The Design of a Two-Week Organic Chemistry Course for High School Students: "Catalysis, Solar Energy and Green Chemical Synthesis"

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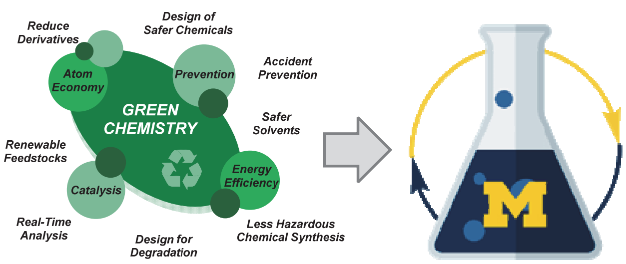
ABSTRACT

A two-week summer camp was designed, implemented, and then updated for high school students focusing on organic chemistry, solar energy, and green chemistry principles. Students learn about laboratory safety, perform organic reactions, go on field trips, and take part in interactive lessons that focus on both fundamental chemistry topics as well as green chemistry. Each lab experiment implements at least one green chemistry principle by reducing waste or reagent use while employing additional safety measures. The course has been edited and modified based on student feedback to include additional lessons, field trips, a student presentation, and other activities. Responses to post-course surveys provided feedback on each component and also indicated that student interest in STEM increased as students gained physical laboratory and research skills.

GRAPHICAL ABSTRACT



KEYWORDS

General Public, High School / Introductory Chemistry, Organic Chemistry, Laboratory Instruction, Curriculum, Hands-On Learning, Catalysis, Green Chemistry, Natural Products, Reactions, Synthesis.

INTRODUCTION

The importance of sustainability and green chemistry became widespread in the early 1990s and particularly in the United States after the passage of the Pollution Prevention Act of 1990.[1] Toward this goal, many institutions and organizations have aligned their sustainability strategies with the United Nations Sustainable Development Goals (UN SDGs), which is a set of goals that aim to improve the life of all people and the planet.[2] Scientists, including chemists, must be trained to adopt green chemistry practices and techniques in order to solve problems while keeping human health and the environment in mind as they perform their research. Ideally, this mindset should be established in the earliest stages of training and education.[3,4] The implementation of these practices in education and curriculum, however, has only recently become more widespread[5] and the number of publications on green chemistry education has steadily risen since 1998.[6] Many educational programs across the country have attempted to fully integrate green chemistry principles into their curriculum, created a separate green chemistry course, chosen a textbook with chapters focused on green chemistry,[7] or used greener experiments in their laboratory courses.[8,9] The ability to include green chemistry concepts allows students to understand fundamental chemistry curriculum through a context of applicability.

One way to increase interest in green chemistry at an earlier stage is to provide opportunities to younger students *via* programs that allow them to experience the curriculum of upper-level collegiate classes that embrace these principles and also, to encourage them to learn about scientific applications in everyday life. A few programs designed for high school students incorporating an early interaction with chemistry include the University of Minnesota's "Polymer Day"[10], the Anson L. Clark Scholars Program at Texas Tech University[11] and Beyond Benign,[12] a foundation focused on green chemistry education offering a variety of resources for educators, including those specifically teaching at the K-12 level. These programs and resources for educators[13] are examples of efforts to bring science to high school students by directly sharing research and scientific resources while creating educational networks. The University of Michigan offers a summer program for high school students called the Michigan Math and Science Scholars (MMSS) program[14] which is designed to introduce students to current developments in science research, specifically at the University of Michigan (UM), and to inspire an interest in mathematics, engineering, and the sciences. MMSS offers a variety of STEM-focused courses designed and led by university faculty[15] and graduate students. We have designed a course titled "Catalysis, Solar Energy and Green Chemical Synthesis" and it was first offered in the summer of 2015. The course was created to provide the unique opportunity for high school students to learn and experience a variety of undergraduate-level laboratory experiments focused on green chemistry and its application in organic reactions. The theme focuses on the explanation and implementation of alternate energy sources and the 12 principles of green chemistry[16a] in a laboratory setting as well as in industry.

COURSE DESIGN

Course Objectives and Theme

The overall goal of the course is to provide an interesting and exciting experience for the students and the specific course objectives are as follows:

1. Students will learn and/or review basic chemistry topics (i.e. nomenclature, drawing structures, acid-base chemistry).
2. Students will perform laboratory experiments and analyze their data.
3. Students will identify green chemistry principles in each experiment and suggest additional ways to make a reaction more environmentally friendly.
4. Students will gain insight into the undergraduate experience in a STEM course.

The course is designed to focus on methods and synthetic techniques surrounding the 12 principles of green chemistry developed and published on by Dr. Paul Anastas and Dr. John Warner[17] and adopted by the American Chemical Society (ACS).[16b] While the title and theme of the course is "Catalysis, Solar Energy and Green Chemical Synthesis", another major aspect of the course is the opportunity for the students to take away an overall experience of undergraduate life and coursework as a STEM major. By providing upper-level experiments that are commonly offered in 200-level laboratory courses for students majoring in STEM fields, the students not only learn new information, but they gain new skills prior to what they would otherwise experience in their early years of college.

Setting and Participants

The "Catalysis, Solar Energy and Green Chemical Synthesis" course has an average enrollment of 15 high school students, per two-week session, and is offered twice over the summer with students meeting in the laboratory for two 3-hour sessions each weekday. Alternate activities are provided by the MMSS program over the weekend and students are housed in the UM dormitories or commute to campus each day. No prerequisite courses or preparation is required prior to attendance. The MMSS program utilizes a rolling admissions system for enrollment and also offers need-based financial aid opportunities.[18]

Individual departments within the college of LSA of the University of Michigan refer to the MMSS program that many of their faculty participate in *via* respective outreach links on the faculty websites. Students range from ages 14-17 and are primarily rising sophomores and juniors (Table 1, below). Additionally, an increasing number of international students have participated over the last 5 years and the ratio of male to female students has remained approximately 1:1. In 2019, over half of the total enrollment in both sessions were students of Asian ethnicity with the remaining students identified primarily as white (Table 1).

Table 1. Student Information

Student Data	2016	→ 2019
Year 9 (Fresh.)	5	10
Year 10 (Soph.)	11	9
Year 11 (Junior)	12	12
Year 12 (Senior)	0	0
International	3	9
US	25	22
Female	13	14
Male	15	17
2019 Student Ethnicity Data		
Caucasian/White	11	
Asian	17	
Hispanic/Latino	1	
Other	2	

Table 1 includes data on the high school students, including: school year, country of origin, ethnicity, and gender.

The course is primarily led by graduate student instructors (GSIs) from the chemistry department at the University of Michigan. Two GSIs lead each day of lab experimentation with at least one new GSI per day to increase contact with graduate students of different backgrounds and specialties. The experiments are performed in an undergraduate teaching laboratory in the chemistry building at the University of Michigan that is equipped with basic micro-scale glassware, fume hoods, IR spectrometers, Mel-Temps, benchtop NMR spectrometers and ovens.

Course Text

A lab manual was written and has since been updated to reflect any additions and changes to the course. It includes a short introduction to the course, detailed instructions and background for each experiment, and follow-up questions for students to answer during and after the conclusion of the experiment. Reference tables and additional information are also included in the manual. The main updates to the lab manual have included: streamlined and outlined experimental procedures to allow for the students to have more straightforward instructions, additional space for notes, data and observations, and step-by-step tutorials for basic lab techniques and calculations, such as TLC and dimensional analysis. The complete and most recent version can be found in the Supporting Information.

SAFETY AND HAZARDS

The experiments described herein present specific hazards that must be managed by the instruction staff. These hazards include the use of flammable, corrosive and toxic reagents and solvents (i.e. hexanes, DMF, NaOH pellets), exposure to high temperature surfaces (100-150 °C hot plate and distillation set up), and the handling of glass and sharp objects. To minimize overall student exposure to the aforementioned hazards, the instructors handle most of the hazardous tasks by setting up hot plates and distillation glassware along with dispensing the most toxic reagents such as NaOH. Students begin the course with an extensive safety training session and safety scavenger hunt that requires them to find the location of various items in the laboratory (i.e. fire extinguisher, eye wash, exits, and other equipment) in order to familiarize themselves with the lab space. The safety training session was designed based on the protocol used by the UM Chemistry Department for undergraduate teaching labs.[19] Additionally, each experiment begins with a discussion of the specific hazards related to its set up, reagents, and work up and aims to recognize hazards, assess and minimize the risks of those hazards, and prepare the students for possible emergencies or accidents. All experiments are performed in a fume hood and proper PPE (lab coats, goggles, gloves, long pants, and closed-toed shoes) is worn at all times, aligning with the lab safety requirements outlined by the UM Chemistry department. More detailed safety information for each experiment is outlined in the lab manual in the Supporting Information.

EXPERIMENTS

The experiments for the course were developed by graduate students and based on the following: ongoing research in the department, previous experiments from 200-level organic chemistry labs in the department, and green chemistry-focused literature reports describing undergraduate-level experiments. The initial course schedule displayed in Figure 1 has been optimized to the most recent version based on the timing or length of experiments, level of difficulty and complexity, and the addition of field trips. While safety training has remained as the initial section of the course, the order of experiments was altered to reflect an increase in difficulty both in knowledge and technique. For example, the Wittig reaction utilizes only solid reagents and no solvent, as the students grind the starting materials together in a mortar and pestle.[24] The aldol reaction[27] is better suited for a later experiment as it employs micro-scale amounts of reagents, requires a liquid-liquid extraction work up, and multiple analytical techniques that must be taught beforehand. By placing the more advanced experiments later in the course, the students performed better by utilizing their new lab experiences and recent technique development. Additionally, experiments like the Transfer Hydrogenation reaction[20] and Suzuki reaction[21] were eliminated based on low student ratings in closing surveys. As one of the other main topics of the course is solar energy, the last activity that the students do in the lab is to create their own solar cell and to learn about alternative energy sources. The solar cells are assembled from a kit[22] that uses relatively benign materials so the students can take the cells home with them. The solar cell kit is distributed by the Institute for Chemical Education (ICE) through the University of Wisconsin-Madison and allows students to build a solar cell that generates electricity from the absorption of solar energy by natural dye from berries.

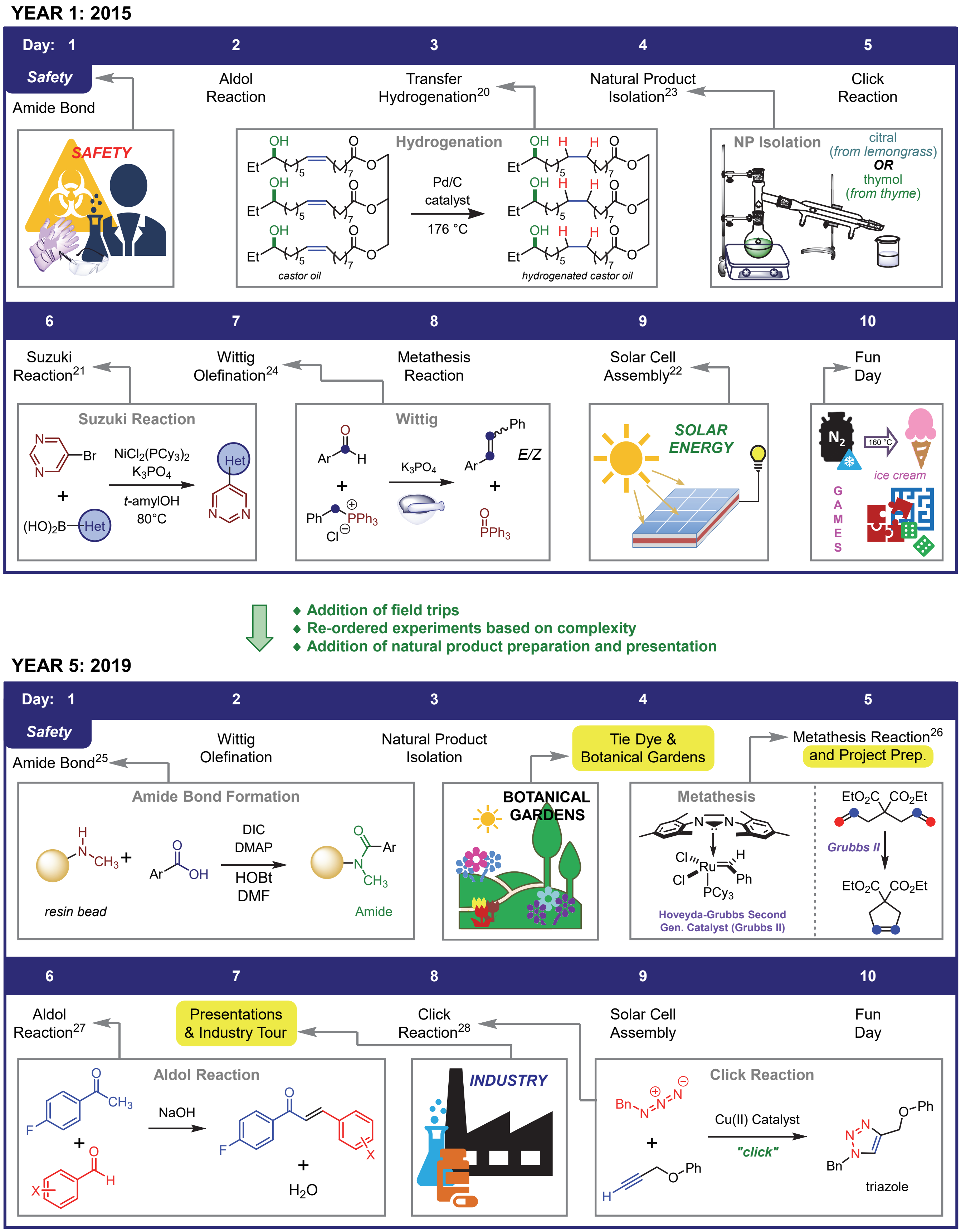

YEAR 1: 2015
Day: 1
2
3
4
5
Safety
Amide Bond
Aldol Reaction
Transfer Hydrogenation[20]
Natural Product Isolation[23]
Click Reaction
SAFETY
Hydrogenation
castor oil
Pd/C catalyst
176 °C
hydrogenated castor oil
NP Isolation
citral (from lemongrass)
OR
thymol (from thyme)
6
7
8
9
10
Suzuki Reaction[21]
Wittig Olefination[24]
Metathesis Reaction
Solar Cell Assembly[22]
Fun Day
Suzuki Reaction
NiCl2(PCy3)2
K3PO4
t-amylOH
80°C
Wittig
K3PO4
E/Z
SOLAR ENERGY
ice cream
GAMES
Addition of field trips
Re-ordered experiments based on complexity
Addition of natural product preparation and presentation
YEAR 5: 2019
Day: 1
2
3
4
5
Safety
Amide Bond[25]
Wittig Olefination
Natural Product Isolation
Tie Dye & Botanical Gardens
Metathesis Reaction[26] and Project Prep.
Amide Bond Formation
resin bead
DIC
DMAP
HOBt
DMF
Amide
BOTANICAL GARDENS
Metathesis
Hoveyda-Grubbs Second Gen. Catalyst (Grubbs II)
Grubbs II
6
7
8
9
10
Aldol Reaction[27]
Presentations & Industry Tour
Click Reaction[28]
Solar Cell Assembly
Fun Day
Aldol Reaction
NaOH
INDUSTRY
Click Reaction
Cu(II) Catalyst
"click"
triazole

Figure 1. Initial course calendar from 2015 session and updated course calendar from 2019 session. Activities highlighted in yellow were added following the 2015 session.

As the theme of the course is focused on green chemistry, the course was designed to incorporate some greener practices in the experiments. Figure 2, below, describes how many of the principles are implemented or discussed throughout the course. The use of solvents is minimized or eliminated, as in the case for the Wittig reaction,[24] to prevent waste. The discussion of atom economy is mentioned early in the course but best displayed in the aldol reaction where all carbon atoms from the starting materials are maintained in the aldol product. Additionally, the input of energy to perform the reactions is also minimized. Therefore, few reactions are heated, and the Wittig reaction is not stirred by a mechanical stir plate but ground by hand in a mortar and pestle. Significant catalytic reactions are also utilized, specifically the Click reaction[28] which employs a copper(II) catalyst and the metathesis reaction[26] which uses the Grubbs(II) catalyst.

Green Chemistry Principle	*Experiment*	*Implemented in Course*
Prevention	Wittig Reaction	Solvent-free
Atom Economy	Aldol Reaction	All carbons retained in product
Less Hazardous Chemical Synthesis	Click Reaction	Removable, inoffensive byproducts
Safer Solvents and Auxiliaries	Aldol Reaction	Ethanol and water as co-solvents
Design for Energy Efficiency	Wittig Reaction and Solar Cell Assembly	"Human" energy (mortar and pestle) and atlernate energy source
Use of Renewable Feedstock	Natural Product Isolation	Use of food (herbs, energy drinks) for caffeine isolation
Catalysis	Click and Metathesis Reactions	$CuSO_4$•$5H_2O$ and Grubbs catalysts
Real-Time Analysis	Amide Bond Formation Reaction	Use of color to monitor progress

Figure 2. Incorporation of green chemistry principles in each laboratory experiment.

ADDITONAL ACTIVITIES

As per GSI input and student request, additional activities were added to the course schedule. These additional activities included lessons on fundamental chemistry topics such as: nomenclature, drawing structures, acid-base reactions, periodic trends, and analytical techniques (see Figure 3) during the waiting periods or "down time" of an experiment. By adding in these lessons, students were able to get more out of the experiments with an increased understanding of structure and reactivity in what would otherwise be abstract reactions. While some lessons (i.e. nomenclature or acid-base reactions) represented review material for the older students that had already taken chemistry courses at their high school, they allowed for a more "even playing field" for the younger students. The students were able to expand their scientific vocabulary allowing for more critical thinking about the transformation itself when it came to analyzing reaction outcomes and experimental directions. Each lesson was accompanied by an activity that ranged from a worksheet to a group discussion or a game that incorporated what they had just learned (Figure 3). This allowed for the students to practice a few examples of each topic and interact with more of their peers during the lab session. Most students provided comments about these lessons in the closing surveys, showing their appreciation in helping them prepare for any upcoming chemistry courses in high school and college. These additional activities are outlined in the Supporting Information.

A chemistry laboratory course is often stressful for students at the collegiate level so it would be unsurprising that high school students partaking in a similar course with new classmates in a university chemistry laboratory might also feel intimidated. In order to alleviate some of this stress for the high school students, themed games were added as a more relaxing and fun way to learn chemistry terms and facts. Some of these games included chemistry-themed word searches, element spelling races, chemistry jeopardy, and the making of liquid nitrogen ice cream[29] on Day 10 (Fun Day).

Lesson Topics and Activities	
Topic	
• Nomenclature	• Green Chemistry principles
• Drawing structures	• Dimensional analysis
• Functional groups	• TLC
• Acid-base reactions	• IR
• Periodic trends	• NMR
Activity	
♦ worksheets	♦ Q&A Game
♦ word search	♦ video (TED Talk)
♦ group work/discussion	♦ spelling with elements

Figure 3. Topics and related activities for added lessons.

The incorporation of chemical demonstrations was also well-received by the high school students. Apart from the demonstration by the GSI of the reaction set up or a technique necessary for a particular experiment, real-world application demonstrations were a good way to spark interest in some of the otherwise not viewed or seen chemical phenomena in everyday life. For example, we performed the flame test using a variety of salts and discussed how they relate to fireworks due to the different colors that are created when the salts are burned.[30] Additionally, things like the gummy bear combustion[31] experiment and silver mirror in a bottle experiment[32] were popular. A chemical demonstration on the history and use of dyes was implemented *via* the t-shirt tie-dye[33] activity that the students were also able to participate in (Figure 4). This also allowed students to create their own design on a MMSS t-shirt to take home with them.

We have recently incorporated the use of benchtop NMR analysis into the lab experiments. Previously, the high school students had only been able to utilize TLC, IR spectroscopy, and melting point determination to analyze their products from the experiments. Short lectures and demonstrations are given on how to perform all of these types of analyses as well as an explanations and worksheets describing how to interpret the data. The use of the 60 MHz benchtop NMR in the teaching lab allowed students to perform high level analysis that even most undergraduates do not have the opportunity to do outside of a research setting. While this is a complex topic to learn without a strong background in chemical structure, it was a fitting example of what chemists use on a daily basis as they perform cutting edge organic research.

Additionally, a long-term project was incorporated into the curriculum. Students were asked to put together a 10-minute PowerPoint presentation on an impactful natural product. They were assigned a molecule, such as caffeine, vitamin B12, tetrodotoxin, etc. and given directions on how to put together a presentation including suggestions on where to look for information on the use, discovery, and synthesis of the molecule. This project was assigned in the first few days of the two-week course and then presented in the last 2-3 days, allowing time for the students to put the presentation together and practice their delivery. Dedicated time during the lab sessions was included for students to work on their presentations with GSIs present to allow for students to ask questions and to minimize outside lab expectations.

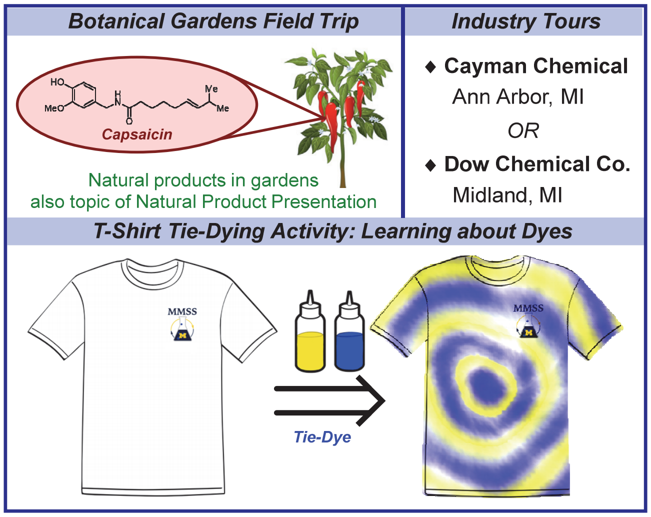


Figure 4. Outline of added activities and field trips.

The addition of field trips to industrial companies in the greater Ann Arbor area to Dow Chemical Company or Cayman Chemical, was added in 2016 to allow for the students to gain information on possible career paths in chemistry. The companies provide tours of their facilities, presentations on what they research or manufacture, and offered some parting information on their outreach services for high school and college students. The students also visit the Matthaei Botanical Gardens and Nichols Arboretum[34] in Ann Arbor, each year. This trip connects well with the natural product presentations as most of the molecules that the students research and present on are isolated from plants that the gardens cultivate and maintain on the grounds. The students are sent on a scavenger hunt to find as many of these natural product-containing plants as possible and it also encourages them to explore the medicinal plant garden to learn about even more biologically active molecule-containing plants (Figure 4).

STUDENT PERCEPTIONS

The students were given closing surveys inquiring about their thoughts on each experiment, the overall program, the use of the field trips, and their interest in pursuing STEM majors in the coming years. The survey data relating to the rating of activities for the 2016 and 2019 sessions is displayed in Figure 5, below. The most popular laboratory experiments were the natural product isolation and solar cell assembly. This is due to the real-life applications and relationships that these experiments contain. The two experiments with the lowest ratings in 2016, Transfer Hydrogenation and Suzuki Reaction, were removed prior to 2019. Students found these experiments to be less interactive (as they involved less set up and manipulation) and the reaction concepts were less accessible due to their complex catalytic processes.

The students enjoyed the field trips to the botanical gardens and local industries (rated highly in both sessions, see Figure 5) as not only an opportunity to take a break from the lab but to gain more real-world application and information about future career opportunities. The ability to have both educational and casual interactions with the GSIs over the two-week period was also highly commented on as a positive aspect that allowed the high school students to gain insight into the paths of STEM majors in college, graduate programs and what options can come from the various degrees. For the most recent session in 2019, one GSI was kept constant with one rotating GSI allowing for students to continue to meet multiple graduate students with a variety of backgrounds, ethnicities, and pathways to chemistry, but also allowed for the expectations of daily lab and course etiquette to be more consistent. Many students also commented on their appreciation for the course to offer a less stressful introduction to undergraduate chemistry lab work as this was not a graded course that most students experience for the first time in their early years of college. Across the board, students indicated that their interest in science was increased following the experience with most indicating that they plan to pursue a career in STEM.

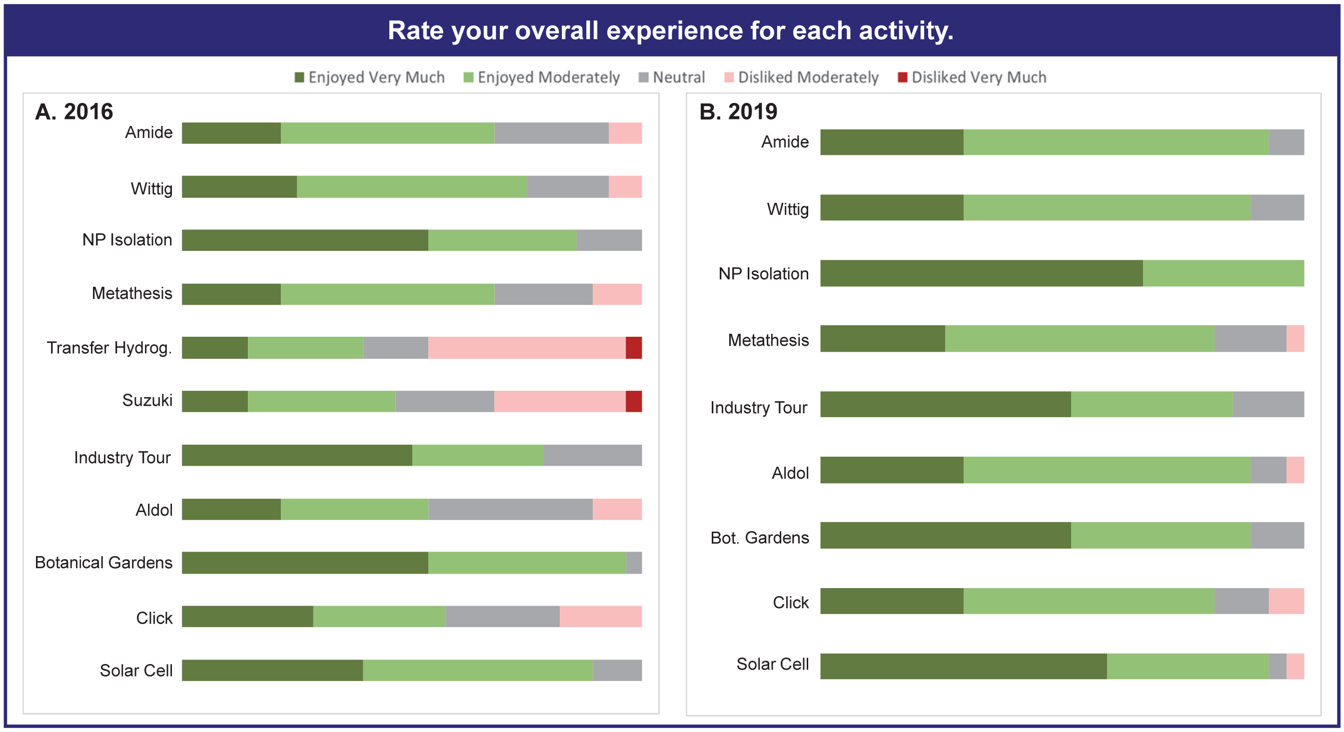


Figure 5. Student feedback on laboratory experiments and course activities. A. Responses from 2016 session that included additional experiments and the initial implementation of field trips. B. Responses from 2019 session following the removal of low-rated experiments and addition of the natural product presentation (which was not rated by the students in closing surveys).

To investigate the students' understanding of chemistry and gain insight into their general opinions on science, we prompted the students to answer the following question in their closing surveys. "How has this experienced changed your opinions on chemistry and science, in general?" Many of the responses from the high school students expressed their increase in overall interest in chemistry after completing the course. A few students commented on their new appreciation for the work that chemists do on a daily basis and that they were surprised to learn "that chemistry is a huge part of everyone's life and that chemistry enhances these lives." Some students also stated that their understanding of the scientific method was realized as this course "has shown me that creating new reactions is a bit about trial and error" or that they are able to relate the ability to help others and the planet through green chemistry practices. Complete student responses are included in the Supporting Information.

SUMMARY

In summary, we have designed and optimized a two-week course for high school students to gain experience in undergraduate-level organic chemistry course work with a focus on the principles of green chemistry and solar energy. The course has been updated to increase reflection on the green chemistry principles and by adding fundamental chemistry lessons to encourage more background understanding of experiments. Students were able to perform undergraduate-level chemistry experiments and analyze the data that they collected by employing their newly learned laboratory skills and techniques. Additionally, this course was able to offer the opportunity for students to gain insight into the undergraduate experience at the University of Michigan and most students indicated their interest in applying to UM in the future. Future changes to the course may include an added emphasis on student-centered analysis of green chemistry and how it is implemented in the course or an added section in the lab manual for an assigned lab write-up that would more closely simulate a written lab report assigned in an undergraduate lab course. In conclusion, we have achieved our overall goal to communicate science at an earlier stage and increased student interest in STEM with most students indicating that they plan to pursue a career in a STEM field.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX. [ACS will fill this in.] Example brief descriptions with file formats indicated are shown below; customize for your material.

2019 Lab Manual (PDF)

Survey Responses and Additional Activities (PDF)

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REFERENCES

1. Pollution Prevention Act of 1990. https://www.epa.gov/p2/pollution-prevention-act-1990 (accessed 2021-04).
2. Sustainable Development Goals. https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals (accessed 2021-04).
3. Lee, N. E.; Gurney, R.; Soltzberg, L. Using Green Chemistry Principles As a Framework To Incorporate Research into the Organic Laboratory Curriculum. *J. Chem. Educ.* **2014**, *91*, 1001−1008.
4. Timmer, B. J. J.; Schaufelberger, F.; Hammarberg, D.; Franzen,´ J.; Ramström, O.; Diner, P. Simple and Effective Integration of Green´ Chemistry and Sustainability Education into an Existing Organic Chemistry Course. *J. Chem. Educ.* **2018**, *95*, 1301−1306.
5. Haack, J. A.; Hutchison, J. E. Green chemistry education: 25 years of progress and 25 years ahead. *ACS Sustainable Chem. Eng.* **2016**, *4*, 5889−5896.
6. Aubrecht, K. B.; Bourgeois, M.; Brush, E. J.: MacKellar, J.; Wissinger, J. E. Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety and Sustainability. *J. Chem. Educ.* **2019**, *96*, 2872-2880.
7. Leontyev, A. Content analysis of green chemistry concepts in organic chemistry textbooks and laboratory manuals. National Meeting of the American Chemical Society, Orlando, FL, March 31−April 4, 2019; CHED 138.
8. (a) University of Toledo, http://www.utoledo.edu/nsm/sgce/ (accessed 2021-04). (b) Doxsee, K.; Hutchison, J. E. *Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments*; Brooks/Cole, Cengage Learning: Belmont, CA, USA, 2004. (c) Environmental and Green Chemistry, University of Minnesota, https://chem.umn.edu/research/environmental-green-chemistry (accessed 2021-04).
9. For examples of green chemistry undergraduate laboratory experiments, see the following articles: (a) Lang, P, T.; Harned, A. M.; Wissinger, J. E. Oxidation of Borneol to Camphor Using Oxone and Catalytic Sodium Chloride: A Green Experiment for the Undergraduate Organic Chemistry Laboratory. *J. Chem. Educ.* **2011**, *88*, 652-656. (b) Fahnhorst, G. W.; Swingen, Z. J.;

Schneiderman, D. K.; Blaquiere, C. S.; Wentzel, M. T.; Wissinger, J. E.; Fahey, J. T.; Maelia, L. E. Synthesis and Study of Sustainable Polymers in the Organic Chemistry Laboratory: An Inquiry-based Experiment Exploring the Effects of Size and Composition on the Properties of Renewable Block Polymers. *ACS Symp. Ser.* **2016**, *1233*, 123−147. (c) Dintzner, M. R.; Maresh, J. J.; Kinzie, C. R.; Arena, A. F.; Speltz, T. A Research-Based Undergraduate Organic Laboratory Project: Investigation of a One-Pot, Multicomponent, Environmentally Friendly Prins-Friedel-Crafts-Type Reaction. *J. Chem. Educ.* **2012**, *89 (2),* 265−267. (d) Bannin, T. J.; Datta, P. P.; Kiesewetter, E. T.; Kiesewetter, M. K. Synthesizing Stilbene by Olefin Metathesis Reaction Using Guided Inquiry to Compare and Contrast Wittig and Metathesis Methodologies. *J. Chem. Educ.* **2019**, *96*, 143−147. (e) Ong, J.-Y.; Chan, S.-C.; Hoang, T.-G. Empowering Students to Design and Evaluate Synthesis Procedures: A Sonogashira Coupling Project for Advanced Teaching Lab. *J. Chem. Educ.* **2018**, *95*, 1078−1081. (f) Torres King, J. H.; Wang, H.; Yezierski, E. J. Asymmetric Aldol Additions: A Guided-Inquiry Laboratory Activity on Catalysis. *J. Chem. Educ.* **2018**, *95*, 158−163.

10. Ting, J.M.; Ricarte, R.G.; Schneiderman, D.K.; Saba, S.A.; Jiang, Y.; Hillmyer, M.A.: Bates, F.S.; Reineke, T.M.; Macosko, C.W.; Lodge, T.P. Polymer Day: Outreach Experiments for High School Students. *J. Chem. Educ.* **2017***, 94*, 1629-1638.
11. Welcome to The Anson L. Clark Scholars Program. https://www.depts.ttu.edu/honors/academicsandenrichment/affiliatedandhighschool/clarks/ (accessed 2021-04).
12. Beyond Benign: Green Chemistry Education. Higher Ed. https://www.beyondbenign.org/cur-high-school/ (accessed 2021-04).
13. (a) Dicks, A. P. Green Organic Chemistry in Lecture and Laboratory; CRC Press: Boca Raton, 2016. (b) ACS Green Chemistry Resources. https://www.acs.org/content/acs/en/greenchemistry/students-educators.html (accessed 2021-04)
14. Michigan Math and Science Scholars. https://sites.lsa.umich.edu/mmss/ (accessed 2021-04).
15. Fagnani, D. E.; Hall, A. O.; Zurcher, D. M.; Sekoni, K. O.; Barbu, B. N.; McNeil, A. J. Short Course on Sustainable Polymers for High School Students. *J. Chem. Educ.* **2020**, *97*, 2160-2168.

16. (a) American Chemical Society. About the ACS Green Chemistry Institute. http://www.acs.org/content/acs/en/greenchemistry/about.html (accessed 2021-04). (b) American Chemical Society. 12 Principles of Green Chemistry. https://www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html (accessed 2021-04).

17. Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press: New York, 1998.

18. Michigan Math and Science Scholars. Financial Aid and Scholarship Opportunities. https://sites.lsa.umich.edu/mmss/apply-to-the-mmss-program/financial-aid-and-scholarship-opportunities/ (accessed 2021-04).

19. LSA Chemistry. Lab Course Safety. https://lsa.umich.edu/chem/Safety/lab-course-safety.html (accessed 2021-04).

20. Alwaseem, H.; Donahue, C.J.; Marincean, S. Catalytic Transfer Hydrogenation of Caster Oil. *J. Chem. Educ.* **2014**, *91*, 575-578.

21. Hie, L.; Chang, J.J.; Garg, N.K. Nickel-Catalyzed Suzuki–Miyaura Cross-Coupling in a Green Alcohol Solvent for an Undergraduate Organic Chemistry Laboratory. *J. Chem. Educ.* **2015**, *92*, 571-574.

22. (a) Smestad, G.P.; Gratzel, M. Demonstrating Electron Transfer and Nanotechnology: A Natural Dye-Sensitized Nanocrystalline Energy Converter. *J. Chem. Educ.* **1998**, *75*, 752-756. (b) University of Wisconsin-Madison. Nanocrystalline Solar Cell Kit. https://icestore.chem.wisc.edu/product/nanocrystalline-solar-cell-kit (accessed 2021-04).

23. Torress y Torres, J.L.; Hiley, S.L.; Lorimor, S.P.; Rhoad, J.S.; Caldwell, B.D.; Zweerink, G.L.; Ducey, M. Separation of Caffeine from Beverages and Analysis Using Thin-Layer Chromatography and Gas Chromatography–Mass Spectrometry. *J. Chem. Educ.* **2015**, *92*, 900-902.

24. Leung, S.H.; Angel, S.A. Solvent-Free Wittig Reaction: A Green Organic Chemistry Laboratory Experiment. *J. Chem. Educ.* **2004**, *81*, 1492-1493.

25. Hailstone, E.; Huther, N.; Parsons, A.F. A Polymer-Supported Organic Reaction: Seeing Is Believing. *J. Chem. Educ.* **2003**, *80*, 1444-1445.

26. Schepmann, H.G.; Mynderse, M. Ring-Closing Metathesis: An Advanced Guided-Inquiry Experiment for the Organic Laboratory. *J. Chem. Educ.* **2010**, *87*, 721-723.

27. Hammond, C.N.; Schatz, P.F.; Mohrig, J.R.; Davidson, T.A. Synthesis and Hydrogenation of Disubstituted Chalcones. A Guided-Inquiry Organic Chemistry Project. *J. Chem. Educ.* **2009**, *86*, 234-239.

28. Hansen, T.V.; Wu, P.; Sharpless, W.D.; Lindberg, J.G. Just Click It: Undergraduate Procedures for the Copper(I)-Catalyzed Formation of 1,2,3-Triazoles from Azides and Terminal Acetylenes. *J. Chem. Educ.* **2005**, *82*, 1833-1836.

29. Jansen, K. Making liquid-nitrogen ice cream safely. *C&EN Global Enterprise* **2018**, *96*, 4.

30. Johnson, K.A.; Schreiner, R. A dramatic flame test demonstration. *J. Chem. Educ.* **2001**, *78*, 640-641.

31. Sullivan, D.M. The howling gummy bear. *J. Chem. Educ.* **1992**, *69*, 326.

32. Kemp, M. Silver Mirror. *J. Chem. Educ.* **1981**, *58*, 655.

33. Alpha Chi Sigma. Tie Dye Outreach Program. https://www.alphachisigma.org/about-us/outreach/bonding-with-color (accessed 2021-04).

34. Matthaei Botanical Gardens and Nichols Arboretum https://mbgna.umich.edu/ (accessed 2021-04).