version 3.0, 2019. https://www.sqa.org.uk/files_ccc/HigherCourseSpecChemistry.pdf (accessed 2025-11-29).

(12) AQA. *AQA AS and A-Level Chemistry Specifications 2016*, Version 1.1 1, December 2015. https://cdn.sanity.io/files/p28bar15/green/9bc48d822ce0f2a5b8a6ce62de590a4c06281535.pdf?_gl=1*1kyok3f*_gcl_au*MTM4MDE2NjYwNy4xNzY0MzM2NDcw (accessed 2025-11-29).

(13) Pearson Education Limited. *Pearson Edexcel A Level Chemsiry, Level 3 Advanced GCE in Chemistry*, Issue 3, February 2024. https://qualifications.pearson.com/content/dam/pdf/A%20Level/Chemistry/2015/Specification%20and%20sample%20assessments/a-level-chemistry-2015-specification.pdf (accessed 2025-11-29).

(14) Cambridge OCR. *Cambridge OCR A Level Chemistry B (Salters) Specifications*, Version 4.0, November 2025. https://www.ocr.org.uk/Images/171723-specification-accredited-a-level-gce-chemistry-b-salters-h433.pdf (accessed 2025-11-29).

(15) WJEC CBAC. *WJEC GCE AS/A Level in Chemistry*, Version 3, October 2023. https://www.wjec.co.uk/media/akbbkvwh/wjec-gce-chemistry-spec-from-2015.pdf (accessed 2025-11-29).

(16) American Chemical Society. ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs. *Undergraduate Professional Education in Chemistry*, 2015.https://www.acs.org/content/dam/acsorg/about/governance/committees/training/2015-acs-guidelines-for-bachelors-degree-programs.pdf (accessed 2025-11-29).

(17) Royal Society of Chemistry. *RSC Accreditation of Degree Programmes*. https://www.rsc.org/getContentAsset/6f31fbff-f4a7-4af6-ae6c-194590ae438b/f4c91d86-ac3e-4675-bdf3-f8325ded9710/accreditation-of-degree-programmes.pdf?language=en (accessed 2025-11-29).

(18) Lai, W.; Li, B. A Green Synthesis of Pyrrole Derivative and Green Chemistry Learning for Beginners in Undergraduate Organic Chemistry Curriculum. *J. Chem. Educ.* **2025**, *102* (2), 760−764.

(19) Mooney, M.; Vreugdenhil, A. J.; Shetranjiwalla, S. A Toolkit of Green Chemistry and Life-Cycle Analysis for Comparative Assessment in Undergraduate Organic Chemistry

Experiments: Synthesis of (*E*)-Stilbene. *J. Chem. Educ.* **2020**, *97* (5), 1336−1344.

(20) Palleros, D. R. Solvent-Free Synthesis of Chalcones. *J. Chem. Educ.* **2004**, *81* (9), 1345−1347.

(21) Rosales Martínez, A.; Rodríguez-García, I.; López-Martínez, J. L. Green Reductive Regioselective Opening of Epoxides: A Green Chemistry Laboratory Experiment. *J. Chem. Educ.* **2022**, *99* (7), 2710−2714.

(22) Wu, N.; Kubo, T.; Sekoni, K. N.; Hall, A. O.; Phadke, S.; Zurcher, D. M.; Wallace, R. L.; Kothari, D. B.; McNeil, A. J. Student-Designed Green Chemistry Experiment for a Large-Enrollment, Introductory Organic Laboratory Course. *J. Chem. Educ.* **2019**, *96* (11), 2420−2425.

(23) Abraham, L.; Stachow, L.; Du, H. Cinnamon Oil: An Alternate and Inexpensive Resource for Green Chemistry Experiments in Organic Chemistry Laboratory. *J. Chem. Educ.* **2020**, *97* (10), 3797−3805.

(24) Franco-Pérez, H.-D.; Franco-Pérez, M.; González-González, S.; Rodríguez-Lozada, J.; Zamudio-Medina, A. Synthesis of the Biginelli Reaction Using a Variety of Juices As Catalyst in the Heterocyclic Chemistry Laboratory. *J. Chem. Educ.* **2025**, *102* (1), 331−337.

(25) Bru, F.; Vanden Broeck, S. M. P.; Pisanò, G.; De Buysser, K.; Cazin, C. S. J. Learning Green Chemistry Principles by Comparing Three Synthetic Routes to a Copper-NHC (NHC = N-Heterocyclic Carbene) Complex. *J. Chem. Educ.* **2023**, *100* (6), 2359−2366.

(26) Khuong, K. S. Greener Oxidation of Benzhydrol: Evaluating Three Oxidation Procedures in the Organic Laboratory. *J. Chem. Educ.* **2017**, *94* (4), 534−537.

(27) Fennie, M. W.; Roth, J. M. Comparing Amide-Forming Reactions Using Green Chemistry Metrics in an Undergraduate Organic Laboratory. *J. Chem. Educ.* **2016**, *93* (10), 1788−1793.

(28) Edgar, L. J. G.; Koroluk, K. J.; Golmakani, M.; Dicks, A. P. Green Chemistry Decision-Making in an Upper-Level Undergraduate Organic Laboratory. *J. Chem. Educ.* **2014**, *91* (7), 1040−1043.

(29) American Chemical Society. *Green Chemistry Activities & Experiments*. https://www.acs.org/green-chemistry-sustainability/education/online-educational-resources/green-chemistry-activities-experiments.html (accessed 2026-02-07).

(30) Numanoi, S.; Hashimoto, M.; Hashimoto, S.; Kazawa, K.; Sakaguchi, R.; Miyata, K.; Iwakami, R.; Mitome, T.; Anju, S.; Shinotsuka, R.; Oba, T. Synthesis of Green Fluorescent Protein Chromophore Analogues for Interdisciplinary Learning for High School Students. *J. Chem. Educ.* **2019**, *96* (3), 503−507.

(31) Albright, H.; Stephenson, C. R. J.; Schindler, C. S. Design of a Two-Week Organic Chemistry Course for High School Students: "Catalysis, Solar Energy, and Green Chemical Synthesis.". *J. Chem. Educ.* **2021**, *98* (7), 2449−2456.

(32) Yanu, P.; Porter, L.; Topp, K.; Kradtap Hartwell, S. Green Chemistry Experiment with Intercultural Virtual Exchange at the High School Level. *J. Chem. Educ.* **2025**, *102* (7), 2755−2762.

(33) Grewal, M.; Greenberg, S.; Luska, K. L. Investigating Chemistry's Potential Roles in the Life Cycle of Plastics - An Outreach Laboratory Activity for High School Students. *J. Chem. Educ.* **2026**, *103*, 912−919.

(34) Seery, M. K.; Agustian, H. Y.; Christiansen, F. V.; Gammelgaard, B.; Malm, R. H. 10 Guiding Principles for Learning in the Laboratory. *Chem. Educ. Res. Pract.* **2024**, *25*, 383.

(35) Smallwood, Z. M.; Campbell, C. D.; Worrall, A. F.; Cahill, S. T.; Stewart, M. I. Synthesis and Evaluation of Ammonia Borane: A Modular, Multifaceted Approach Introducing Experimental Design through Guided Inquiry. *J. Chem. Educ.* **2021**, *98* (11), 3514−3523.

(36) Campbell, C. D.; Birkett, T. C.; Stewart, M. I. Applying a Guided Inquiry Approach to a Classic Practical on Chemoselective Reduction. *J. Chem. Educ.* **2024**, *101* (8), 3434−3444.

(37) Wilmore, J. T.; Forsyth, E.; Campbell, C. D.; Rowlands, L. J.; Hancox, C. C.; Stewart, M. I. Introducing Group-Based Experimental Design to UK First-Year Undergraduates: An Investigation of Solvent Polarity. *J. Chem. Educ.* **2026**, *103*, 879−889.

(38) Thomson, P. I. T.; Lamie, P. Introducing Elements of Inquiry and Experimental Design in the First Year of an Undergraduate Laboratory Program. *J. Chem. Educ.* **2022**, *99* (12), 4118−4123.

(39) Moloney, J. G.; Campbell, C. D.; Worrall, A. F.; Stewart, M. I. Hands-on Inquiry-Based Qualitative Identification of Metals in Coins Utilizing Atmospheric Pressure Chemical Ionization Mass Spectrometry. *J. Chem. Educ.* **2022**, *99* (7), 2697−2703.

(40) Department of Education. *New curriculum to give young people the skills for life and work*; U.K. Government, 2025. https://www.gov.uk/government/news/new-curriculum-to-give-young-people-the-skills-for-life-and-work#:~:text=A%20new%20primary%20oracy%20framework,existing%20GCSEs%20and%20A%20levelshttps://www.gov.uk/government/news/new-curriculum-to-give-young-people-the-skills-for-life-and-work#:~:text=A%20new%20primary%20oracy%20framework,existing%20GCSEs%20and%20A%20levels (accessed 2025-12-08).

(41) Shaikh, S. K. J.; Kamble, R. R.; Bayannavar, P. K.; Kariduraganavar, M. Y. Benzils: A Review on Their Synthesis. *Asian J. Org. Chem.* **2022**, *11* (2), No. e202100650.

(42) Weiss, M.; Appel, M. The Catalytic Oxidation of Benzoin to Benzil. *J. Am. Chem. Soc.* **1948**, *70* (11), 3666−3667.

(43) Zhou, Y.-M.; Ye, X.-R.; Xin, X.-Q. Solid State Synthesis of Benzils at Low-Heating Temperatures. *Synth. Commun.* **1999**, *29* (13), 2229−2234.

(44) Depreux, P.; Bethegnies, G.; Marcincal-Lefebvre, A. Synthesis of Benzil from Benzoin with Copper(II) Acetate. *J. Chem. Educ.* **1988**, *65* (6), 553.

(45) Solanke, J. N.; Vasanth, S.; Kumar, M. P.; Vishnuvardhan, M.; Dhayalan, V.; Dandela, R. Green One-Pot Strategy for the Direct Synthesis of Benzil. *Asian J. Org. Chem.* **2025**, *14* (9), No. e00568.

(46) Bishop, M. J.; Sheehan, M. D.; Arnett, L. B.; VanderWoude, J.; Bosscher, M. A. A Safe-at-Home Solventless Air Oxidation of Benzoin by Microwave. *J. Chem. Educ.* **2026**, *103*, 803−808.

(47) Navarro, C.; Arenas, B. E.; Haddow, M. F.; Kirkham, A. J.; Thomson, P. I. T. A Snapshot of UK Prelab Practices and Instructor Perceptions of Their Purpose and Effective Design. *J. Chem. Educ.* **2025**, *102* (9), 3893−3900.

(48) Walker, J. P.; Sampson, V. Learning to Argue and Arguing to Learn: Argument-Driven Inquiry as a Way to Help Undergraduate Chemistry Students Learn How to Construct Arguments and Engage in Argumentation During a Laboratory Course. *J. Res. Sci. Teach.* **2013**, *50* (5), 561−596.

(49) Seery, M. K.; Agustian, H. Y.; Christiansen, F. V.; Gammelgaard, B.; Malm, R. H. Incorporating Dialogue in Laboratory Teaching. *Anal. Bioanal. Chem.* **2024**, *416* (28), 6165−6170.

(50) Kirschner, P. A.; Sweller, J.; Clark, R. E. Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching. *Educ. Psychol.* **2006**, *41* (2), 75−86.

(51) Najmr, S.; Chae, J.; Greenberg, M. L.; Bowman, C.; Harkavy, I.; Maeyer, J. R. A Service-Learning Chemistry Course as a Model To Improve Undergraduate Scientific Communication Skills. *J. Chem. Educ.* **2018**, *95* (4), 528−534.

(52) Stone, S.; Arenas, B. E. Characterising the Nature and Effect of Sensory Overload in an Undergraduate Chemistry Teaching Laboratory. *Chem. Educ. Res. Pract.* **2026**, *27*, 304.

(53) Scottish Qualifications Authority. SQA Advanced Higher Course Specification, Version 3.1, 2021. https://www.sqa.org.uk/

sqa/files_ccc/RNQAHChemistryCourseSpecification.pdf (accessed 2025-12-18).

(54) Anderson, C. A.; Lindsay, J. J. The Development, Perseverance, and Change of Naive Theories. *Soc. Cogn.* **1998**, *16* (1), 8−30.

(55) Pullen, R.; Thickett, S. C.; Bissember, A. C. Investigating the Viability of a Competency-Based, Qualitative Laboratory Assessment Model in First-Year Undergraduate Chemistry. *Chem. Educ. Res. Pract.* **2018**, *19* (2), 629−637.

(56) Shepherd, N.; Jacimovic, N.; Chen, K.; Abrams, B. Improving Student Confidence in General Chemistry Laboratories through Skill Check-Ins (SCIs). *J. Chem. Educ.* **2025**, *102* (9), 3931−3935.

(57) Hensiek, S.; DeKorver, B. K.; Harwood, C. J.; Fish, J.; O'Shea, K.; Towns, M. Improving and Assessing Student Hands-On Laboratory Skills through Digital Badging. *J. Chem. Educ.* **2016**, *93* (11), 1847−1854.

(58) Galloway, K. R.; Malakpa, Z.; Bretz, S. L. Investigating Affective Experiences in the Undergraduate Chemistry Laboratory: Students' Perceptions of Control and Responsibility. *J. Chem. Educ.* **2016**, *93* (2), 227−238.

(59) Duarte, R. C. C.; Ribeiro, M. G. T. C.; Machado, A. A. S. C. Using Green Star Metrics To Optimize the Greenness of Literature Protocols for Syntheses. *J. Chem. Educ.* **2015**, *92* (6), 1024−1034.

(60) Ribeiro, M. G. T. C.; Costa, D. A.; Machado, A. A. S. C. "Green Star": A Holistic Green Chemistry Metric for Evaluation of Teaching Laboratory Experiments. *Green Chem. Lett. Rev.* **2010**, *3* (2), 149−159.

(61) Sheldon, R. A. The E Factor 25 Years on: The Rise of Green Chemistry and Sustainability. *Green Chem.* **2017**, *19* (1), 18−43.