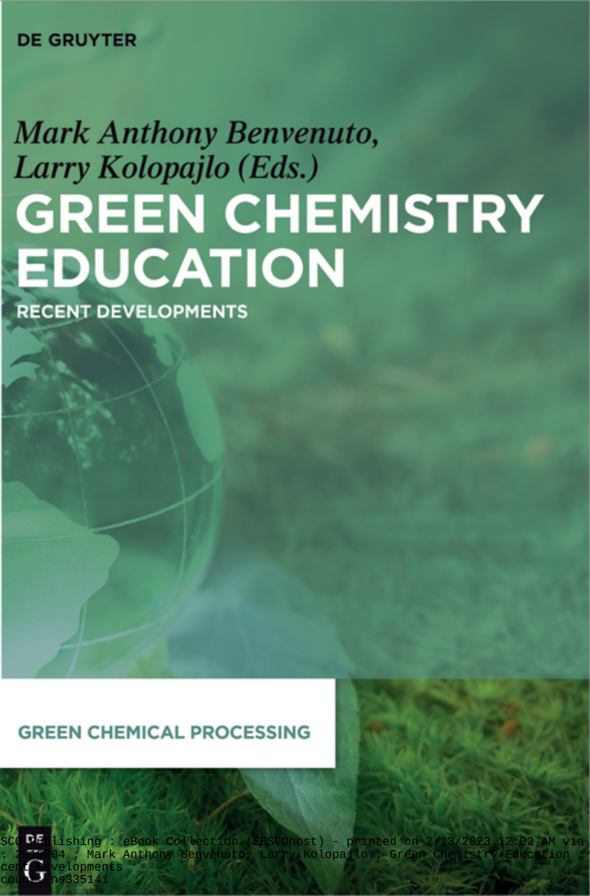


DE GRUYTER

Mark Anthony Benvenuto,
Larry Kolopajlo (Eds.)

GREEN CHEMISTRY EDUCATION

RECENT DEVELOPMENTS

GREEN CHEMICAL PROCESSING

Mark Anthony Benvenuto and Larry Kolopajlo (Eds.)

Green Chemistry Education

Green Chemical Processing

Green Chemical Processing

Edited by
Mark Anthony Benvenuto

Volume 4

Green Chemistry Education

Recent Developments

Edited by
Mark Anthony Benvenuto and Larry Kolopajlo

DE GRUYTER

Editors
Prof. Dr. Mark Anthony Benvenuto
University of Detroit Mercy
Department of Chemistry & Biochemistry
4001 W. McNichols Rd.
Detroit, MI 48221-3038
USA
benvenma@udmercy.edu

Dr. Larry Kolopajlo
Eastern Michigan University
Department of Chemistry
541C Mark Jefferson Science Complex
Ypsilanti, MI 48197
USA
lkolopajl@emich.edu

ISBN 978-3-11-056578-2
e-ISBN (PDF) 978-3-11-056649-9
e-ISBN (EPUB) 978-3-11-056588-1

Library of Congress Control Number: 2018960081

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.dnb.de.

Cover image: scyther5/iStock/Getty Images Plus
Typesetting: Integra Software Services Pvt. Ltd.
Printing and binding: CPI books GmbH, Leck

www.degruyter.com

About the series

Green Chemical Processing is a continuing series of volumes composed of refereed chapters, with upcoming volumes having submission dates of 15 June and 15 December each year. All areas of green chemistry, pending as well as established, are considered and welcome.

If you are interested in contributing a chapter, please contact series editor Mark Benvenuto, of the University of Detroit Mercy, at: benvenma@udmercy.edu concerning the appropriateness of your topic. We are interested in any and all new ideas that examine any of the twelve principles of green chemistry.

For more information on all previous and upcoming volumes of *Green Chemical Processing*, see www.degruyter.com/view/serial/462886.

https://doi.org/10.1515/9783110566499-201

Larry Kolopajlo and Mark Benvenuto

Preface: the continuum of green chemical education

Abstract: The theme of this introductory chapter is that green chemistry education is evolving as a continuum with many interconnecting subdisciplines. In this chapter are previewed ten articles of deep scholarly inquiry that should pique one's green interest and imagination.

Keywords: green chemistry, education, diversity, outreach, chemical feedstocks

1 Introduction

Welcome to *Green Chemistry Education*, the fourth volume of Green Chemical Processing. This volume is intended for science professionals, both academic and industrial, who want to keep abreast of how green chemistry is evolving across the educational spectrum. From work done at universities to high schools, readers will be introduced to authoritative narratives that treat specific topics in depth, rather than review recent developments.

In retracing previous published work in this series, Volume 1, titled *Sustainable Green Chemistry*, explored the philosophy of green chemistry, some practical applications in solvent synthesis and disposal, educational pedagogy, and how green chemistry has influenced the teaching of organic chemistry. Last of all, courses for both non-science and science majors were elaborated. In Volume 2, *Green Chemical Processes: Developments in Research and Education*, a notable contribution by George Bodner, set the stage by explaining the value of incorporating green chemistry in the undergraduate major. By recognizing contributions from Middle Eastern academicians, Kolopajlo asserted the importance of a diverse international effort in attaining a green and sustainable environment on a global scale. *Green Chemistry in Industry*, Volume 3, shifted the focus to industrial research and development, the heart and soul of green chemistry.

2 This volume

Volume 4, *Green Chemistry Education: Recent Developments*, promotes an inclusive approach, treating the educational spectrum as a continuum by including papers authored by prestigious scientists, academicians at smaller colleges, and creative scholars who do the invaluable work of secondary science instruction. Volume 4 is divided into four parts.

https://doi.org/10.1515/9783110566499-202

3 Part I: Pure and applied green chemistry at large institutions

3.1 Green chemistry and the grand challenges of sustainability

We are privileged to have the *Chair of the ACS Committee on Environmental Improvement*, Anthony M. Noce, present an inspiring opening chapter to volume 4. Noce's scientific acumen is apparent throughout this first chapter through which he knowledgeably discusses the foremost challenges to a sustainable future, which succeeding authors in this volume will elaborate on.

3.2 Turning the tables on metal ion pollution by using an invasive species

Jillian Goldfarb, Assistant Professor of Energy Engineering in the John and Willie Leone Family Department of Energy and Mineral Engineering at Penn State University, has graciously put forward a paper with her colleagues Michael Berger, and Madeline Karod of Simmons College. Their paper will merit much attention in the green chemistry community for its ecological significance in using an invasive plant species, phragmites, to filter out harmful manganese (II) ion in the Muddy River of Massachusetts.

3.3 Green biological chemistry for chemical feedstocks

We are indebted to Professor Trant and his colleagues, S. Iraj Sadraei and Brent St Onge, of the University of Windsor for contributing an intriguing paper on how widely available carbohydrates, in the form of chitin, chitosan and cellulose, may be utilized as renewable and sustainable chemical feedstocks that can help replace the production of chemicals from fossil fuels. Work in this field is of the utmost importance in combating climate change.

3.4 Understanding how synthetic organics become ecological problems

It is a distinct pleasure to have three distinguished scientists: Theodore Mill of the Stanford Research Institute and both Jay M. Patel and Caroline Tebes-Stevens of the US EPA write a veritable treatise on the serious problem of environmental toxins produced through the degradation of organic compounds. Their paper reviews the physical and chemical processes through which synthetic substances are transported and transformed in the environment, thereby illuminating the field and providing a wealth of valuable examples to be used in both teaching and research. As this chapter wraps up contributions made by authors at prestigious institutions, the focus shifts to work done at smaller facilities.

4 Part II: Green chemistry at the undergraduate level

In this section are four papers on green chemistry at non-research I institutions.

4.1 A summer of fun in green chemistry

To a college professor, there is no more important a task than the teaching and training of the next generation of scientists. Mark Benvenuto of the University Detroit Mercy has built a very successful career in transforming the lives of his students, and colleagues, and that is why his chapter has been chosen to open this section. Professor Benvenuto's offering also bridges the gap between research done at large and smaller institutions. In his contribution, Benvenuto details how in a collaborative research program, he led a team of high-school students and a teacher to synthesize multidentate ligands that can be used in the water remediation of eight transition metals, including copper, zinc, and iron. This work is also important because it serves as a way to attract talented high-school students to the field of green chemistry.

4.2 SOTL in green chemistry

Professors Kovacs, Krikke, and Mack of Grand Valley State University have contributed greatly to the scholarship of teaching and learning of green chemistry by writing an authentic metacognitive reflection on the design, implementation, and evaluation of a series of undergraduate green chemistry courses. Their groundbreaking work can be used as a model for others who plan to introduce green chemistry courses for both majors and non-majors into their curriculum.

4.3 Streamlining laboratory work through cheminformatics

Professor Wathen of Sienna Heights University has contributed an impressive account addressing the underappreciated intersection of green chemistry and cheminformatics, a discipline that offers a unique way of understanding and evaluating new and greener chemicals for their toxicity. Cheminfomatics also allows scientists to assess the risk/reward status of proposed green chemicals by evaluating physical properties such as solubility without undertaking expensive laboratory work. With the ever-increasing, ubiquitous, and accessible online databases, one grand challenge is to educate chemical professionals in the efficient use of such resources as part of their research programs.

4.4 Rethinking outreach

Dr Kolopajlo at Eastern Michigan has been using green chemistry to reach out to a diverse and underrepresented audience of students and teachers through a myriad of methods designed to address social, cognitive, and affective modes of thought. This last section on green chemistry at the undergraduate college level uses outreach to make a transition to the next section addressing green chemistry at the high-school level.

5 Part III: Green chemistry in secondary schools

We are thrilled to have two invited contributions from teachers who have distinguished themselves in the science classroom.

5.1 A bioenergy-based green chemistry curriculum for high schools

Craig Kohn has delivered an impressive paper that provides an in-depth view on a revolutionary biotechnology laboratory course on biofuels taught in a Wisconsin high-school agriscience department. Through collaborations with universities, federal research facilities, and the surrounding community, students were able to engage in rigorous learning experiences in a sociocultural setting in a manner that maximized their preparation for college and sustainable careers.

5.2 Green chemistry through the lens of a high-school teacher

Robert Ause of the prestigious Greenhills High School in Ann Arbor, Michigan, has contributed a chapter explaining how green chemistry has been infused into his school’s science curriculum with the goal of educating students on how to lead a sustainable lifestyle. It is very obvious that Ause has succeeded in reaching his students by incorporating and applying the 12 green chemistry postulates to many broader and more relevant problems like climate change.

Acknowledgements: The contributors and reviewers are thanked for their work. Finally, the editors wish to gratefully acknowledge the work of Lena Stoll of DeGruyter who has patiently and tirelessly supported work in all four volumes of Green Chemical Processing.

Contents

Steven P. Wathen

Larry Kolopajlo

List of Contributing authors

Robert Ause
Greenhills School
850 Greenhills Drive
Ann Arbor MI 48105
USA
rause@greenhillsschool.org

Michael Berger
Simmons College
Chemistry Department
300 The Fenway
Boston MA 02115
USA

Jillian L. Goldfarb
The Penn State Institutes of Energy and the Environment
The Pennsylvania State University
University Park
PA 16802
USA
jzg321@psu.edu

Polly R. Fitzgerald

Madeline Karod
Simmons College
Chemistry Department
300 The Fenway
Boston MA 02115
USA

Craig Kohn
Michigan State University
133 Erickson Hall
East Lansing MI 48824
USA
kohncrai@msu.edu

Steven Kosmas
Grosse Pointe North High School
707 Vernier Road
Grosse Pointe Woods MI 48236
USA
Steven.Kosmas@gpschools.org

Dalila Kovacs
Grand Valley State University
Chemistry Department
1 Campus Drive
312 Padnos Hall
Allendale MI 49401
USA
kovacsd@gvsu.edu

James Krikke
Grand Valley State University
Chemistry Department
1 Campus Drive
312 Padnos Hall
Allendale MI 49401
USA
krikkeji@gvsu.edu

Kristina Mack
Grand Valley State University
Chemistry Department
1 Campus Drive
312 Padnos Hall
Allendale MI 49401
USA
mackkr@gvsu.edu

Theodore Mill
Retired from
Stanford Research Institute
Menlo Park
CA 94025
USA
tm11842@gmail.com

Anthony Noce
Tetra Tech
8 Southwoods Boulevard
Albany NY 12211
USA
tony.noce@tetratech.com

Brent S. Onge
University of Windsor
Department of Chemistry & Biochemistry
401 Sunset Ave.

https://doi.org/10.1515/9783110566499-203

Windsor ON N9B 3P4
Canada

Jay M. Patel
U.S. Environmental Protection Agency
National Exposure Research Laboratory
Athens GA 30605
USA

Justin Pothoof
University of Detroit Mercy
Department of Chemistry &
Biochemistry
4001 W. McNichols Rd.
Detroit MI 48221-3038
USA

Michal Ruprecht

S. Iraj Sadraei
University of Windsor
Department of Chemistry &
Biochemistry
401 Sunset Ave.
Windsor ON N9B 3P4
Canada

Ben D. Sliwinski

Ben M. Sosnowski

Caroline Tebes-Stevens
U.S. Environmental Protection Agency
National Exposure Research Laboratory
Athens GA 30605
USA

John F. Trant
University of Windsor
Department of Chemistry & Biochemistry
401 Sunset Ave.
Windsor ON N9B 3P4
Canada
j.trant@uwindsor.ca

Steven P. Wathen
Siena Heights University
1247 E. Siena Heights Dr.
Adrian MI 49221
USA
swathen@sienaheights.edu

Anthony M. Noce

1 Green chemistry and the grand challenges of sustainability

Abstract: In its simplest form, green chemistry may be defined as the design of chemical products and processes that reduce or eliminate the generation of hazardous substances. The brief history of green chemistry is marked with extraordinary creativity and accomplishments in meeting the “triple bottom line” of sustainability in economic, social, and environmental performance. Green chemistry is about redesigning chemical processes from the ground up, and it goes hand in hand with the sustainable practice of chemistry. We need to start at the undergraduate level, and to provide a better foundation in green chemistry and systems thinking if we are to prepare a generation of chemists able to respond to the grand challenges of sustainability.

Keywords: green chemistry, sustainability, systems thinking, undergraduate chemistry curriculum

1.1 Introduction

Green chemistry was born out of the Pollution Prevention Act of 1990. In its simplest form, green chemistry may be defined as the design of chemical products and processes that reduce or eliminate the generation of hazardous substances. Joe Breen, who played a major role in creating the Design for the Environment and Green Chemistry Programs during his time at the United States Environmental Protection Agency, has been called the heart and soul of green chemistry. Ken Hancock, the Chemistry Director at the National Science Foundation, made a point to publicly advocate green chemistry as an economically viable strategy. And Paul Anastas and John Warner literally wrote the book, publishing *Green Chemistry: Theory and Practice* in 1998.

To date, green chemistry has primarily aimed to reduce the use of toxic chemicals and production of waste in industrial processes. Other aspects place the principles in a systems approach and focus on factors such as energy and water usage, as well as minimization of critical materials usage. Green chemistry looks to achieve pollution prevention through molecular design. This strategy minimizes the negative impacts of industrial chemistry on the environment through cooperation among academia, government, and industry.

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Noce, A. Green Chemistry and the Grand Challenges of Sustainability. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0072

https://doi.org/10.1515/9783110566499-001

Done properly, green chemistry looks at the complete life cycle of products and associated processes and is better for the environment. Although chemists and the chemical enterprise have become more environmentally aware and responsible over the past few decades, significant challenges remain. Sustainability is a key principle, and it must be placed front and center in the practices of the chemical enterprise.

Practitioners throughout the chemical enterprise are looking to make their current processes greener. In industry, this is often associated with cost-cutting and efficiency efforts, which brings us to another reality: Cost-benefit analysis will be a key driver in the greening of any given process. Green chemistry doesn't automatically win; it has to make economic sense. It has often been noted that industry is ahead of academia in the area of green chemistry because there are often larger and more obvious economic drivers for industry. Having said that, it is also frequently noted that the adoption of green chemistry in industry to date has been focused primarily on incremental improvements in existing processes to increase efficiency.

The brief history of green chemistry is marked with extraordinary creativity and accomplishments in meeting the "triple bottom line" of sustainability in economic, social, and environmental performance. This has generally been accomplished by improving a single crucial element or characteristic, such as toxicity, persistence, or energy consumption. Green chemists and engineers are working to get their research and innovations into everyday products and processes, redesigning the basic building blocks of our economy in sustainable ways. If you calculate the total cost of a product, green chemistry is better for the bottom line.

We have a long way to go to see processes redesigned from scratch and plants rebuilt from the ground up, however, and that is a matter of economics as well as chemistry. The vast majority of all organic chemicals in commerce are still derived from petroleum, which presents a host of other challenges – challenges which can be solved through the practice of green chemistry throughout the chemical enterprise.

Green chemistry is about redesigning chemical processes from the ground up, and it goes hand in hand with the sustainable practice of chemistry.

In many ways, the chemical enterprise continues to wrestle with a shallow, limited environmental awareness. Although significant improvements have been made, we still have a long way to go. This can be traced, at least in part, to the academic training system for chemists. We tend to focus on specialization for most candidates earning advanced degrees, and only rarely does the established academic framework reward researchers who anticipate environmental harm associated with their work. We need to start at the undergraduate level, and to provide a better foundation in green chemistry and systems thinking if we are to prepare a generation of chemists able to respond to the grand challenges of sustainability.

1.2 Conclusion

The American Chemical Society's Committee on Environmental Improvement (CEI) is tackling this head on. What follows is a document prepared by a CEI working group in conjunction with the ACS Green Chemistry Institute (GCI) documenting how green and sustainable chemistry can be incorporated into the undergraduate chemistry curriculum. This is how we are going to rise to the grand challenges of sustainability in the chemical enterprise in the long run.

1.3 Green chemistry: Preparing students to meet the grand challenges of sustainability

1.3.1 Context

In order for chemists to play a central role in addressing the grand challenges of sustainability, an integration of green chemistry principles and systems thinking is needed throughout the traditional chemistry subdisciplines. **Green chemistry** strives to promote innovations in chemistry that result in a net benefit to society [1]. Green chemistry provides the technical and practical knowledge required for identifying the need for and strategy toward designing new chemical products and processes, while minimizing adverse impacts on human and environmental health [2]. Many undergraduate chemistry programs have already integrated green and sustainable chemistry concepts benefiting the students and the program through increased laboratory safety, decreased volume and toxicity of waste, and engaged and inspired students. This supplement suggests ways to progressively integrate green chemistry strategies, concepts and practices throughout the chemistry curriculum providing students with the skills and vision to contribute to a sustainable future through chemistry.

1.3.2 Conceptual topics

Green chemistry leverages chemists' ability to design new beneficial/sustainable substances and processes while taking into account the interconnectedness with local and global systems. This approach, called **systems thinking**, is a problem-solving strategy which identifies and understands the key components of a system, in contrast to an isolated part, then investigates solutions based on the system interactions [3]. Teaching a systems approach challenges students to apply scientific principles to solve real-world problems, demonstrates chemistry's role as an essential science in finding solutions, and prepares future scientists for the collaborative interdisciplinary work required. Integrating green chemistry into today's chemistry curriculum, and system thinking as we look to the future, can be accomplished by scaffolding in these **Conceptual Topics**:

- Continuing advances in chemistry research are integral to meeting society's essential needs of food, energy, and water in a sustainable path forward [4].
- Chemicals and chemical products provide many benefits to society; however, unintended consequences can negatively impact humankind and the Earth. Green chemistry products and technologies have shown great potential for alleviating these impacts, in particular those that may disproportionately affect people based on lower socioeconomic status [5].
- The best approach to developing new chemical products and syntheses:
  - Is guided by the principles of green chemistry and life cycle thinking in order to minimize harm [6].
  - Employs molecular design for reduced hazards to the environment, health, and safety. It is a fundamental responsibility of chemists to design and synthesize safer chemicals [7].
  - Analyzes impacts throughout the lifecycle, from feedstock to end of final life using appropriate metrics [8].
  - Uses available knowledge and computational tools to design for function in concert with predicting hazards and environmental fate [8].
- Relationships between molecular structure and predicted properties such as metabolism, rates of chemical or biodegradation, and fate in the environment can be used for rational design of chemicals with reduced negative impact.
- Toxicology concepts expand a chemist's understanding of the relationship between structure and toxicity, and how exposure to chemicals, their degradation products and metabolites impact human and environmental health.
- Chemical risk is a function of hazard and exposure. In the past, risk management focused on strategies to reduce the exposure after it occurred. Incorporating green chemistry principles into risk management reduces the hazard before it occurs.
- The use of renewable feedstocks and alternative reaction media can be used to produce products with an improved sustainability profile.
- Increasing the efficiency and reducing energy requirements of syntheses, isolations, and purifications in producing products can reduce the environmental impact.

1.3.3 Practical topics

Green chemistry can be used to illustrate many fundamental chemistry principles throughout the curriculum. Numerous opportunities exist to include experiments and demonstrations in addition to infusing green chemistry in lecture courses. A sampling of illustrative examples within each subdiscipline is described below.

1.3.3.1 General chemistry

Foundational courses in chemistry cover a broad spectrum of topics from atoms to reaction energetics, thus providing ample opportunity to demonstrate the cross-disciplinary nature of sustainable chemistry. The study of the periodic table can include the relative abundance and toxicity of elements and their uses in products such as electronics and cell phones. Lessons in balancing equations, stoichiometry, and classes of reactions can be used to contrast high and low atom economy and energy-efficient reactions, as well as metrics to assess the sustainability of a chemical product. Thermodynamics can provide a platform for discussing energy sources and current efforts to derive fuels from biomass and replace fossil fuels with renewable wind and solar energy. Laboratory experiments based on consumer products can emphasize the importance of science-based decisions in choosing safer products. Although some of these topics are currently found in many general chemistry textbooks as “boxes of interest,” a more integrated and systems thinking approach to study would provide a stronger context for understanding current and future technological successes based on green chemistry principles.

Illustrative examples include:

- Chemical property discussions of elements, ions, and chemical compounds should include chemical hazards and safety in the lab. For example, Cr^{3+} is relatively non-toxic whereas Cr^{6+} is a carcinogen.
- Physical properties such as polarity, solubility, and volatility can be discussed in the context of partitioning in the human body and the environment related to toxicity and transport.
- The study of gases, such as CO_2, N_2O, $CH_{4,}$ and, O_3, and their molecular shape and properties can be tied to global warming potential.
- Teaching of skills such as number representations, graphing, and kinetic calculations can employ examples relating methods of assessing water quality, toxicity levels, and catalytic reactions.
- Life cycle thinking can be covered with topics such as the production of steel, renewable versus non-renewable polymers, and pharmaceuticals. A basic material and energy balance in the form of lists of inputs and outputs can be used to introduce the concept of life cycle inventory/assessment.
- Case studies can serve as accessible and inspirational models for the potential of green chemistry and a systems thinking approach. Examples include the use of renewable soybeans in making foam mattresses or study of the Flint, Michigan water contamination event.

1.3.3.2 Organic chemistry

Green chemistry, systems thinking, and toxicology concepts are readily woven into the undergraduate organic chemistry lecture and lab through discussions of: alternative reaction pathways and starting materials; the design of more efficient small molecule and macromolecular synthetic reactions; the role of solvents and rationale in their selection; the use of catalysts; how control of selectivity can maximize desired products while minimizing both by-products and the use of protecting groups; reducing or eliminating waste; and the relationship between a chemical hazard and its toxicity mechanisms. The application of green chemistry principles and systems thinking will specifically allow for an overall critical assessment of chemical processes using appropriate metrics [9].

Illustrative examples include:

- The teaching of organic chemistry reactions and mechanisms has traditionally focused more on the organic products. Side products, catalysts and solvents are often ignored. Balancing organic chemical reactions and illustrating mechanisms as balanced elemental equations will improve conceptual understanding of reactivity, efficiency and production of waste by-products.
- An understanding of how chemical structure (as well as the presence of particular functional groups) impacts the function of a molecule, including the toxicity and environmental impact of the chemical, is important to designing chemicals with reduced human and environmental hazards and predicting the potential hazards associated with chemicals.
- The role of solvents in a reaction and the selection of solvents (or solvent-free systems) is important for understanding how to reduce waste in a chemical process and reducing the hazards associated with a chemical process.
- Catalysts and bio-inspired chemistry play a key role in the design of more efficient multistep syntheses where improved chemoselectivity, regioselectivity, and stereoselectivity can minimize the number of steps, use of protecting groups, and waste production.
- Assessment of reaction efficiency will be quantified, in part, through the more traditional metrics of reagent costs, reaction selectivity, product yield, and atom economy.
- Identifying the source and chemical nature of waste produced in an organic synthesis also impacts the overall efficiency. Students will be introduced to the Environmental factor (e-factor) and process mass intensity (PMI) for evaluating the material efficiency and environmental impact of a synthetic process [10].
- Synthetic polymers are an indispensable part of our daily lives and the economy, but their production, use and disposal have a negative impact on the environment. Green chemistry technologies have been proven to reduce these impacts through the use of renewable monomer feedstocks and well-designed end of life fate (biodegradation, mechanical recycling, and chemical recycling) [11].
- A basic understanding of toxicology principles might include relevant molecular mechanisms (i. e., S_N, S_N2, acylation, Schiff Base formation, Michael Addition, and S_NAr) of how organic compounds can affect human health and the environment.

- Students can be challenged to apply green chemistry principles interfaced with non-science ideas to solve real-world challenges through a systems thinking laboratory case study examining the unintended consequences of an organic chemical: diesel fuel, Bisphenol A, thalidomide, DDT, brominated flame retardants, methyl isocyanate, etc. Students will define the problem, identify key system components, and investigating solutions based on the system interactions.
- Organic chemistry is the best time to introduce the concept of Molecular Design. The application of green chemistry principles to optimizing synthetic pathways and product design with minimum toxicity and maximum material/energy efficiency fits in well, particularly for students transitioning to upper level course work and undergraduate research projects [8].

1.3.3.3 Analytical chemistry

Understanding and addressing the effects of anthropogenic chemicals on human health and the environment is predicated upon the accurate identification and quantification of contaminants in air, water, soil, sediment, and biota. Developing students' awareness of the essential role of analytical chemistry in characterizing and reducing pollution does not prescribe any particular analytical or instrumental methods. It only requires that the choice of problems for analysis affords opportunities for students to understand and address applications to green chemistry [12].

Illustrative examples include:

- Understanding the environmental and human health impacts of contaminants of emerging concern and their metabolites, and conducting risk assessments requires the establishment of accurate dose-effect relationships.
- Real-time and *in situ* analyses can help to improve the mass and energy efficiency of chemical production processes while reducing the amount and toxicity of waste.
- Environmental impacts of analytical methods can be reduced through the use of: direct analysis (involving no sample preparation), miniaturized and/or assisted extractions, lower solvent volumes and less toxic solvents, and energy efficient methods.
- Analytical characterization of the composition, molecular mass, metal content, and stability of polymers is essential to a complete life cycle assessment of these materials.

1.3.3.4 Inorganic chemistry

The undergraduate inorganic chemistry curriculum focuses on inorganic species as atoms, molecules, coordination compounds, macromolecular, and solid state materials. Students should also have the opportunity to recognize inorganic species as being derived from Earth's minerals and consider their fate as they are returned to the environment at end of life [13].

Illustrative examples include:

- Some metals and metalloids are classified as critical or endangered due to geological abundance, geopolitical, and/or economic factors.
- Ore extraction and processing can have significant environmental impacts.
- For synthetic inorganic chemistry or applications of catalysts, synthetic efficiency can be evaluated through the application of appropriate metrics.
- Catalysts should be designed to be recyclable or recoverable and/or use Earth abundant metals.
- Metals in the environment have human and environmental health impacts. Bioavailability and toxicity are functions of many factors including speciation, particle size and morphology, and chemical similarity.
- Metals can be both physiologically necessary and toxic. The same metal can be both, depending upon the dose. Organisms bind, transport, store, and excrete metals to maintain beneficial concentrations.
- Inorganic materials are central to renewable energy technologies in applications such as batteries, photovoltaics, and materials for artificial photosynthesis.
- Biomimetic polymer/inorganic materials have potential for the design of unique mechanically stable hybrid materials.
- Discussion of cornerstone principles of nanotechnology and its wide spread applications can be accompanied with evaluation of benefits and drawbacks of nanomaterials. Discussion can also include how to synthesize and utilize these materials in a more sustainable and environmentally benign manner.

1.3.3.5 Physical Chemistry

The undergraduate physical chemistry curriculum explains fundamental principles underlying all chemistry subdisciplines via mathematical models and experimental techniques. Since these models and techniques are applicable to chemical systems ranging from atoms to macroscopic materials, physical chemistry provides a perfect opportunity to reinforce and/or introduce green chemistry concepts in the context of all chemistry subdisciplines.

Illustrative examples include:

- Evaluation of chemicals and chemical processes can be presented in terms of environmental, health, and safety outcomes using physical and physico-chemical properties such as boiling points, heat capacities, vapor pressure and explosivity limits of the materials involved.
- Arguments based on thermodynamic parameters (such as Gibbs free energy, enthalpy, and entropy) can be used to compare and contrast the efficiency of synthesizing compounds via traditional covalent bond-forming methods versus supramolecular strategies involving non-covalent interactions (such as hydrogen bonding and van der Waals).

- The principles of thermodynamics and kinetics are necessary to understand and improve the efficiency of chemical and/or bio-chemical reactions, plus environmentally important reactions like stratospheric ozone depletion, and the formation and reactions of atmospheric hydroxyl radical.
- Chemical potential, partitioning, phase behavior, etc. are important physical chemistry concepts in chemical reactivity, separations, etc., and are key to a better understanding of human and environmental health impacts, environmental fate and effects of chemicals, and chemical process sustainability.
- Importance of computational and spectroscopic techniques can be emphasized by applying them to green chemistry-related concepts such as designing environmentally friendly reaction conditions, polymerization kinetics, evaluating toxicity of various materials, and studying gas phase molecules and solids present in Earth’s atmosphere.

1.3.3.6 Biochemistry

Biochemistry is the study of biological phenomena at the molecular level. Biochemistry integrates elements from biology, chemistry, and physics to provide students with insight into the fundamental chemical principles that govern complex biological systems. Because biochemistry examines the chemistry of biological systems, it is uniquely positioned to incorporate green chemistry principles. It also affords instructors the opportunity to stress the differences between essential versus excessive. For example, iron in hemoglobin is necessary, iron in vitamins may potentially be toxic, while iron in the environment is hazardous under some conditions.

Illustrative examples include:

- Disturbances in the normal redox state of cells can cause local and systemic toxicities. Redox regulation may dictate enzyme activity.
- Proteins serve many intra/intercellular functions, none more important than enzymatic catalysis. Many key enzymatic transformations are governed by metalloenzymes. The metal-protein complex offers insight into the role of metals in biology.
- Synthetic biologists strive to manipulate the sequence of chemical reactions/transformations that occur within the cell in the hope of producing a different outcome.
- The study of biosynthetic pathways and enzymatic (biopolymer) transformations can lead to streamlined syntheses of beneficial molecules occurring in water at 37°C.
- The unique features of natural polyamides and polyesters may be compared with commercial materials made from non-renewable sources.
- Predictive toxicology based on key molecular initiating events and higher level mechanisms of action may allow us to develop adverse outcome pathways to supplant conventional *in vivo* testing.

- Epigenetic changes alter the physical structure of DNA. An example is DNA methylation; addition of a simple functional group can prevent genes from being expressed. Epigenetic changes are driven by a wide range of chemical and environmental exposures.

Acknowledgements: Special thanks to the following members of the ACS CEI working group on Green Chemistry in the Curriculum for their efforts in preparing this curriculum supplement:

- Dr Katherine Aubrecht, State University of New York at Stony Brook
- Dr Marie Bourgeois, University of South Florida
- Dr Edward Brush, Bridgewater State University (Massachusetts)
- Dr James Hutchison, University of Oregon
- Ms Jennifer MacKellar, ACS Green Chemistry Institute
- Dr Catherine “Cathy” Middlecamp, University of Wisconsin
- Dr Jane Wissinger, University of Minnesota

References

[1] Anastas PJ, Warner JC. Green chemistry: theory and practice. New York: Oxford University Publishing, 1998.
[2] EPA Green Chemistry. https://www.epa.gov/greenchemistry. Accessed July 2017.
[3] Meadows DH. Thinking in systems: a primer. White River Junction, VT: Chelsea Green, 2008.
[4] Burmeister M, Rauch F, Eilks I. Education for sustainable development (ESD) and chemistry education. Chem Educ Res Pract. 2012;13:59–68. DOI: 10.1039/C1RP90060A
[5] Lasker GA, Mellor KE, Mullins ML, Nesmith SM, Simcox NJ. Social and environmental justice in the chemistry classroom. J Chem Educ. 2017;94:983–7. DOI: 10.1021/acs.jchemed.6b00968
[6] Jiménez-González C, Constable DJC. Green chemistry and engineering: a practical design approach. Hoboken: John Wiley & Sons, Inc., 2011.
[7] Coish P, Brooks BW, Gallagher EP, Kavanagh TJ, Voutchkova-Kostal A, Zimmerman JB, et al. Future challenges in molecular design for reduced hazard. ACS Sustainable Chem Eng. 2016;4:5900–06. DOI: 10.1021/acssuschemeng.6b02089
[8] ACS Green Chemistry Institute. https://www.acs.org/content/acs/en/greenchemistry.html. Accessed July 2017.
[9] Doxsee KM, Hutchison JE. Green organic chemistry: strategies, tools, and laboratory experiments. Belmont: Brooks/ Cole,Cengage Learning, 2004.
[10] ACS GCI Pharmaceutical Roundtable Process Mass Intensity (PMI) Calculator. https://www.acs.org/content/acs/en/greenchemistry/research-innovation/tools-for-green-chemistry.html. Accessed August 2017.
[11] Zhu YQ, Romain C, Williams CK. Sustainable polymers from renewable resources. Nature. 2016;540:354–62. Doi:10.1038/nature2100
[12] De La Guaria M, Garrigues S, editors. Handbook of green analytical chemistry. Chichester, UK: John Wiley & Sons, Ltd, 2012.
[13] Graedel TE, Harper EM, Nassar NT, Nuss P, Reck BK. Criticality of metals and metalloids. Proc Natl Acad Sci USA. 2015;112:4257–62. DOI: 10.1073/pnas.1500415112

Resources

ACS Division of Organic Chemistry Green Organic Chemistry Resources. https://www.organicdivision.org/greenchemistry/. Accessed July 2017.

Anastas, P.; Eghbali, N. Green chemistry: principles and practice. Chem. Soc. Rev. 2010, 39, 301–312. (DOI: 10.1039/b918763b)

Andraos, J.; Dicks, A. P. Green chemistry teaching in higher education: a review of effective practices. Chem. Educ. Res. Pract. 2012, 13, 69–79. (DOI: 10.1039/C1RP90065J)

Beyond Benign. http://www.beyondbenign.org/. Accessed July 2017.

Collins, T. J. Review of the twenty-three year evolution of the first university course in green chemistry: teaching future leaders how to create sustainable societies. J. Clean. Prod. 2017, 140, 93–110. (DOI: 10.1016/j.jclepro.2015.06.136)

EPA (Presidential) Green Chemistry Challenge Winners. https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-winners. Accessed July 2017.

Greener Education Materials for Chemists. (GEMs) http://greenchem.uoregon.edu/gems.html. Accessed July 2017.

Matlin, S. A.; Mehta, G.; Hopf, H.; Krief, A. One-world chemistry and systems thinking. Nat. Chem. 2016, 8, 393–398. (DOI: 10.1038/nchem.2498)

Middlecamp, C. H.; Jorgensen, A. D., Eds. Sustainability in the Chemistry Curriculum; ACS Symposium Series 1087, American Chemical Society: Washington, DC, 2011.

Rational Molecular Design for Reduced Toxicity (ACS) https://www.acs.org/content/acs/en/green-chemistry/research-innovation/research-topics/rational-molecular-design-for-reduced-toxicity. html. Accessed July 2017.

Roesky, H. W.; Kennepohl, D. K., Eds. Experiments in Green and Sustainable Chemistry; Wiley VCH: Weinheim, 2009.

Michael Berger, Madeline Karod and Jillian L. Goldfarb

2 Invasive species or sustainable water filters? A student-led laboratory investigation into locally sourced biomass-based adsorbents for sustainable water treatment

Abstract: Designing sustainable products requires a holistic consideration of issues at the Food-Energy-Water Nexus. One of the world's greatest challenges is to insure clean water access for all inhabitants. Across the globe, communities often suffer from metal contamination in their water. We must develop low-cost, sustainable materials to treat this contamination, without putting undue stress on other systems. Biomass-based carbon adsorbents are often touted as one potential solution, but to be sustainable the biomass must be locally sourced, not grown on land that could be used to cultivate food, not require extensive water to grow, and not need undue amounts of energy to process. In this laboratory investigation, students were challenged to use a locally available, problematic biomass – *phragmites*, an invasive species in the Muddy River in Boston, Massachusetts – to develop a green adsorbent to remove metals from water. Specifically, students focused on the removal of manganese, as it is a local problem for several Massachusetts communities. Students activated the *phragmites* biomass using a room and low (40 °C) temperature KOH treatment, which opened the porous network of the reed to enable adsorption of Mn^{+2} upwards of 8 mg/g of biomass. In doing this experiment, students were exposed to the concept of adsorption, a separation process not often covered in the traditional chemistry curriculum. Students gained experience in performing adsorption isotherm experiments using atomic adsorption spectroscopy and UV–Vis spectrophotometry and learned to analyze data within adsorption isotherm models. Finally, students made connections between their laboratory data and adsorption theory, and how this data can be used to design greener materials to address environmental issues.

Keywords: food-energy-water nexus, water filtration, invasive species

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Berger, M., Karod, M., Goldfarb, J. L. Invasive Species or Sustainable Water Filters? A Student-Led Laboratory Investigation into Locally Sourced Biomass-Based Adsorbents for Sustainable Water Treatment. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0073

https://doi.org/10.1515/9783110566499-002

2.1 Green materials for clean water

Clean water has now equaled or even surpassed oil as the world's most desired and contested resource. The ability to secure access to freshwater is charting a new landscape in global conflict over what the United Nations considers to be a fundamental human right [1]. In the industrialized world, new analytical techniques have led to the detection of a plethora of emerging contaminants that previously went unnoticed in the water supply including disinfection by-products, alkylphenolic surfactants, endocrine disruptors, veterinary and human antibiotics, flame retardants, trace metals and inorganic complexes [2–5]. Removing these contaminants from the water supply is one of the most pressing technological and policy challenges facing industrialized societies. In the developing world, the primary technological challenge is to make water remediation economically viable and technologically implementable [6].

Biomass-based carbonaceous materials are promising candidates for low-cost water treatment via adsorption of both organic and inorganic contaminants from water. For example, activated carbons made from pyrolyzed fruit stones are known to possess high adsorption capabilities for organic contaminants such as polychlorinated biphenyls, basic dyes, and basic pharmaceuticals [7], though they are not as effective with acidic groups, hydrophilic substances, vat dyes, and some inorganic complexes [8]. De-acetylated chitin-based materials (obtainable from crustacean shells and insect exoskeletons), can be used to remove a range of compounds including acidic components, disperse dyes, and inorganic/metallic complexes [9–11]. Intriguingly, others have demonstrated how raw biomasses such as coconut bunch, nut shell and potato peel waste can treat organic and heavy metal contaminated waters, even without energy-, time- and material-intensive activation techniques [12–14].

While biomass-based sorbent materials are greener in terms of raw material requirements than traditional activated carbons manufactured from crude oil or coal, the positive gains achieved by using biomass as a petroleum substitute can be offset if the biomass must be transported long distances. To advance sustainable water treatment, we must consider not only the raw material, but also the distance that it must travel, the land footprint required for cultivation, and the water consumption for it to grow. Using locally sourced biomass mitigates long-range transport, and identifying an otherwise "problematic" biomass may negate land and water use issues. *Phragmites*, a common reed, is an invasive species that can change the hydrology, sedimentation, clarity, and nutrient balance of freshwater systems [15]. This reed has spread widely in Massachusetts; its high colonization rate is attributed to overuse of road salt increasing the sodium chloride concentration in fens, also known as peatlands, that have strong alkaline, minerotrophic groundwater [16]. One such area exists nearby to the campus of Simmons College in Boston; students learn about this invasive species and, over the past several years, have tracked its ability to sequester heavy metals from the Muddy River as part of an Environmental Chemistry course. To introduce concepts such as contaminant remediation, green materials, and adsorption into the Freshman chemistry curriculum, the present laboratory exercise shows students how this invasive species could be used as a resource for remediation for contaminated water and, in the process, help to conserve the Muddy River ecosystem.

One reason that *phragmites australis* is such a hardy reed and a successful invasive species is due to its extensive and unique root system, which hosts a biofilm that during the growing season traps many heavy metals in the roots. This prevents translocation of metals into the rest of the plant that could be harmful to the plant [17]. Our interest in evaluating this invasive species as a resource for remediation of contaminated drinking water, however, is not in the living *phragmites*, but instead in using the dead *phragmites* stems that litter the Muddy River every fall as the plant goes dormant, with quantities estimated at 2500–5000 kg annually. Currently the dead *phragmites* is left to decay, resulting in biomass that adds to Muddy River sedimentation, which left unchecked could convert the river into a marshland. Harvesting the *phragmites* as a biomass for remediation simultaneously helps to conserve the current ecosystem and provides a renewable feedstock for producing "green" adsorbents.

There are myriad anthropogenic and biogenic sources of heavy metals and trace inorganic contaminations to our water supply, including industrial sources such as metal plating, mining, and painting, agricultural sources such as fertilizers and fungicides, and natural sources of metals from underlying bedrock. The town of Topsfield, Massachusetts has seen elevated levels of Mn(II) in its drinking water over the last several years. Records indicate that since 2013, the Mn(II) level has been, on average, 313 ppb at one site and 391 ppb at another [6]. The residents of Holliston, MA, a town of over 13,000 residents in the Boston MetroWest region, consistently face high levels of naturally occurring manganese in their water. Across Holliston's drinking water supply, Mn concentrations routinely exceed the 50 ppb secondary standard for drinking water (often testing at 1.3 mg/L). The naturally occurring Mn is due to underlying bedrock and a lack of hydrogeologic barriers in the town's shallow aquifers. Repeated studies show that exposure to elevated levels of Mn in early life leads to adverse neurobehavioral outcomes [18, 19], while others detail neurotoxic consequences to early-life exposure of TCE and TCA [20–22]. Residents have documented brown water flowing routinely from their taps, but no solution has yet to be presented. One possible stopgap solution is to use carbon-based adsorbents to remove the Mn from water with point-of-use (in home) filters.

2.2 Learning goals of laboratory investigation

The challenge issued to students at Simmons College was to determine if they could use *phragmites* – known to sequester metals such as manganese while growing – as an adsorbent material to help the communities of their state suffering from high concentrations of manganese in tap water. While this exercise uses *phragmites* as the raw biomass and manganese as the model contaminant, this experiment is designed to work with many locally available biomasses, such as peanut shells, corn stover, potato peels, etc. Students in upper level courses can be challenged to learn about the properties of a good adsorbent and to propose their own biomass. As water contamination issues exist across the country and globe, students can also be challenged to identify the contaminant to investigate that is locally relevant using their biomass-based adsorbent.

The pedagogical goals of this laboratory exercise and associated classroom content include:

- Introduce students to local environmental issues, such as the history of the Muddy River, sources of pollution, and invasive species.
- Cultivate an understanding of the dire need for clean water worldwide, and the inextricable nature of food, energy and water to satisfy this need.
- Introduce students to the concept of adsorption and aspects of bioremediation.
- Expose students to analytical techniques such as UV–Vis spectrophotometry, atomic adsorption spectrometry and/or inductively coupled plasma mass spectrometry to quantify the amount of heavy metals removed from simulated contaminated water.
- Teach students how to develop calibration curves and use Beer’s law to analyze adsorption data, to “fit” data to theoretically grounded models, using the models to explain adsorption mechanisms, and to evaluate the reliability of students’ individual data.
- Challenge students to identify sustainable resources that could be used as sorbent materials for water remediation in their own communities.

2.3 Adsorption as a tool to introduce separation processes to chemistry students

Separations processes are key unit operations across scales and applications, from removing trace contaminants from water to refining petroleum fuels, and are often the most expensive unit operations for chemical, petroleum, petrochemical, and pharmaceutical plants. Separating a mixture can be accomplished in many ways, including: manipulating phases of a mixture (distillation, stripping, boiling); using barriers (membranes); applying external fields and gradients (centrifugation, electrolysis, electrophoresis) and using solid agents (chromatography, ion exchange and adsorption). While chemical engineering students have a course on separations and/or mass transfer, chemistry students are not introduced to such “unit operation” concepts, which may hamper their ability to work with chemical engineers in the future. While a thorough introduction to the rate-based mechanisms behind adsorption is beyond the scope of this laboratory exercise, and indeed most chemistry curricula, we find that students can easily visualize the adsorption process, make connections between the classroom, laboratory, and "real world," and understand concepts of green chemistry by using a simple equilibrium-based approach. The following discussion is provided to assist the instructor in developing a pre-lab discussion or lecture, though of course is not an exhaustive treatment of adsorption. Recommended further readings on adsorption theory and applications, as well as biomass-based adsorbents, are provided at the end of this chapter.

2.3.1 The adsorption process

Adsorption is a separation technique that isolates contaminants (adsorbates) from a fluid (liquid or gas), and selectively transfers them onto a solid adsorbent. Many students have used adsorption in their daily routines; Brita® filters are comprised of activated carbons (sourced from coconut biomass) and ion exchange resin. When tap water runs through the filters, the activated carbon sequesters mercury, chlorine, and other organics, while the ion exchange resin captures metals such as zinc, copper, and cadmium.

The driving force for adsorption is usually electrostatic or van der Waals interactions, where the adsorbate has a higher affinity for the solid surface of the adsorbent than the fluid it is in. Such reversible interactions lead to a sorbent than can often be regenerated; the stronger the interaction the more difficult the regeneration. Conversely, adsorbates can also be chemisorbed, or irreversibly adsorbed, to the surface of a sorbent by forming a chemical bond. In practice, adsorption is an equilibrium limited process, whereby the adsorbent is in equilibrium with a fluid. Adsorption is considered a mass transfer operation because it has four overall "steps" during the process, as illustrated by Figure 2.1.

These four steps are:

1. Adsorbate transfer from the bulk fluid phase to the surface (boundary layer) of the adsorbent. The rate at which this occurs depends on convective and turbulent mixing to bring the adsorbate "close enough" to the adsorbent surface.
2. Diffusion of the adsorbate across the surface film to the outside surface of the adsorbent.
3. Movement of the adsorbate from the surface of the adsorbent into the porous network via diffusion (through fluids in the pores or along their surface).
4. Physical or chemical attachment of the adsorbate to the inner pores of the adsorbent.

Both bulk fluid transfer and physisorption/chemisorption (Steps 1 and 4) occur quite rapidly, whereas diffusion is a much slower process, with Step 3 usually the rate-determining step. When evaluating an adsorbent's suitability to separate a particular mixture, we use both kinetics experiments, to determine the rate at which adsorption occurs, as well as isotherm experiments, to determine the equilibrium loading

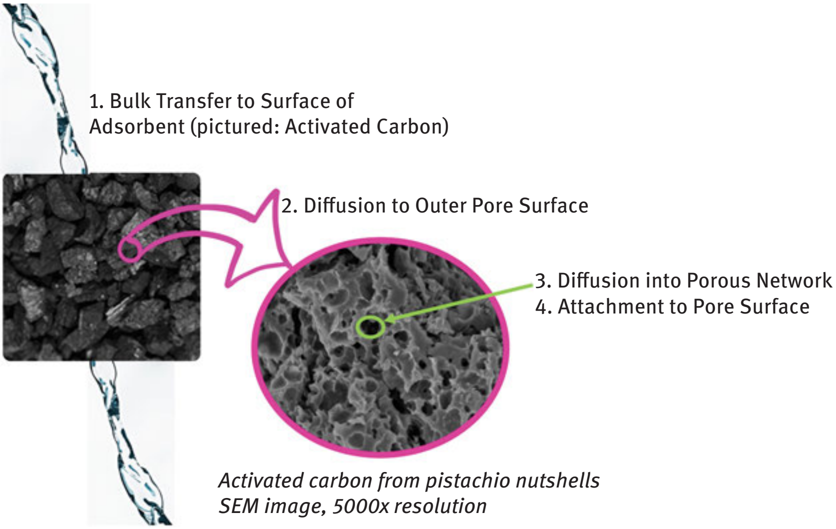


Figure 2.1: Four steps of adsorption.

capacity of a given solute for the solid adsorbent. While both experiments could make excellent laboratory exercises, the present experiment assesses the equilibrium adsorption capacity of biomass-based adsorbents as it (at least in our experience) leads to more reproducible data, especially in lower level chemistry courses, as consistent sampling over time required for kinetics studies introduces considerable error in the undergraduate laboratory.

2.3.2 Assessing equilibrium adsorption capacity

By immersing solid adsorbent particles in a liquid mixture, the pores (assuming they are larger than the liquid molecules) will "wet," or fill with fluid. A dynamic equilibrium will eventually be established, whereby the concentration of the adsorbate (for example, a contaminant such as manganese) in the bulk liquid is in equilibrium with the interface concentration. Such adsorption equilibria studies provide critical physical-chemical information concerning the nature of adsorbate-adsorbent interactions [23]. This equilibrium behavior is expressed by isotherms, the Langmuir and Freundlich being two of the most common, as given in Table 2.1

Briefly, the Langmuir isotherm model was originally developed to describe adsorption of gas phases onto solid activated carbon. Its key assumption is monolayer adsorption (the adsorbed layer is only one molecule thick), such that adsorption can only happen at a finite number of locations on the surface of the adsorbent. For this reason, the equilibrium saturation point is reached when no more molecules can

Table 2.1: Adsorption isotherms used to investigate equilibrium adsorption behavior.

	Langmuir		**Freundlich**	
Nonlinear isotherm	$q_e = \frac{q_{\max} b C_e}{1 + b C_e}$	(2.1)	$q_e = K_F C_e^{1/n}$	(2.2)
Linearized isotherm	$\frac{C_e}{q_e} = \frac{1}{bQ_{\max}} + \frac{C_e}{q_e}$	(2.3)	$\ln q_e = \ln gK_F + \frac{1}{n} \ln C_e$	(2.4)
Plot	$\frac{C_e}{q_e}$ vs. C_e		$\ln q_e$ vs. $\ln C_e$	
Variables	– C_e: equilibrium concentration of adsorbate in bulk liquid (mg/L) – q_e: amount of adsorbate adsorbed per mass of adsorbent at equilibrium (mg/g)			
	– $q_{\max}$: monolayer adsorption capacity of the activated carbon for a particular sorbent (mg/g) – b: empirical Langmuir constant (L/mg)		– K_F: empirical Freundlich constant (mg/g) $(L/g)^n$ – n: adsorption intensity (empirical; dimensionless)	

occupy an adsorption site, and the adsorption curve plateaus. The separation factor, R_L, a dimensionless constant, can be used to describe the nature of adsorption [24]:

$$R_L = \frac{1}{1 + K_L C_0}, \tag{2.5}$$

when $R_L > 1$ adsorption is "unfavorable," favorable with $R_L < 1$, and irreversible when $R_L = 0$ [25].

Conversely, the Freundlich isotherm describes reversible adsorption that is not restricted to monolayer adsorption or homogeneous adsorption site distribution like the Langmuir isotherm. It is often applied to heterogeneous systems such as organic compounds adsorbed on activated carbons [24]. It assumes an exponential decay in sorption site energy distribution, and while critics note that it does not have a fundamental thermodynamic basis (as it does not reduce to Henry's law at very dilute concentrations), it is an empirical model used throughout adsorption studies to capture heterogeneous adsorption behavior [23].

Adsorption capacity depends on both the properties of the adsorbent (functional groups, surface area, porosity, particle size), the adsorbate (acidic/basic, organic/inorganic, size, affinity for adsorbent surface), and system factors (temperature, pH, and ionic strength of the media to be separated). While investigating all these confounding factors is beyond the scope of this investigation, it would make excellent follow-up discussions and potential laboratory investigations. However, what students *can* take away from this laboratory exercise is an understanding of how adsorption can be used to remove a contaminant from the aqueous phase and sequester it on the surface of a solid adsorbent.

2.4 Laboratory experiment: materials and methods

The experiments for this laboratory exercise were first performed by an undergraduate student and faculty mentor in Summer 2017, and then adapted for the undergraduate laboratory setting. We explored the adsorption properties of one biomass (*phragmites*) as both a raw biomass and after moderate activation procedures, as described below.

2.4.1 Biomass collection and activation

Phragmites biomass samples were collected in April 2015, and dried, ground, and sieved to particle sizes between 250 and 600 µm according to ASTM E11. As a rough guide, each experimental team requires approximately 70–100 mg of total solid sorbent to perform the adsorption experiments. A portion of the milled *phragmites* was kept as “raw” biomass and used directly. A portion was treated with 1 M potassium hydroxide (1.0 g biomass to 10 mL of 1 M KOH) and allowed to mix at room temperature (23 °C) for 2 h under constant stirring using a magnetic stirrer. A second portion was treated with the same biomass to KOH ratio, but heated at 40 °C for 2 h under constant stirring. Both KOH-treated samples were filtered and washed with DI water using a Buchner funnel until the filtrate was neutral as measured with pH paper, and then dried at 100 °C for 24 h. KOH was chosen as it is a known porogen, or material that opens the porous network of carbonaceous materials, increasing surface area and therefore adsorption capacity [7, 26].

2.4.2 Preparation of solutions

The raw and activated biomasses were used to treat water “contaminated” with manganese, using atomic adsorption spectroscopy for concentration measurements, and with zinc, using UV–Vis spectrophotometry to monitor concentration via the Zn(II) colored complex formed with zincon. This also afforded an opportunity to compare the effectiveness of sorption of a different metal cation (though same oxidation state) by *phragmites*. Stock solutions were prepared in advance of the laboratory to insure students all began with the same baseline for experiments such that data could be compared across groups.

2.4.2.1 Manganese solutions

A 20 ppm Mn(II) stock solution was prepared by adding 0.07265 g of $MnCl_2$ to a 1 L volumetric flask and filling with deionized water. Equilibrium experiments were conducted at different initial manganese concentrations made by appropriate dilution of the 20 ppm [Mn] stock solution with deionized water. Calibration solutions over the range 0.2–10.0 ppm [Mn] for the Atomic Absorption Spectrometer (Agilent 240FS, Santa Clara, CA, USA) were prepared by diluting a 1000 ppm [Mn] standard (Ricca Chemical Co. AZN1KN-100, Arlington, TX, USA) with a 2 % solution of trace metal grade HCl (32–37 % Fisher A508-P500, https://www.fishersci.com/us/en/contactus.html). One of the laboratory assistants prepared this calibration curve in advance given the sensitivity and instrument time required.

2.4.2.2 Zinc solutions

A 20 ppm zinc stock solution was prepared in 1 L of DI water using 0.0880 g of zinc sulfate heptahydrate. In this case, students prepared calibration solutions over the range of 1–20 ppm from the 20 ppm stock solution. The analytical method is based on the formation of a colored complex between Zn and the zincon indicator as described by Areco and co-authors [27]. The zincon indicator solution is prepared by adding 0.065 g of zincon (CAS 62625-22-3) to 1 mL of 1 M NaOH in a weighing bottle to dissolve the zincon. This solution was then transferred to a 50 mL volumetric flask and filled with deioinized water. Once homogenous, the solution was wrapped in aluminum foil and refrigerated for up to one week. A pH 9 buffer solution is necessary to develop the Zn-zincon complex prepared by first dissolving 2.4 g NaOH pellets in 60 mL of water; this solution is then transferred to a 100 mL volumetric flask to which is added 3.73 g of KCl, 3.1 g of boric acid, and DI water to the fill line.

2.4.3 Adsorption experiments

Depending on the equipment available and local or global water concerns, the analytes used can vary according to the instructor's specific pedagogical goals and laboratory limitations. There are thousands of papers in the literature detailing adsorption studies of metals and organics to carbonaceous sorbents using a myriad of detection techniques – a simple Google Scholar search of “adsorption of metal onto carbon” returns over 24,000 results published from 2016 through August 2018! For both the Mn and Zn experiments, student groups were supplied with raw and activated biomass, stock solutions, and 15 mL polypropylene centrifuge tubes.

2.4.3.1 Mn adsorption experiments

Given the small class sizes at Simmons College, but the desire to have multiple data points at each isotherm loading, students were assigned to one biomass loading (5, 10 or 15 mg) at multiple Mn(II) concentrations (5, 10, 15 ppm) or multiple biomass loadings at a single concentration. To each of centrifuge tube, students added either 5, 10 or 15 mg of biomass to 10 mL Mn(II) solutions at concentrations of 5, 10, and 15 parts per million. The vials were closed and allowed to agitate on a twister laboratory shaker (Clay Adams Nutator, USA) for 1 h in order to reach equilibrium.[1] After 1 h, vials containing initially 5 and 10 ppm [Mn] were acidified with trace metal grade HCl, and the contents then filtered through a 10 mL Luer-lock syringe equipped with a 0.22 µm cellulose acetate syringe filter into a clean vial for AA analysis. Samples with initial concentrations of 15 ppm were diluted 1:1 with a solution of 2 % hydrochloric acid in DI water in order to yield final samples that would fall within the calibration range.

2.4.3.2 Zn adsorption experiments

For the Zn experiments, again biomass at various loadings (5, 10, and 15 mg) was added to 15 mL polypropylene centrifuge tubes and 10 mL of Zn solutions at concentrations of either 5, 10, or 15 ppm [Zn] were added. Samples were shaken on a twister laboratory shaker (Clay Adams Nutator) for 1 h in order to reach equilibrium. After the elapsed hour, 1.0 mL sample was pipetted from the centrifuge tube into a 10 mL volumetric flask. The zincon complex is then formed by adding the following reagents in the following order with mixing after each addition: (1) 0.5 mL of buffer, agitate; (2) 0.3 mL of zincon solution, agitate; (3) dilute to 10 mL with DI water. The 10 mL volumetric flask is mixed thoroughly after the addition of the deionized water and then an aliquot is transferred to a cuvette for analysis on a Spectronic 20 (Baucsh and Lomb, Madison, WI, USA) at 623 nm.

2.5 Results and discussion

This laboratory exercise engages students in selecting greener materials to remediate contaminated water while instilling in them a need to take precise data and understand the uses and limitations of various equations.

2.5.1 Calibration and Beer’s law

For this laboratory exercise, freshmen students diluted a stock solution to make the Zn standards and developed the zincon complex to prepare calibration standards. The resulting calibration curve for Zn is shown in Figure 2.2. This exercise presented an excellent opportunity to discuss the validity of Beer’s law over different ranges of concentrations; namely the good linearity of the calibration

---

[1] Preliminary kinetics experiments performed by the laboratory assistant on each biomass demonstrated that 1 h was sufficient time to reach equilibrium for the raw and activated biomasses for both metals.

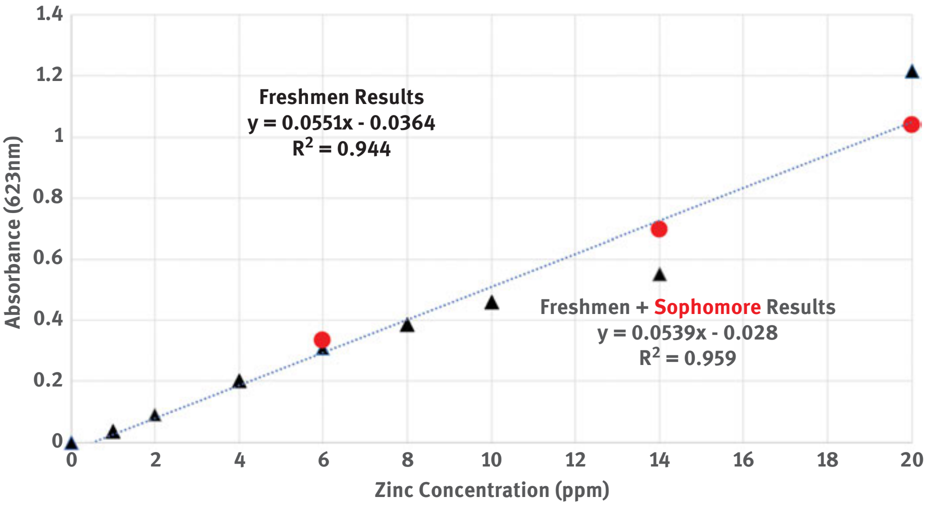
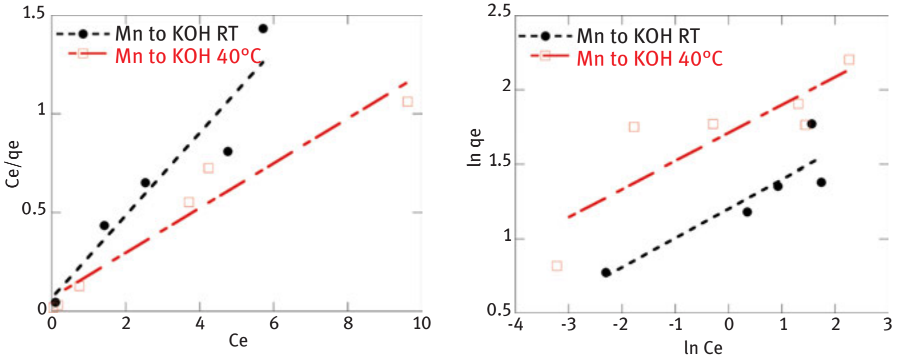


Figure 2.2: Calibration curve of Zn in zincon complex; black triangles represent points taken by freshman chemistry students and red circles points taken by sophomore laboratory assistants.

curve for Zn over the concentrations of interest using UV–Vis spectroscopy (as compared with a non-linear calibration curve for Mn using Flame atomic absorption spectroscopy over the same range of concentrations, provided to students). The black triangles are data that the freshmen students collected and the red dots are data that the sophomore students recreated, generating a more precise calibration curve, with the overall regression relationship being quite similar. The lab inexperience of the freshmen has undoubtedly contributed to the larger scatter in their data; upon reflection, they questioned their competence to work with volumetric glassware and operation of the Spectronic 20.

2.5.2 Determination of adsorption capacity for Mn and Zn

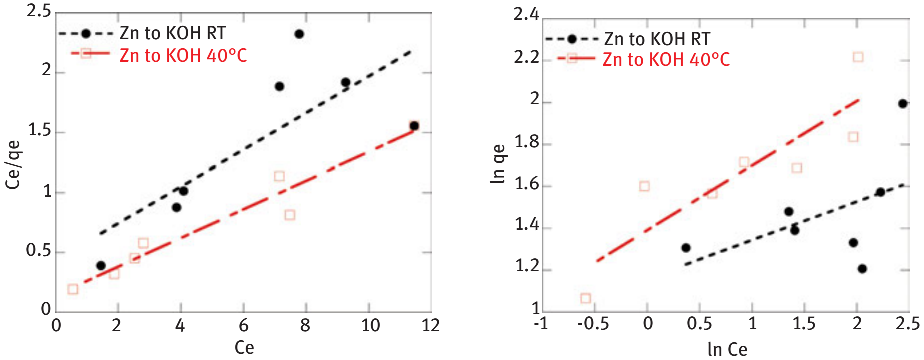
While there are many mechanisms and models to describe the process of adsorption, two are commonly employed to explain the adsorption of analytes onto surfaces – Langmuir adsorption, which describes an equilibrium situation of a single layer of adsorbed analytes, and Freundlich adsorption, which describes equilibrium with multilayer adsorption as the predominant mechanism. By plotting the isotherms of the analyte in solution in two different ways consistent with their mechanisms, it is often possible to gain an insight into the mechanisms of adsorption – single or multilayer. See Figure 2.3 and Figure 2.4. By using the intercept and slope of the linear regression, we can determine the maximum adsorption capacity, $q_{\max}$.



a. Langmuir model applied to adsorption of Mn onto room temperature (blue circles) and 40°C KOH-activated (red squares) *phragmites*

b. Freundlich model applied to adsorption of Mn onto room temperature (blue circles) and 40°C KOH-activated (red squares) *phragmites*

Figure 2.3: Isotherms for KOH-activated *phragmites* stems for Mn adsorption. (a) Langmuir model applied to adsorption of Mn onto room temperature (blue circles) and 40 °C KOH-activated (red squares) *phragmites*. (b) Freundlich model applied to adsorption of Mn onto room temperature (blue circles) and 40 °C KOH-activated (red squares) *phragmites*.



a. Langmuir model applied to adsorption of Zn onto room temperature (blue circles) and 40°C KOH-activated (red squares) *phragmites*

b. Freundlich model applied to adsorption of Zn onto room temperature (blue circles) and 40°C KOH-activated (red squares) *phragmites*

Figure 2.4: Isotherms for KOH-activated *phragmites* stems for Zn adsorption. (a) Langmuir model applied to adsorption of Zn onto room temperature (blue circles) and 40 °C KOH-activated (red squares) *phragmites*. (b) Freundlich model applied to adsorption of Zn onto room temperature (blue circles) and 40 °C KOH-activated (red squares) *phragmites*.

2.5.2.1 Mn adsorption

All participants in the project met in teams to analyze their data to plot Langmuir and Freundlich isotherms. The results are shown in Figure 2.3 (adsorption to KOH activated stems shown). Figure 2.3(a) shows the data fit to a Langmuir isotherm for Mn adsorption to room temperature (RT) and 40 °C KOH treated stems. Figure 2.3(b) is the Freundlich model for Mn adsorption to RT and 40 °C KOH treated stems. There are two major observations from these plots that the students were easily able to see. For both materials, the Langmuir model appears to be more suitable to describe the isotherm data gathered by the class than the Freundlich, suggesting that single layer adsorption of Mn(II) is the predominant mechanism for adsorption onto KOH treated stems.

2.5.2.2 Zn adsorption

The results for the adsorption of Zn are plotted in Figure 2.4. As with Mn adsorption, the Langmuir model appears to better describe the data than the Freundlich model, again suggesting that single layer adsorption is the predominant model for adsorption of Zn onto KOH treated stems.

2.5.2.3 Comparison of adsorption capacities

When C_e is plotted against C_e/q_e, the Langmuir isotherm gives a slope of $1/q_{\mathrm{max}}$, the inverse of the monolayer adsorption capacity of the adsorbent for a given analyte of interest. As the slope is inversely related to the maximum adsorption, the adsorbent with a smaller slope, or the lower line, will have the higher adsorption capacity of the two treatments. Table 2.2 gives the calculated maximum adsorption capacity of both metals to the raw *phragmites* stems and two KOH treated stems as determined by the class. It also includes the q_{max} of stem treated with KOH at room temperature in an earlier experiment, which was done only by the laboratory assistant to show that though the class' combined data may not be "as good" as a well-trained laboratory assistant, even the Freshman chemistry students are able to produce data that make sense in terms of adsorption capacity. We note that the adsorption to raw stems was so low that students were unable to plot isotherms.

Table 2.2: Maximum adsorption capacity of Mn(II) and Zn(II) to raw and KOH-treated phragmites stems as determined via Langmuir isotherms.

Sample	$[Mn^{2+}]$ adsorption		$[Zn^{2+}]$ adsorption	
	q_{max} (mg_{Mn}/g)	R^2 Langmuir	q_{max} (mg_{Zn}/g)	R^2 Langmuir
Raw stem (Nov., class)	~0	<0.5	N/A	N/A
RT KOH stem (August, TA)	3.1	0.98	N/A	N/A
RT KOH stem (Nov., class)	4.9	0.90	4.2	0.88
40 °C KOH stem (Nov., class)	8.8	0.94	8.4	0.94

From these data it is clear that the stems treated at 40 °C have an increased ability to adsorb both manganese and zinc, and even RT KOH treatment is an improvement over raw biomass. We would expect such a finding here; KOH is a porogen, which, especially at elevated temperatures, is known to disrupt the cellulosic and lignin structures of plant materials, as well as remove mineral matter, increasing the surface area of the biomass [17, 28]. As we see here, increasing temperature of activation even from room temperature to 40 °C doubles the adsorption capacity for both metals. The KOH treated stems have very similar absorption capacities for both Mn and Zn, both of which were in + 2 oxidation states for this experiment, and of similar atomic size, such that this behavior is not surprising. The two metals were measured using different analytical techniques, but clearly the sensitivity provided by atomic adsorption is not necessary for a student investigation to achieve reasonable results.

2.5.3 Qualitative evidence from SEM imaging

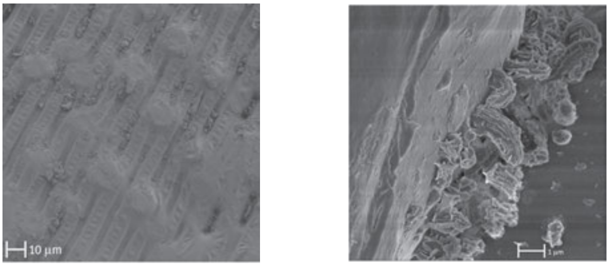
While many undergraduate laboratories do not have access to scanning electron microscopy (SEM), and such images are not necessary for this laboratory exercise, we provide the images below to show the impact of KOH treatment on helping to break down the fibrous network of the *phragmites* and open the porous structure. As seen in Figure 2.5, the raw biomass (Figure 2.5(a) and Figure 2.5(b)) has a fairly "solid" surface, smooth and fibrous dotted with (likely) mineral deposits; the grinding produces some friable edges as seen in Figure 2.5(b). The RT KOH treatment (Figure 2.5(c) and Figure 2.5(d)) show some degradation of the fibrous nature, with removal of the amorphous surface deposits and a slight opening of the porous structure where the KOH attacked the weaker carbon and mineral structures. Even at low magnification (<1000×, Figure 2.5(e)) the opening of the porous network with 40 °C KOH treatment is evident, and at higher magnification (Figure 2.5(f)) the voids are clearly evident. This increased porosity and surface area observed with stems treated with KOH at 40 °C (Figure 2.5(e,f)) is consistent with the greater sorption capacity of the stems treated with KOH at 40 °C, as we would expect from the preceding discussion.

2.6 Pedagogical implications

As discussed in the Introduction, there were multiple learning goals for this laboratory investigation, performed by Freshman chemistry students at Simmons College. A variety of methods were used to assess student outcomes, include student surveys, pre- and post-laboratory assessments, and a graded laboratory report.

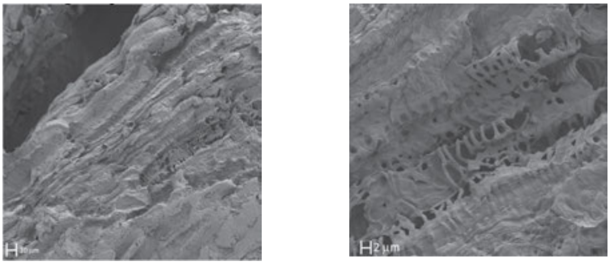
2.6.1 Introduce students to local environmental issues

One set of outcomes was to introduce the students to local environmental issues focusing on the Muddy River. Many of the pre-assessment responses to questions



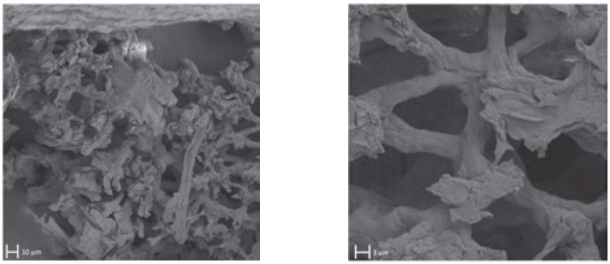
a. Raw *phragmites;* scale bar indicates 10 μm

b. Raw *phragmites;* scale bar indicates 1 μm



c. RT KOH treated *phragmites;* scale bar indicates 10 μm

d. RT KOH treated *phragmites;* scale bar indicates 2 μm



e. 40°C KOH treated *phragmites;* scale bar indicates 10 μm

f. 40°C KOH treated *phragmites;* scale bar indicates 3 μm

Figure 2.5: SEM images of raw and KOH treated phragmites stem. (a) Raw *phragmites*; scale bar indicates 10 μm. (b) Raw *phragmites*; scale bar indicates 1 μm. (c) RT KOH treated *phragmites*; scale bar indicates 10 μm. (d) RT KOH treated *phragmites*; scale bar indicates 2 μm. (e) 40 °C KOH treated *phragmites*; scale bar indicates 10 μm. (f) 40 °C KOH treated *phragmites*; scale bar indicates 3 μm.

such as “What are sources of contamination in the Muddy River?” were rather non-specific (i. e. litter and sewage), as shown in Table 2.3. The post-assessment responses were more detailed and corresponded to the curriculum in the course. Students demonstrated that they had applied their lab work to understanding the challenges in this local river. We were overall encouraged that students had a clear grasp on potential anthropogenic impacts of urban activities on natural ecosystems before the laboratory, which strengthened with a more specific awareness of local issues after the experiment.

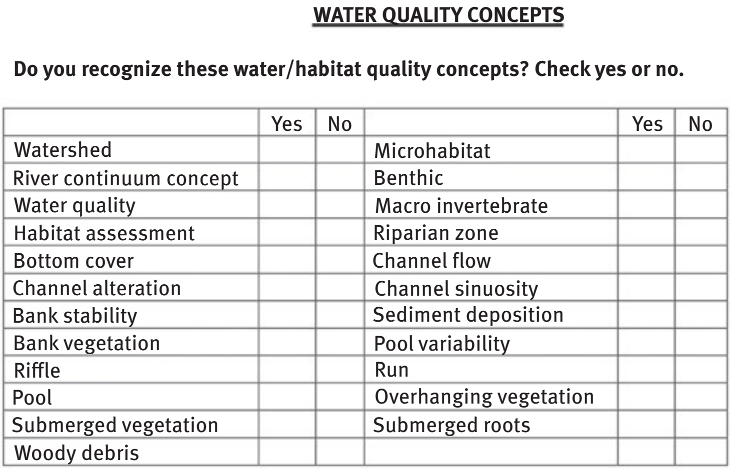
Table 2.3: Pre- and post-assessment of student knowledge of local environmental issues.

Question	Pre-course responses	Post-course responses
Sources of contamination in the Muddy River	Litter, sewage, salt and other run-off from the road	Road and storm run-off, sewage, heavy metals, *E. coli*
Contaminants of concern	Litter, fumes from road, plastic, animal waste, hydrocarbons	*E. coli*, heavy metals, PAH's, lead, arsenic, hydrocarbons
Problems addressed by remediation project	Litter, road runoff, flooding, invasive species, water quality, biodiversity, sediment deposition	Invasive species (phragmites), sediment build-up, sewage run-off, heavy metals
Name invasive species in Muddy River	Ivy, geese, ferns	Phragmites

2.6.2 Cultivate an understanding of clean water issues

We asked students both pre- and post-assessment questions focused on water quality, as detailed in Figure 2.6. Although they did not actually perform a laboratory on water quality in the traditional sense of total dissolved solids, pH, organic analysis, etc., class discussion about water quality issues and its relation to the ecosystem exposed students to several water quality concepts. This assessment instrument asked the students how many water concepts they recognized.

Figure 2.7 shows a dramatic increase in the number of concepts recognized – initially recognizing only 44 % of the concepts and increasing to 86 % of the concepts at the end of the semester. While we note, of course, that "recognition" and "understanding" are not the same, our goal with this laboratory was for students to develop



WATER QUALITY CONCEPTS

Do you recognize these water/habitat quality concepts? Check yes or no.

	Yes	No		Yes	No
Watershed			Microhabitat		
River continuum concept			Benthic		
Water quality			Macro invertebrate		
Habitat assessment			Riparian zone		
Bottom cover			Channel flow		
Channel alteration			Channel sinuosity		
Bank stability			Sediment deposition		
Bank vegetation			Pool variability		
Riffle			Run		
Pool			Overhanging vegetation		
Submerged vegetation			Submerged roots		
Woody debris					

Figure 2.6: Water quality assessment of student term recognition.

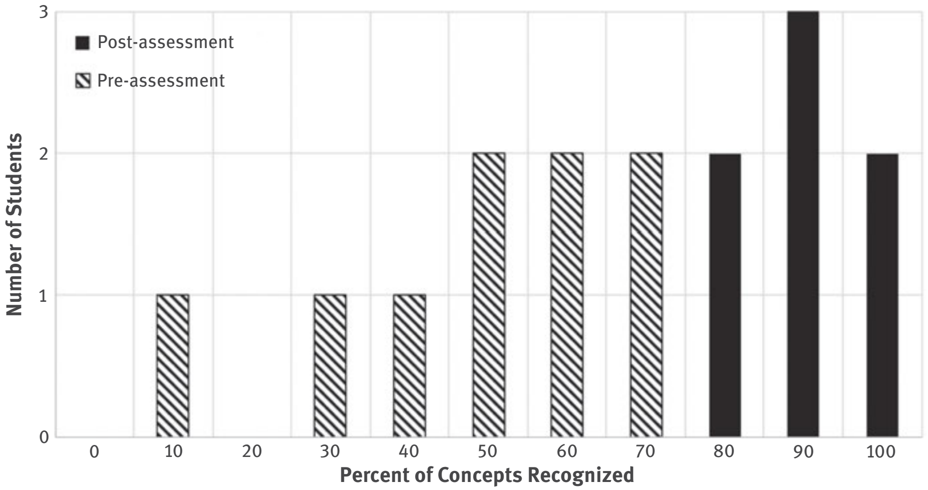


Figure 2.7: Student recognition of water quality concepts. Number of students recognizing differing percentages of water quality concepts. Crosshatch indicates student responses at the beginning of the course and solid black at the end of the course.

a sense that there are many impediments to supplying clean water, and natural and anthropogenic ecosystem deterioration in urbanized areas can degrade water quality.

2.6.3 Laboratory concepts: techniques, measurements, and analysis

The students were introduced to a series of scientific concepts and laboratory techniques, from adsorption and bioremediation to use of spectrophotometry and spectrometry from calibration to data analysis. To determine student achievement in learning these laboratory concepts, a third instrument used was a self-assessment survey at the beginning and at the end of the course. Students were asked to rate their comfort level with respect to a number of different concepts that they were exposed to during the course: biosorbant, adsorption capacity, adsorption isotherm, bioremediation, buffer, atomic absorption spectroscopy, Beer's law, calibration, UV–Vis spectroscopy, heavy metals, linear regression both at the beginning and end of the course. The results are shown in Figure 2.8. As many of the freshmen students had advanced chemistry in high school, they felt that they were very familiar with buffers, but not with other concepts such as biosorbents and bioremediation. A Likert scale of 1–5 was used with 1 = very uncomfortable and little knowledge to 5 = very comfortable and knowledgeable. The increase in Likert score is consistent with the hours spent in class on particular topics; for example, only 2 h were spent on adsorption isotherms while several labs focused on biosorbents.

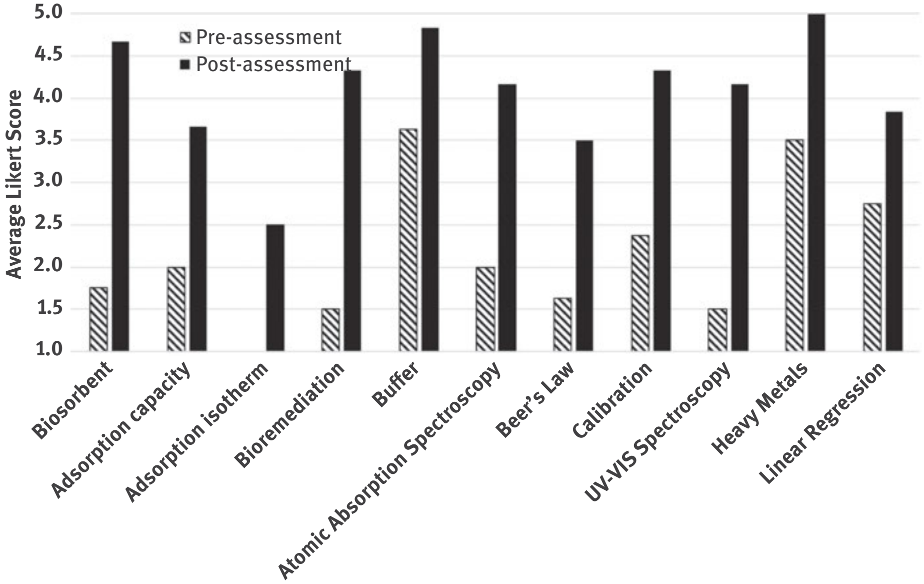


Figure 2.8: Student self-assessment of concept comfort at beginning and end of course. Light crosshatch at the beginning of the course and solid fill at the end of the course.

A fourth instrument probed students' self-assessment of their comfort level at the beginning and end of the course. Many of these skills and tasks were involved with their student research during the course. Students were asked how comfortable they were performing different laboratory tasks and on a scale from 0 to 100, where 0 was "I don't know what that task is or I could not perform the task" – to 100 "corresponding complete confidence in performing the task." As shown in Figure 2.9, the overall average pre-assessment score of comfort level was 52 %, while the post-assessment shows a self-assessed comfort level of 89 % across the skills or tasks listed.

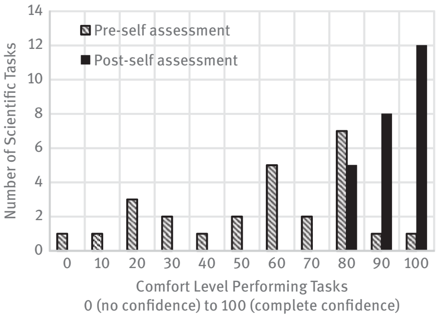
Finally, while the previous assessments were student self-evaluations, a fifth assessment measures their actual knowledge level. Figure 2.10 shows scores of an exam where students solved problems relevant to the topics covered in the course with mean scores increasing from 34 % to 60 %.

2.7 Conclusions: green chemistry in the laboratory

The drive to incorporate green chemistry and sustainable engineering concepts into the classroom and undergraduate laboratory is paramount to training the next generation of scientists and engineers. We must incorporate fundamental concepts and theory, integrated into such Green activities, to insure students are trained for the future workforce. The laboratory experiment detailed in this chapter was designed as a Freshman Chemistry activity broadly designed to:

Skills or Tasks for Self Assessment
Balance a chemical reaction
Find safety information about a chemical
Write a lab report in the proper format
Analyze a sample using X-ray Fluorecence
Draw a Lewis Structure
Identify a limiting reagent
Calculate an empirical formula
Calculate % Theoretical Yield
Summarize a scientific paper from a Journal
Use a Mass Spectrometer to analyze an unknown
Perform a scientific literature search
Use a Gas Chromatograph
Conceive, execute, and implement a research project
Identify the intermolecular forces between oxygen and water molecules
Identify a redox reaction
Figure out how to make a dilute solution from a concentrated stock solution
Generate a calibration curve
Evaluate the quality of data generated in an experiment
Prepare an effective Presentation Poster
Perform a titration
Evaluate the quality of research reported in a presentation or journal
Use a UV-VIS spectrophotometer
Perform a linear regression
Use High Performance Liquid Chromatography to analyze a mixture
Explain colligative properties to a non-science major
Describe the difference between pseudo science and real science

(a)



(b)

Figure 2.9: Student self-assessment of comfort level on performing science “tasks” listed. Light crosshatch denotes beginning of the course and solid fill end of the course. (a) Skills/tasks used for self-assessment. (b) Pre- and post-assessments of comfort level on performing task.

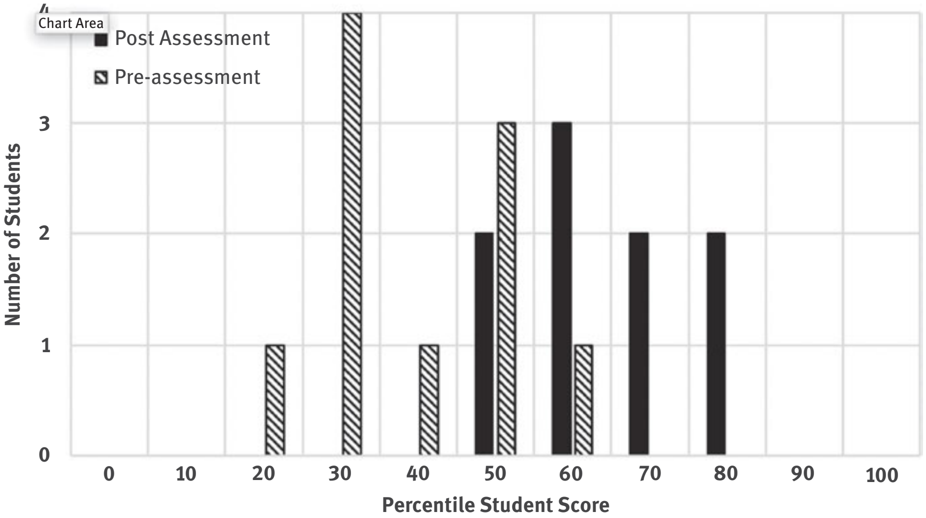


Figure 2.10: Average pre- and post-exam scores on topics listed in Figure 2.9. Light crosshatch at the beginning of the course and solid fill at the end of the course.

- Challenge students to cultivate a knowledge of local environmental issues and sustainable materials to remediate such issues;
- Introduce students to broader concepts of water quality issues both locally and globally.

This was accomplished by having students study the adsorption of metals, especially Mn(II), a persistent local water issue in western MA, to raw and activated *phragmites* stems, an invasive local species. In doing so, students gained knowledge on:

- Adsorption as a separation process, specifically on adsorption equilibria;
- Analytical instrumentation and techniques, including precision weighing and pipetting, generating calibration curves, and using atomic adsorption spectroscopy and UV–Vis spectrophotometry;
- Data analysis in terms of applying two different adsorption isotherm models to a class-collected set of data, evaluating raw “fit” to data and interpreting the meaning of this fit to the theory behind the isotherm.

While this experiment used an invasive species biomass that plagues our local ecosystem as the sorbent material, students (especially in upper levels) could be encouraged to perform a literature survey on what biomasses make “good” adsorbents and choose their own biomass and/or activation techniques in a hypothesis-driven investigation. Instructors are encouraged to investigate local water quality issues to make the adsorbate relevant to their communities, in order to increase student engagement.

Acknowledgements: The authors thank R. Jayne for assistance with SEM images. The authors gratefully acknowledge the Summer Undergraduate Research Program at Simmons and the Simmons College Department of Chemistry and Physics, as well as the contributions of sophomores B. Boschetti and E. Robinson, and the entire CHEM 115 freshman class. A portion of this material is based upon work supported by the National Science Foundation under Grant No. NSF CMMI Award 1727316.

References

[1] Klare MT. Resource wars: the new landscape of global conflict. New York, NY: Henry Holt and Company, LLC, 2001.
[2] Meffe R, De Bustamante I. Emerging organic contaminants in surface water and groundwater: a first overview of the situation in Italy. Sci Total Environ. 2014;181:280–95.
[3] Snyder SA, Adham S, Redding AM, Cannon FS, DeCarolis J, Oppenheimer J, et al. Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. Desalination. 2007;202:156–81.
[4] Sorlini S, Rondi L, Gomez AP, Collivignarelli C. Appropriate technologies for drinking water treatment in Mediterranean countries. Environ Eng Manag J. 2015;14:1721–33.

[5] Sly LI, Hodgkinson MC, Arunpairojana V. Deposition of manganese in a drinking water distribution system. Appl Environ Microbiol. 1990;56: 628–39. DOI: aem00068-0054.

[6] Downs TJTJ. Making sustainable development operational: integrated capacity building for the water supply and sanitation sector in Mexico. J Environ Plann Manag. 2001;44:525–44. DOI: 10.1080/09640560120060948.

[7] Goldfarb JL, Buessing L, Gunn E, Lever M, Billias A, Casoliba E, et al. Novel integrated biorefinery for olive mill waste management: utilization of secondary waste for water treatment. ACS Sustain Chem Eng. 2017;5:876–84. DOI: 10.1021/acssuschemeng.6b02202.

[8] Tan X, Liu S, Liu Y, Gu Y, Zeng G, Hu X, et al. Biochar as potential sustainable precursors for activated carbon production: multiple applications in environmental protection and energy storage. Bioresour Technol. 2017;227:359–72. DOI: 10.1016/j.biortech.2016.12.083.

[9] Bhatnagar A, Sillanpää M. Applications of chitin- and chitosan-derivatives for the detoxification of water and wastewater – a short review. Adv Colloid Interface Sci Elsevier. 2009;152:26–38. November 30.

[10] Davila-Rodriguez JL, Escobar-Barrios VA, Shirai K, Rangel-Mendez JR. Synthesis of a chitin-based biocomposite for water treatment: optimization for fluoride removal. J Fluor Chem. 2009;130:718–26. DOI: 10.1016/j.jfluchem.2009.05.012.

[11] Sağ Y, Aktay Y. Kinetic studies on sorption of Cr(VI) and Cu(II) ions by chitin, chitosan and *Rhizopus arrhizus*. Biochem Eng J. 2002;12:143–53. DOI: 10.1016/S1369-703X(02)00068-2.

[12] Hameed BH, Mahmoud DK, Ahmad AL. Equilibrium modeling and kinetic studies on the adsorption of basic dye by a low-cost adsorbent: coconut (*Cocos nucifera*) bunch waste. J Hazard Mater. 2008;158:65–72. DOI: 10.1016/j.jhazmat.2008.01.034.

[13] Pehlivan E, Altun T, Cetin S, Iqbal Bhanger M. Lead sorption by waste biomass of hazelnut and almond shell. J Hazard Mater. 2009;167:1203–8. DOI: 10.1016/j.jhazmat.2009.01.126.

[14] Hoseinzadeh E, Samarghandi M-R, McKay G, Rahimi N, Jafari J. Removal of acid dyes from aqueous solution using potato peel waste biomass: a kinetic and equilibrium study. Desalination and Water Treat. 2014;52:4999–5006. DOI: 10.1080/19443994.2013.810355.

[15] Gallardo B, Clavero M, Sánchez MI, Vilà M. Global ecological impacts of invasive species in aquatic ecosystems. Glob Chang Biol. 2016;22:151–63. January 1.

[16] Rhodes AL, Guswa AJ. Storage and release of road-salt contamination from a calcareous lake-basin fen, Western Massachusetts, USA. Sci Total Environ. 2016;545–546:525–45. DOI: 10.1016/j.scitotenv.2015.12.060.

[17] Soana E, Gavioli A, Tamburini E, Fano EA, Castaldelli G. Porogen effect on characteristics of banana pith carbon and the sorption of dichlorophenols. Ecol Eng. 2018;113:1–10. DOI: 10.1016/j.ecoleng.2017.12.029.

[18] Claus Henn B, Ettinger AS, Schwartz J, Téllez-Rojo MM, Lamadrid-Figueroa H, Hernández-Avila M, et al. Early postnatal blood manganese levels and children's neurodevelopment. Epidemiology. 2010;21:433–9. DOI: 10.1097/EDE.0b013e3181df8e52.

[19] Henn BC, Schnaas L, Ettinger AS, Schwartz J, Lamadrid-Figueroa H, Hernández-Avila M, et al. Associations of early childhood manganese and lead coexposure with neurodevelopment. Environ Health Perspect. 2012;120:126–31. DOI: 10.1289/ehp.1003300.

[20] Wirbisky SE, Damayanti NP, Mahapatra CT, Sepúlveda MS, Irudayaraj J, Freeman JL. Mitochondrial dysfunction, disruption of F-actin polymerization, and transcriptomic alterations in zebrafish larvae exposed to trichloroethylene. Chem Res Toxicol. 2016;29:169–79. DOI: 10.1021/acs.chemrestox.5b00402.

[21] Lash LH, Chiu WA, Guyton KZ, Rusyn I. Trichloroethylene biotransformation and its role in mutagenicity, carcinogenicity and target organ toxicity. Mutat Res Rev Mutat Res. 2014;762:22–36.

[22] Sud P, Nelson LS, Fleming E, Fennell SL. Assessment of serum S100B and neuron specific enolase levels to evaluate the neurotoxic effects of organic solvent exposure. Clin Toxicol. 2013;51:1244. DOI: 10.3109/15563650.2013.851388.

[23] Ho YS, Porter JF, Mckay G. Equilibrium isotherm studies for the sorption of divalent metal ions onto peat: copper, nickel and lead single component systems. Water Air Soil Pollut. 2002;141:1–33.

[24] Foo KY, Hameed BH. Insights into the modeling of adsorption isotherm systems. Chem Eng J. 2010;156:2–10. DOI: 10.1016/j.cej.2009.09.013.

[25] Weber TW, Chakravorti RK. Pore and solid diffusion models for fixed-bed adsorbers. AIChE J. 1974;20:228–38. DOI: 10.1002/aic.690200204.

[26] Istan S, Ceylan S, Topcu Y, Hintz C, Tefft J, Chellappa T, et al. Product quality optimization in an integrated biorefinery: conversion of pistachio nutshell biomass to biofuels and activated biochars via pyrolysis. Energy Conversion Manage. 2016;127:576–88. DOI: 10.1016/j.enconman.2016.09.031.

[27] Areco MM, Dos Santos Afonso M, Valdman E. Zinc biosorption by seaweed illustrated by the zincon colorimetric method and the Langmuir isotherm. J Chem Educ. 2007;84:302. DOI: 10.1021/ed084p302.

[28] Tay T, Ucar S, Karagöz S. Preparation and characterization of activated carbon from waste biomass. J Hazard Mater. 2009;165:481–5. DOI: 10.1016/j.jhazmat.2008.10.011.

[29] Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, et al. Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere. 99;2014:19–33.

[30] Bailey Susan E., Olin Trudy J., Bricka R.Mark, Adrian D.Dean, et al. A review of potentially low-cost sorbents for heavy metals. Water Research. 1999 8;33:2469–79. DOI: 10.1016/S0043-1354(98)00475-8.

[31] Demirbas A. Heavy metal adsorption onto agro-based waste materials: a review. J Hazardous Mater. 157;2008:220–9.

[32] Goldfarb JL, et al. Novel integrated biorefinery for olive mill waste management: utilization of secondary waste for water treatment. ACS Sustainable Chem Eng. 5;2016:876–84.

[33] Dąbrowski A. Adsorption – from theory to practice. Adv Colloid Interface Sci. 93;2001:135–224.

[34] Foo KY, Hameed BH. Insights into the modeling of adsorption isotherm systems. Chem Eng J. 156;2010:2–10.

[35] Ho YS, Porter JF, McKay G. Equilibrium isotherm studies for the sorption of divalent metal ions onto peat: copper, nickel and lead single component systems. Water Air Soil Pollution. 141;2002:1–33.

[36] Pérez-Marín AB, et al. Removal of cadmium from aqueous solutions by adsorption onto orange waste. J Hazardous Mater. 139;2007:122–31.

S. Iraj Sadraei, Brent St Onge and John F. Trant

3 Recent advances in the application of carbohydrates as renewable feedstocks for the synthesis of nitrogen-containing compounds

Abstract: Carbohydrates, in the form of chitin, chitosan and cellulose, are one of the most available, renewable, and sustainable chemical feedstocks. Their conversion to biofuels, fine chemicals, and industrially-relevant monomers is becoming increasingly viable and promising as innovation decreases the price of this technology, and climate change and the price of fossil fuels increases the social and economic costs of using traditional feedstocks. In recent years, carbohydrates have been increasingly used as sources for nitrogen-containing fine chemicals. This chapter, with 86 references, provides a brief overview of the conversion of carbohydrate biomass to the standard hydrocarbon and oxygen-containing derivatives, and then provides a survey of recent progress in converting the biopolymers, and the derived mono and disaccharides, into nitrogen-containing molecules with a special focus on N-heterocycle synthesis for medicinal applications.

Keywords: chitin, biomass, heterocycles, sustainable chemistry, cellulose, chitosan

3.1 Introduction

As the concurrence of concerns regarding climate change, and the inevitable knowledge that over the coming decades the price of oil will increase, due to a combination of scarcity and decreased reliance on it as an energy source, driving up the costs of fine chemicals, there is a growing interest in accessing complex materials, feedstocks and polymers from renewable resources [1–4]. One of the most promising potential sources are the polysaccharides, cellulose, chitosan and chitin. These form the predominant bulk mass of the material obtained from agricultural and fisheries waste products, and would make excellent sources of complex oxygenated materials for the future of the chemical and polymer industries [5–7], and even as catalysts [8]. Research and manufacturing in this field has been ongoing for many years [9], and there are many excellent recent reviews of the subject [10–16]. The primary intermediates generated from these waste polysaccharides are levulinic acid (LA) and 5-Hydroxymethylfurfural (HMF, Figure 3.1) derived from heating lignocellulose (a

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Iraj Sadraei, S., St Onge, B., Trant, J. F. Recent Advances in the Application of Carbohydrates as Renewable Feedstocks for the Synthesis of Nitrogen-Containing Compounds. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0074

https://doi.org/10.1515/9783110566499-003

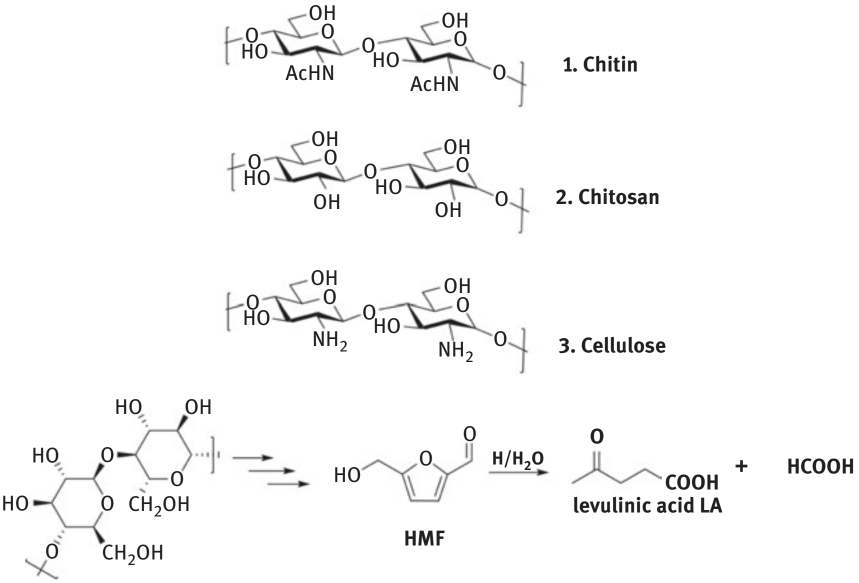


Figure 3.1: Structures of the three predominant sources of carbohydrate biomass: chitin, chitosan, and cellulose, and the primary degradation products obtained from these polysaccharides HMF and LA.

complex mixture of cellulose and lignins obtained from the waste biomass of crops and trees) in acid [17]. Sequential dehydrations lead to the formation of the thermodynamically preferred HMF that can then be further oxidized and degraded to a combination of formic acid and LA.

This current chapter seeks to describe recent advances in this field, with a particular focus on nitrogenous compounds derived from carbohydrates. It is divided into several sections: this introduction; a very brief overview of the chemistry of carbohydrate conversion to LA and HMF; a discussion of some recent work derivatizing HMF into complex natural-products; a discussion around the elaboration of HMF with nitrogen-containing functionalities; a review of the synthesis of nitrogen-containing heterocycles with HMF functionalities; and a review of the preparation of nitrogen containing heterocycles from HMF.

3.2 Levulinic acid and derivatives

LA is the end-product of the acidic digestion of the carbohydrate feedstocks. It has been extensively examined as a potential starting material for the preparation of biofuels, and other materials [18]. This has been an extensively reviewed class of transformations, and there are numerable excellent studies investigating particular aspects or products that can be accessed from this important material

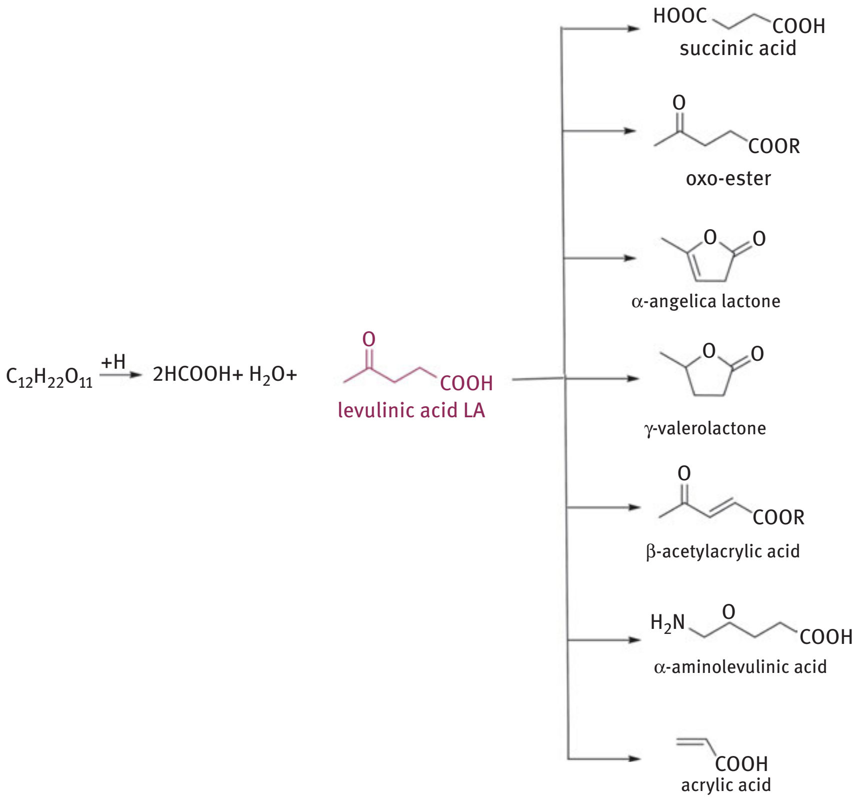


Figure 3.2: Possible products derived from levulinic acid.

including β-acetylacrylic acid, succinic and acrylic acid, acetic acid [19, 20], and γ-valerolactone [21], (Figure 3.2).

A recent advance in the field was provided by Mika and Dibó, who demonstrated that polysaccharides, both cellulose and chitin, could be readily converted to LA under microwave irradiation, accelerating the transformation.[22] Estimates indicate that innovation could drive the production costs as low as 0.08–0.20 USD per kg of LA [23]. The flexibility and ease of synthesis of this material shows great promise, especially as it can access the incredibly important acrylic acid monomer [24]. There is also significant discussion about using LA and other cellulosic derivatives as a route into biofuels [25]. However, the deoxygenation and defunctionalization of LA is not economically ideal due to the loss of the complex oxygenated functionalities. Additionally, it is not currently a particularly energy efficient process, although this could evolve over coming decades as oil prices increase and biomass conversion improves [26, 27]. Thus, the potential for LA to provide access to other heteroatom-containing systems [28] such as maleic anhydride through oxidation using vanadium-based catalysts [29], and the nitrogenous systems described below, might prove a more fruitful use for this material, especially as bio-oil becomes increasingly viable [30].

3.3 Complex derivatives from HMF

3.3.1 HMF overview

5-(Hydroxymethyl)furfural (5-HMF, **6**) is commonly synthesized from chitosan *via* its monomer *N*-acetyl-2-deoxy-2-amino-D-glucose (GlcNAc), prepared from hydrolyzing chitosan with strong acid, often nitric acid with dimethyl sulfoxide (DMSO) as solvent. There have also been other reports using different organic acids in the presence of DMSO for the synthesis of 5-HMF. Significant effort has been dedicated to identifying more efficient routes to HMF, especially through the dehydration of carbohydrates [31–34]; however most suffer from low yields. The major complication is the complex thermodynamics of this system which leads to the generation of a variety of by-products, including the humins [35], as well as a mixture of various oligomers and polymers that can foul the reaction vessel making the transformation complicated to perform on an industrial scale. A better understanding of the pathways and energetics involved could provide important information about the preferred biofeedstocks or the nature of any required pre-treatment. Horvath and coworkers have extensively investigated these issues, especially through careful characterization of the by-products [36]. Much of this science revolves around the formation of fructose, a necessary intermediate in most of the conventional approaches to convert glucose to HMF, involving **1b** and **1c** [37, 38].

3.3.2 Mechanism of formation of HMF

The acid-catalysed elimination of water from the furanose form of fructose, providing fructosyl oxocarbenium ion **2**, is the preferred thermodynamic pathway, Figure 3.3. This oxocarbenium is highly sensitive to anhydro-sugar formation, and the C-6 hydroxyl group can attack intramolecularly, to provide bicyclic **3**. The same oxocarbenium is also highly susceptible to dimerization to form di-D-fructose dianhydrides (DFA) which are reversibly generated. Both pathways can isomerize the furan ring to the pyran. Productively, oxocarbenium **2** can be resolved through α-deprotonation to generate enol ether **4**. Under acidic conditions, this rapidly equilibrates to the enal **5**, which rapidly dehydrates to generate the aromatic HMF *via* dehydration. In the pyran series, oxocarbenium **7** can follow similar chemistry through **8** to **9**. With an inability to collapse to a low energy aromatic structure, this material generally decomposes to the highly-branched polymeric humin polymers. Curiously the balance of these intermediates fluctuates significantly as the reaction proceeds: in early stages, and in concentrated reaction mixtures, the oxocarbeniums appear to be sequestered as

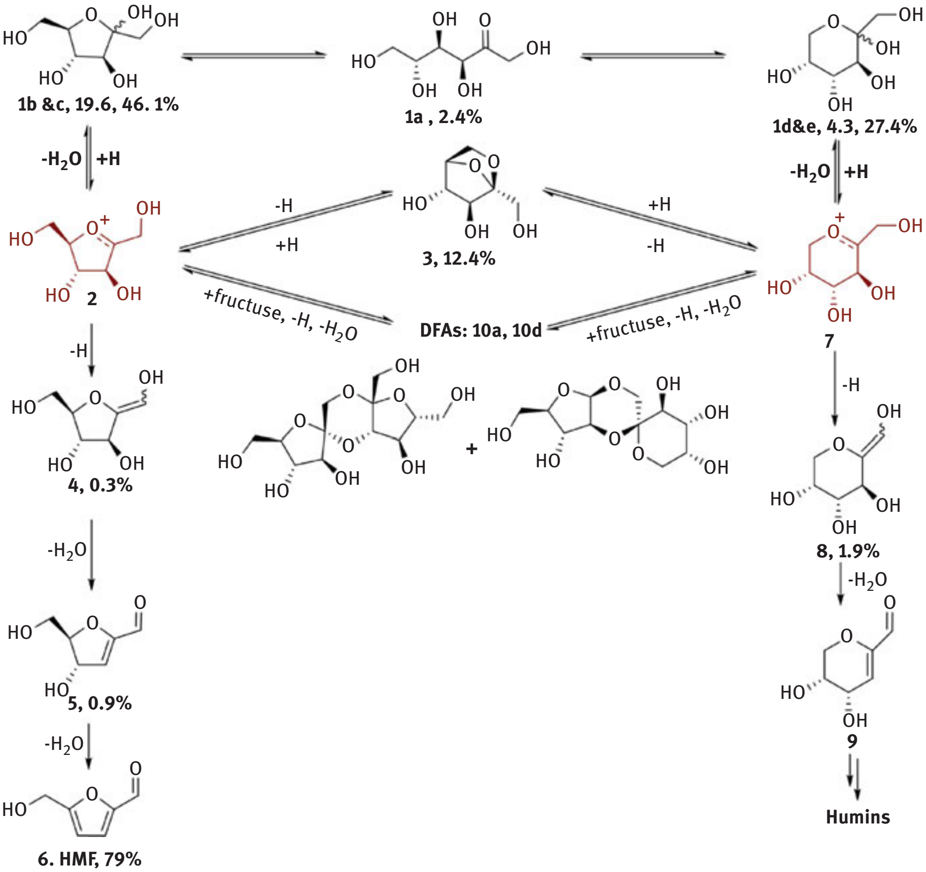


Figure 3.3: Formation of HMF and by-products acid catalysed dehydration processes.

complex **3**, and over time this is consumed through its downhill transformation to HMF or humins. However, as the concentration of water increases, the material primarily returns to resting as either furanosyl sugar **1b** or **1c**, and the solution concentration of both **3** and **4** drops. They determined that the rate-limiting step of this entire mechanism if the tautomerization of oxocarbenium **2** to **3**. Consequently, adjusting the concentration of the reaction mixture has little impact on the yield or reaction rate as has been noted experimentally. There appears to be a theoretical maximum to the yields when using protic solvents.

3.3.3 Alternative routes to HMF

Alternatively, gentler conditions can be used: Kerton reported the generation of levulinic acid (4-oxopentanoic acid, LA) and 5-hydroxymethylfurfural (5-HMF) *via*

Lewis acid catalysed hydrolysis of Chitosan under microwave conditions with $SnCl_4 \times 5H_2O$ [39]. This approach provided higher yields than traditional protic acid chemistry, providing 23.9 wt% LA and 10.0 wt% HMF when run under concentrated or dilute conditions, respectively. The proposed mechanism (Figure 3.4) involves the chelation of the Lewis acid to the C2-amine, which in turn weakens the glycosidic bond. This makes the system more sensitive to hydroxide attack at the anomeric position, hydrolysing the polymer. Elimination of the C3-hydroxyl generates the enal (**13**) which can tautomerize to the imine (**14**) and hydrolyse to the 1,2-dicarbonyl species, **15**. Kinetic cyclization to **16**, followed by double elimination generates the 5-HMF (**6**).

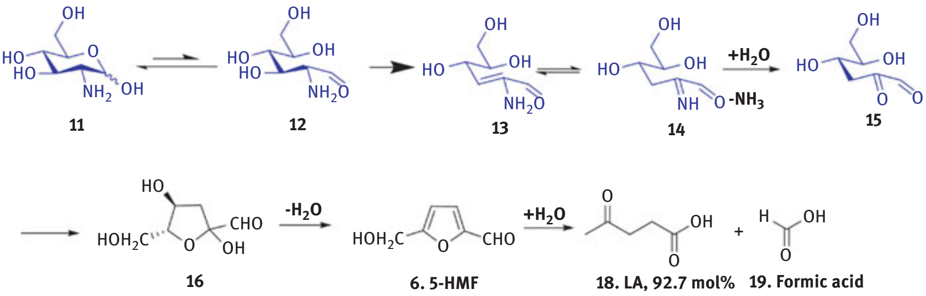


Figure 3.4: Synthesis of levulinic acid through formation of 5-HMF from glucosamine **11**.

Other catalytic processes are also showing significant progress, as are engineering controls. Chemoenzymatic approaches that combine primary processing in a bioreactor with HMF-formation in traditional chemistry processes also show promise [40]. Consequently, it seems likely that alternatives to the protic acid process will become highly viable industrial processes allowing for the generation of large amounts of HMF for further derivatization. HMF can readily used for derivatization to LA (**18**), and can also act as a source for other simple structures through simple treatment: for example, 5-(chloromethyl) furfural can be prepared from HMF in the presence of HCl [41]. However, most efforts have focused on hydrocarbons or carbon-oxygen species. The core furan ring, however, provides significant opportunities for elaboration with nitrogen to access biomedically-relevant materials, and this progress is the focus of the remainder of this review.

3.4 Amine-substituted derivatives of HMF

3.4.1 Ionic liquids as mild reagents

The furan core provides a useful pharmaceutical pharmacophore [42, 43], and the presence of the C-2 amine on chitosan and chitin allows for ready access of 3-amino substituted furans if it can be retained during the hydrolysis. One way to do this is to use more gentle conditions. Ionic liquids are non-flammable, non-volatile, and reusable materials [44]. They are generally considered as “green solvents” due to their easy recyclability, and have seen increasing use in carbohydrate chemistry as their polarity provides an attractive alternative to the often incompatible water [45, 46]. Previously, research on the generation of “renewable” amines has been done through the use of ammonia as the nitrogen source [47]. The work presented by Kerton [48] was the first reported using *N*-acetyl-2-deoxy-2-amino-D-glucose (NAG) as a source of nitrogen in the nitrogen-containing furan derivatives. They reported the direct conversion of NAG (**20**) to 3-acetamido-5-acetylfuran **22** (3A5AF) in a reasonable yield of 25.5% (Figure 3.5) *via* an ionic liquid-solution phase approach. 3-acetamido-5-acetylfuran has been previously identified as part of the complex mixture obtained from the thermal degradation of NAG, but only in a 2% yield [49, 50].

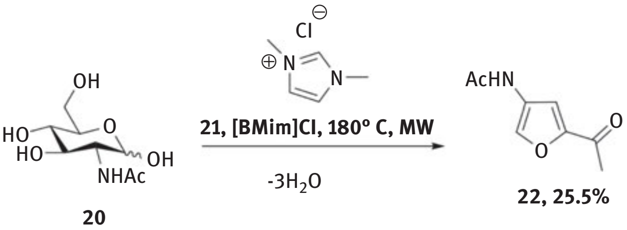


Figure 3.5: Direct conversion of NAG to 3-acetamido-5-acetylfuran.

In their initial attempt, NAG and ionic liquids were mixed and heated under microwave conditions with quantitative reaction monitoring using calibrated liquid chromatography-mass spectrometry (LC-MS) analysis. The dehydration was followed at 120°C in six different ionic liquids including 1-ethyl-3-methylimidazolium bromide ([EMim]Br) and acetate ([EMim]OAc); 1-butyl-3-methylimidazolium chloride ([BMim]Cl), bromide ([BMim]Br), and acetate ([BMim]OAc); and 1,2-dimethyl-3-butylimidazolium chloride [BMMim]Cl (**21**). The reactions were investigated with various hydrocarbon and anionic additives. The results indicated that the best conditions of those screened treated NAG in [BMim]Cl at 120°C for 3 min in the microwave to provide a 14.1% yield of 3A5AF; however, when the temperature was increased to 180°C, the product was obtained in a 25.5% yield. With preferred temperature and ionic liquid identified, the nature of the additives was investigated. The addition of a small amount of water, often critical for biomass transformations, showed only a minimal change in the observed yield (28.7%). During the reactions, a minor impurity had been detected and identified as 1-methylimidazole, which could be isolated in the organic phase following work-up. This material was proposed to result from the partial thermal decomposition of the ionic liquids. Addition of 1-methylimidazole to the reaction however reduced efficiency significantly, and only a 2.9% yield of 3A5AF could be isolated. The study concluded that using more inert reaction conditions would improve the yield as they suspected that the presence of the ionic liquids catalyses the decomposition of the final products.

The proposed mechanism justifies the difference between this and the other approaches described above. Under aqueous acid and the high temperatures employed, the NHAc group is hydrolysed and the resulting amine undergoes the elimination sequence described above in Figure 3.3. Under dryer conditions, this sequence is unlikely. Hydrogen-bonding between the imidazolium ring and the carbohydrate favours the open chain form **23** to a much greater extent than in water (Figure 3.6). The ionic liquid disturbs the usual equilibria of the hexoses, and a significant amount of the furanose form **24** can be generated. Elimination of the C-6 hydroxyl provides enol **25**, and this readily tautomerizes to the ketone form **26**. Two eliminations, favourable in the low-water environment (presumably first of the C-3 hydroxyl to set-up the enone, and rapidly thereafter of the anomeric hydroxyl group to generate the aromatic furan) provide the N-acetylated product **22**. Although NAG is the monomeric unit of chitin, breaking the polymer down into the parent monosaccharide is challenging and the same conditions are not necessarily amenable to a direct conversion of the bio-feedstock chitin to a furan derivative. Building upon this success Kerton and Yan, in 2014, reported the first direct efficient conversion of chitin into this same N-containing furan derivative (3A5AF) [51].

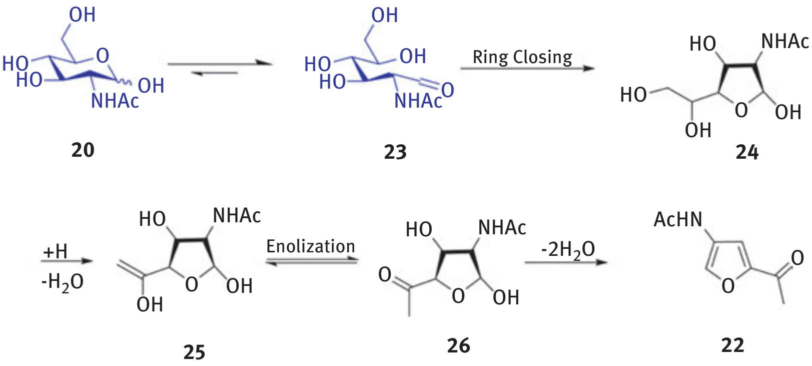


Figure 3.6: The proposed mechanism of formation of 3A5AF (**22**).

3.4.2 High boiling point solvents for thermal conversion of chitin to N-Acetyl furans

Heterocyclic compounds such as pyrroles, pyrazines, furans, and pyridines (Pyr) have been obtained by the pyrolysis or radiolysis of chitin, and chitosan to generate volatile aromatics, but these approaches are extremely energy inefficient, very low yielding, and provide a complex mixture of products. Additionally, many of the materials lose their nitrogen-content during the transformation [52, 53]. The added challenges in working with chitin itself instead of the monomer to produce 3A5AF (**22**) include controlling the degradation of the chitin, avoiding denitration that can readily occur in aqueous acid, and physically breaking up the polymer aggregates that render chitin such a highly insoluble material. Thermal decomposition in the presence of ionic liquids had clearly proven practicable for the conversion of the monomer, and consequently high boiling point solvents were investigated including ethylene glycol (EG) and glycerol (Gly), which are well suited to disturb the inter- and intra-chain hydrogen bonding network present in the biopolymer. These solvents were coupled with the usual polar aprotic solvents to remove the water formed during the conversion process, as water clearly could lead to denitration. However, no product was observed under any of the examined reaction conditions at 215°C in the presence of lithium chloride as a Lewis acid. Other additives, such as HCl or boric acid did result in the formation of low yields of 3A5AF, but the presence of protic solvents, either EG or Gly completely suppressed product formation. N-methyl-2-pyrrolidone (NMP) proved to be the best solvent, and 215°C provided higher yields than either lower or higher temperatures. Alternative additives were screened, including heteropolyacids, metal chlorides, various bases, and organic and inorganic acids. Most bases, the heteropolyacids, and the organic acids completely inhibited product formation, while metal chlorides afforded the N-acetylated furan in a low yield. Boric acid proved to be the most effective additive for the reaction, providing 3A5AF in a very modest yield of 3.6%. The challenge with the system is the incompatible requirements of the various steps (Figure 3.6). Chitin hydrolysis requires water and the ability to solubilize the chitin chains, breaking up the aggregates formed by the very strong hydrogen bonds; while NAG conversion requires mildly Lewis Acidic conditions, and the absence of water to drive the reaction forward and avoid the elimination or hydrolysis of the NAG group. The best results were obtained by using either $CrCl_3$, LiCl, NaCl or $CaCl_2$ in combination with boronic acid; and further improvement was attained using dry HCl. Adding water was also examined: it would certainly accelerate the hydrolysis of chitin; however, it would reduce the rate of dehydration and decrease the solubility of chitin in the solvent. Water showed only an adverse effect on the yield through reducing the conversion of starting material: clearly the solubility of the chitin plays a leading role in determining the pattern of this reactivity. Gas chromatography–mass spectrometry (GC-MS) analysis was used throughout to identify the by-products formed in this complex mixture including 4-(acetylamino)-1,3-benzenediol (**30**), levoglucosenone (**36**), and acetic acid. The research team also identified nitrogen in the inevitable black solid, a chitin-derived analogue of the humins. A mechanistic pathway is proposed to explain these outcomes and to demonstrate the complexity of the competing reactions. Arising from this analysis, and disregarding the complex possibilities involving polymeric chitin, or higher order oligomers, three main sequences define the fate of the NAG under these conditions (Figure 3.7). The first pathway involves the route described above: a formation of the furanose, followed by enolization, and

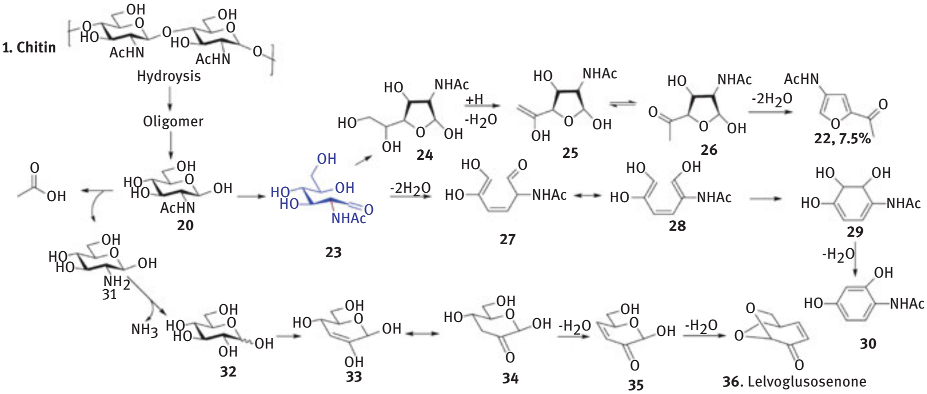


Figure 3.7: Proposed mechanistic pathways leading to the synthesis of levoglucosenone, 3A5AF, and 4-(acetylamino)1,3-benzenediol.

aromatization to provide the desired product. In the second pathway, a proposed diene is generated through the double dehydration of NAG; keto–enol tautomerism provides the hexatriene that would undergo a rapid electrolytic rearrangement, which followed by dehydration, would generate the amide-substituted resorcinol. In the final pathway, acetic acid is first produced by hydrolysis of the amide; a sequence of eliminations and tautomerizations leads to **36**.

3.5 Nitrogenous heterocycles from sugars

3.5.1 Elaboration of a nitrogen heterocycle

3.5.1.1 Synthesis of imidazoles

Although these routes retain the nitrogen of the chitin, more interesting products can arise through interrupting the degrading carbohydrates with a trapping moiety to generate pharmaceutically relevant materials. The synthesis of glycoconjugates with medicinal activity is a very broad subject but using carbohydrates as a source of polyhydroxylated chiral side chains rather than as carbohydrates *per se* is a promising avenue to access new chemical space.

This can allow for the *in situ* generation of highly complex decorated heterocycles, including many involving nitrogen. Some of the earliest of this work was done by Streith, attempting to provide a rapid, protecting-group-free access of glycosylated bioactive imidazole derivatives [54]. In a recent iteration of this approach [55], Brust and co-workers reported a procedure to obtain disubstituted imidazoles with elaborate poly-hydroxylated side-chains derived from mono- and disaccharides using a high pressure *de novo* heterocycle synthesis employing D-fructose or D-glucose, ammonium carbonate and formamidine acetate, or higher order derivatives, as the source of the imidazole nitrogens.

Several different amidines were used as the nitrogen source to generate a small library of 2-substituted imidazole derivatives using ammonium carbonate as acid. The very mild reaction conditions enable this methodology to be readily adapted using different mono- or di-saccharides (and presumably higher order systems as well) to obtain a variety of different products. The combination of formamidine acetate, ammonium carbonate, and carbohydrates (5:1.6:1) forms a low viscosity melt above 60°C allowing for easy agitation. Presumably the ammonium carbonate decomposes *in situ* to generate ammonia, water, and carbon dioxide, providing a very convenient high concentration ammonia solution. Mechanistically, the carbonyl moiety of the carbohydrate condenses with the amidines (derived from the aminolysis of imido esters or their salts by ammonia, Figure 3.8), and undergoes an Amadori rearrangement [56], to provide ketone **40**, which condenses with the remaining primary amine to provide the imidazole after aromatization in 50% yield.

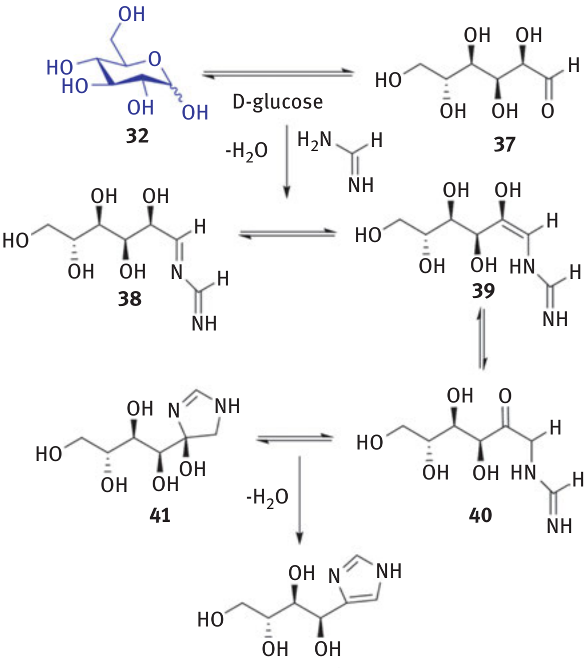


Figure 3.8: Proposed mechanism of imidazole (**42**).

In this same report, the team investigated large scale synthesis of hydrophilic tetrahydroxybutyl imidazoles with different glycosidic linkages from available disaccharides: melibiose, leucrose, maltose, cellobiose, lactose, lactulose, and isomaltulose, most of the readily available disaccharides Figure 3.9. Maltose, cellobiose, lactose, isomaltulose and lactulose are bulk-scale, readily available, and sustainably isolated [9]. They

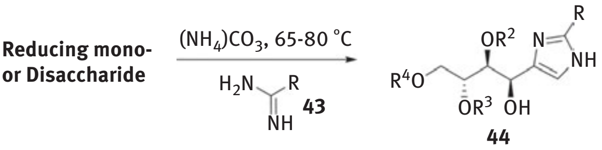


Figure 3.9: Condensation of carbohydrates with amidines in an ammonium carbonate melt.

generated the 2-substituted imidazoles in a one pot procedure, using ethylacetimidate, formamidine acetate, and benzylamidine hydrochloride to introduce a 2-phenyl or 2-methyl moiety into the imidazole. They used the reducing-end ketose, isomaltulose (α-D-Glcp-(1→6)-D-Fruf), as their test case to investigate its applicability to the reaction, and the stability of the glycosidic linkage towards their reaction conditions. The results indicated successful conversion of starting materials to the products, but the amidines are not highly tolerant of substitution, and the yield decreased for both the methyl, and especially the phenyl substituted products. This was attributed to the higher degree of hydrolytic instability of the substituted amidines under the ammonium carbonate melt conditions, and was consistent with the observation that reactions with benzylamidine produced a significant amount of benzoic acid amide as an isolatable side-product. The highest yields were obtained with isomaltulose (49%) with the other disaccharides showing lower conversions (25–40%); this is consistent with the observation that the ketose fructose provided a higher conversion to product (50%) than the aldose glucose (47%). This does not appear to be a theoretically-limited yield reaction, as the moderate yields are justified through the loss of this highly polar material on the silica chromatography columns or the generation of polymeric Maillard by-products Table 3.1.

Table 3.1: Conversion of sugars into imidazoles using different amidine sources as shown in Figure 3.9.

Sugar	R	R4	R3	R2	Yield %
Fructose	H[a]	H	H	H	50
Glucose	H	H	H	H	47
Isomaltose	H	α-D-Glc	H	H	49
Isomaltose	Me[b]	α-D-Glc	H	H	30
Isomaltose	Ph[c]	α-D-Glc	H	H	5
Melibiose	H	α-D-Glc	H	H	38
Melibiose	Me	α-D-Glc	H	H	27
Leucrose	H	H	α-D-Glc	H	38
Leucrose	Me	H	α-D-Glc	H	26
Maltose	H	H	H	α-D-Glc	28
Cellobiose	H	H	H	β-D-Glc	25
Lactose	H	H	H	β-D-Gal	40

Amidines applied in this research: (a) Formamidine acetate. (b) Ethylacetimidate. (c) Benzamidine hydrochloride.

3.5.1.2 Synthesis of quinoxolines, triazines, and related heterocycles

In a follow-up report, the research team used 2-aminoanilines in combination with hydrazines to trap the same Amadori rearrangement products into polycyclic heterocycles: the pyrazoloquinoxalines, quinoxalines, and 1,2,4-triazines [57]. Again, the yields are better for the ketoses than the aldoses, and the products are obtained in useful yields (Figure 3.10).

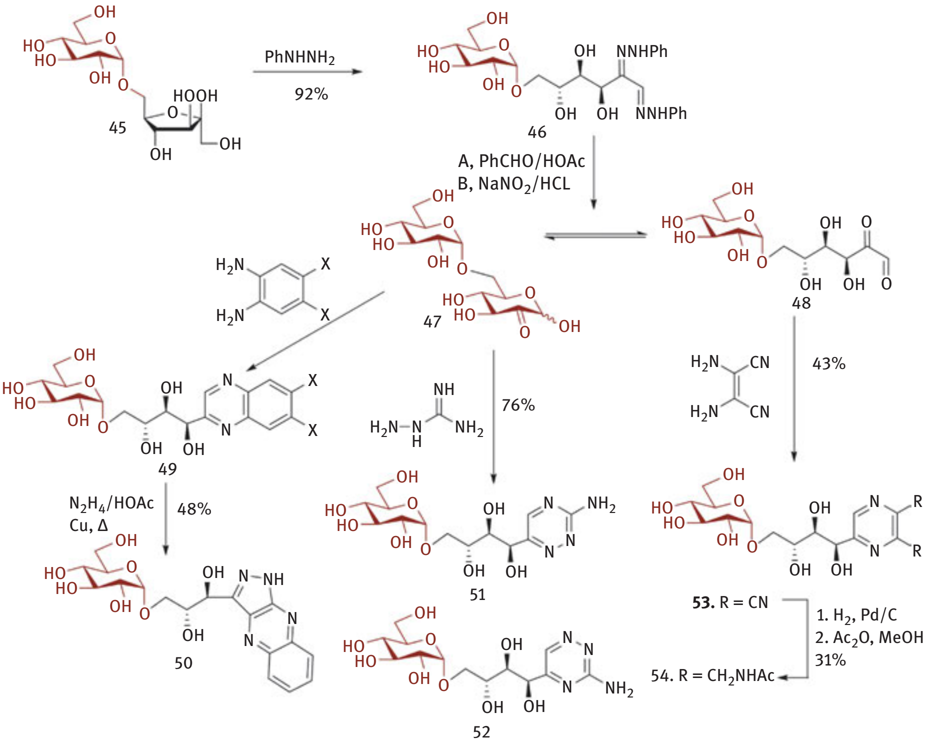


Figure 3.10: Synthesis of polycyclic heterocycles, pyrazoloquinoxalines, quinoxalines, and 1,2,4-triazines.

3.5.1.3 Synthesis of pyrimidine-fused heterocycles

Pyrimidine-fused heterocyclic (PFH) compounds have attracted much attention due to their various biological activities [58, 59] such as antioxidant effects, tyrosine kinase inhibitory activity [60, 61], antimicrobial [62], anticancer [63, 64], antiviral activity [65], and anti-inflammatory properties [66]. Building on this chemistry, Yousefi and Khalafi-Nezhad reported the first synthesis of PFH derivatives, riboflavin analogues, that act as inhibitors of α-Glucosidase (α-Gls) [67]. They synthesized a series of polyhydroxylated pyrimidine-fused heterocycles (PHPFH) incorporating either aliphatic- or aromatic N-substituted systems, and then they investigated their glycosidase inhibitory activities

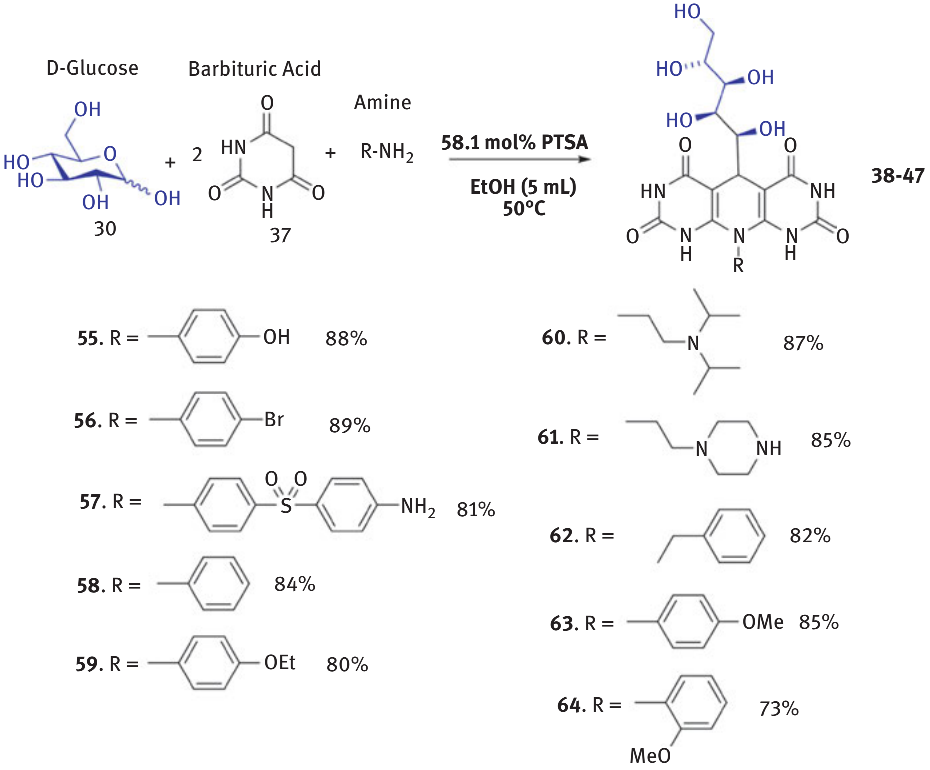
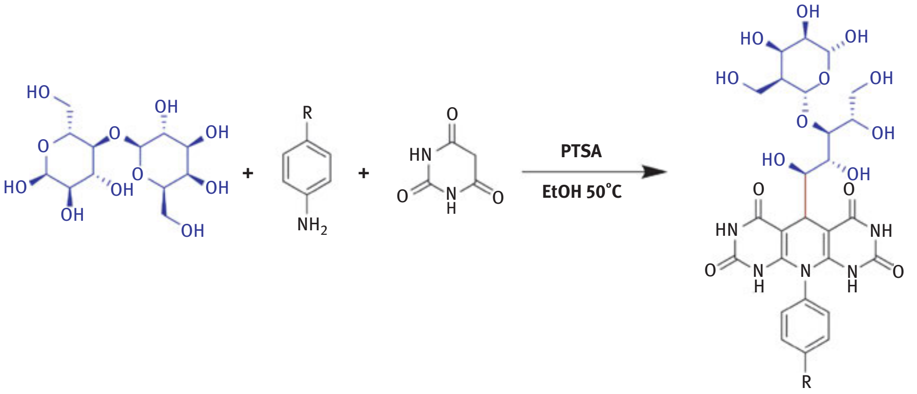


Figure 3.11: Yousefi and Khalafi-Nezhad's synthesis of poly-hydroxy functionalized pyrimidine-fused heterocycles (PHPFHs) using the reaction of D-(+)-glucose, barbituric acid and amines.

(Figure 3.11). This enzyme plays a significant role is the progression of type II diabetes. (+)-D-glucose and primary amines or anilines were treated with barbituric acid and catalytic *p*-toluenesulfonic acid in ethanol to obtain complex tricyclic products in good yield (Figure 3.11). Compounds **55–57, 60, 61** were then screened against both yeast and mouse α-Gls enzymes to determine their inhibitory activity. The aromatic-substituted systems showed stronger inhibitory activity than their aliphatic counterparts with the best performing 4-(4-aminophenylsulfonyl) phenyl **(57)** demonstrating low micromolar non-competitive inhibition with the yeast enzyme, and competitive inhibition against the mouse enzyme, and this difference in activity was ascribed to different binding modes with the two different enzymes.

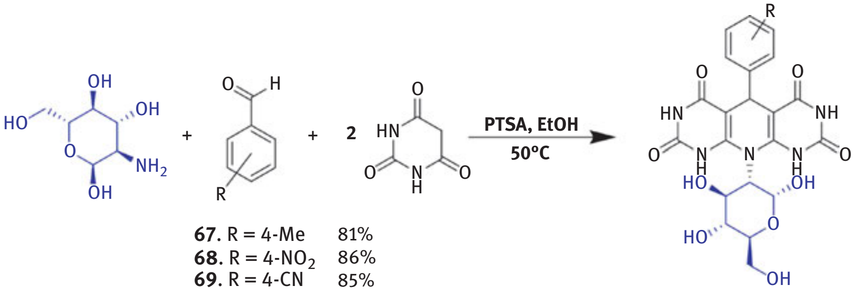
They then extended this research into additional sugars with additional anilines [68]. Electron-rich anilines (**55, 58, 59, 63, 64**) provided better yields of the required tricyclic system, (> 73% for the three component reaction). Glycosidic bonds are stable to the reaction conditions, allowing for functionalization with di-, oligo-, and poly-saccharides (Figure 3.12).



65. R = H 72%
66. R = OMe 75%

Figure 3.12: Coupling of aniline with lactose (Disaccharide).

The reactivity could be inverted by using benzaldehyde derivatives and 2-deoxy-2-amino sugars like glucosamine. Unlike the aniline case above, the nature of the substituent on the benzaldehyde had little effect on the yield of the reaction (**67–72**). This allows for the easy introduction of complex functionality (Figure 3.13). Again, these types of molecules might show promise as vitamin B_2 analogues and competitive inhibitors or chemical biology probes.



67-72

67. R = 4-Me 81%
68. R = 4-NO_2 86%
69. R = 4-CN 85%
70. R = 4-OMe 80%
71. R = 4-SCH_3 81%
72. R = 4-Br 80%

Figure 3.13: Expanded scope of amino sugars coupling to functionalized benzaldehydes.

3.5.2 Formation of N-heterocycles from carbohydrates

The above examples used either the aldehydes, dicarbonyls, or amine functionalities on carbohydrates to form new heterocycles. However, the carbohydrate chain itself was not integrated into the heterocycle. Alternatively, the alkyl chain of the carbohydrate can provide direct access to highly functionalized nitrogen-containing heterocycles. These can be difficult targets to access in other ways: carbohydrates can provide an excellent route to these compounds, especially as the monosaccharides can be readily obtained from biomass waste [69]. The following examples demonstrate how simple carbohydrates can be converted into valuable nitrogen-containing heterocycles for both pharmaceutical and bulk chemical applications [70].

3.5.2.1 Synthesis of pyrrolizidines

Pyrrolizidine based heterocycles are found naturally in many plants, and are generally very toxic, acting as defence mechanisms against herbivore consumption [71]. Xin-Shan Ye recently reported a simple synthesis of these bicyclic scaffolds from nitroglycals (**74**), which are readily accessible from the parent glycal [72], and are useful reagents to access bicyclic and C-glycoside derivatives through Henry, Michael and various cycloaddition reactions. In the current report, the glycal is cleaved in the presence of water to generate a formate (**75**) intermediate that readily hydrolyses to lose the C1-carbon (**75**) (Figure 3.14). This is a promising route to access the analogues of the natural product (–)-Hyacinthacine (**77**) [73].

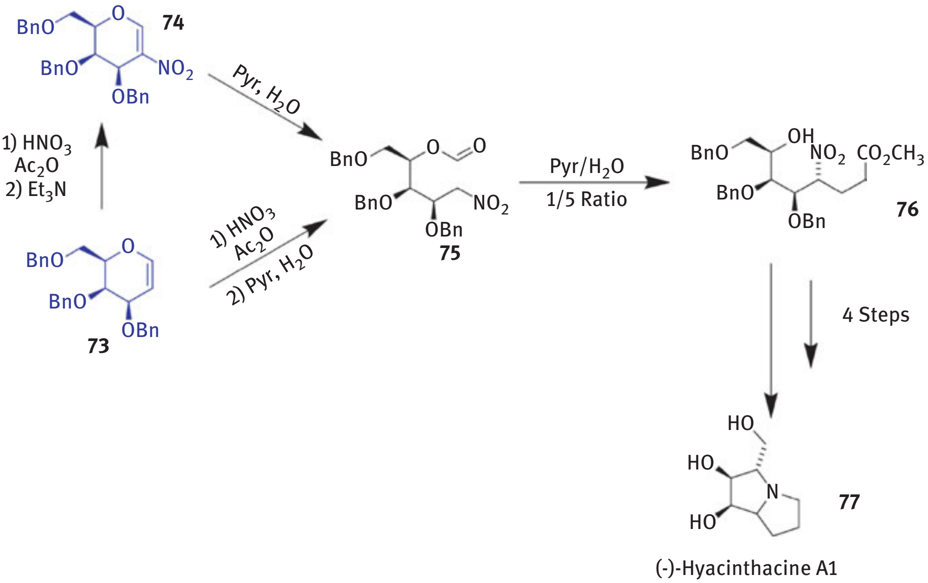


Figure 3.14: Generalized synthetic pathway of (-)-hyacinthacine A1.

The complicating step is the hydrolysis, and the choice of carbohydrate protecting group can have a significant influence on reaction success. Both a one-pot (treatment of the glycal with nitric acid) and two-pot (treatment of the isolated nitroglycal) provided the product, although the isolated yields were moderately higher for the two-pot process (90–99%). In some cases this was not a significant improvement over the more convenient one-pot system (50–80%), especially for benzylated systems. Pyr proved to be a privileged base, substitution with inorganic (KO^tBu, NaOH, K_2CO_3) or tertiary amines (Et_3N) resulted in little to no conversion. The various nitro-polyols were treated with methyl acrylate and Pyr to install the final three carbons required for the pyrrolizidine skeleton through a Michael reaction. Mechanistic studies justified the high observed diastereoselectivity of the Michael by invoking an eight-membered hydrogen-bond-organized intermediate (**79**). The induced conformation effectively shields the *Si*-face of the carbon-nitrogen double bond, force *Re*-attack (Figure 3.15).

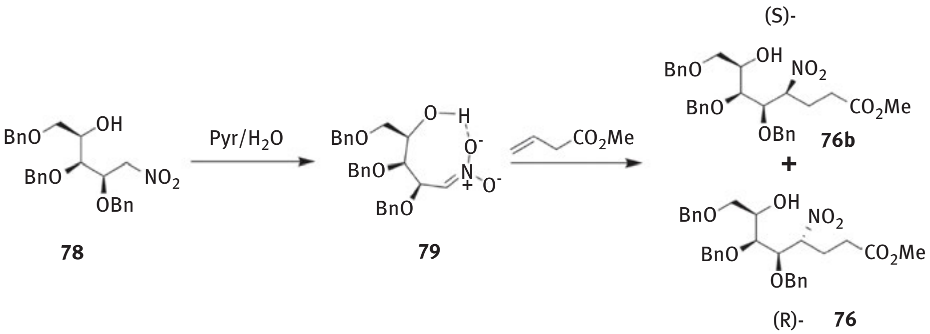


Figure 3.15: Transition state of Michael addition.

The synthesis is completed through a selective reduction of the ester in the presence of the nitro group using $LiAlH_4$ (**80**). Mesylation of the alcohol (**81**), followed by two sequential catalytic hydrogenations allows for the intramolecular cyclization to take place spontaneously (**82**) (after nitro reduction), and perdebenzylation (**77**) to occur (Figure 3.16).

3.5.2.2 Synthesis of pyrroles

In the previous example, the chirality of the carbohydrate is conserved to provide information in the product. But the highly hydroxylated systems also allow for the formation of aromatic pyrroles in a mechanism related to the formation of HMF, obtained from the hydrolytic pyrolysis of polysaccharides in water [19]. Through a nitrogen exchange reaction, furans can be converted to pyrrole in the presence of ammonia. Shown below is a generalized mechanism illustrating how pyrrole is synthesized in Figure 3.17.

The polysaccharide (chitin) readily undergoes hydrolysis to yield the monomer **20**, which is then hydrolysed to release acetic acid as shown above to generate the 2-aminofurnaose which dehydrates to the furan. The authors propose that the furan then dehydrates derivative which rapidly undergoes dehydration (**84**), deamination, and N-O exchange to yield the acetyl pyrrole (**86**) [19]. This acetyl pyrrole is a useful

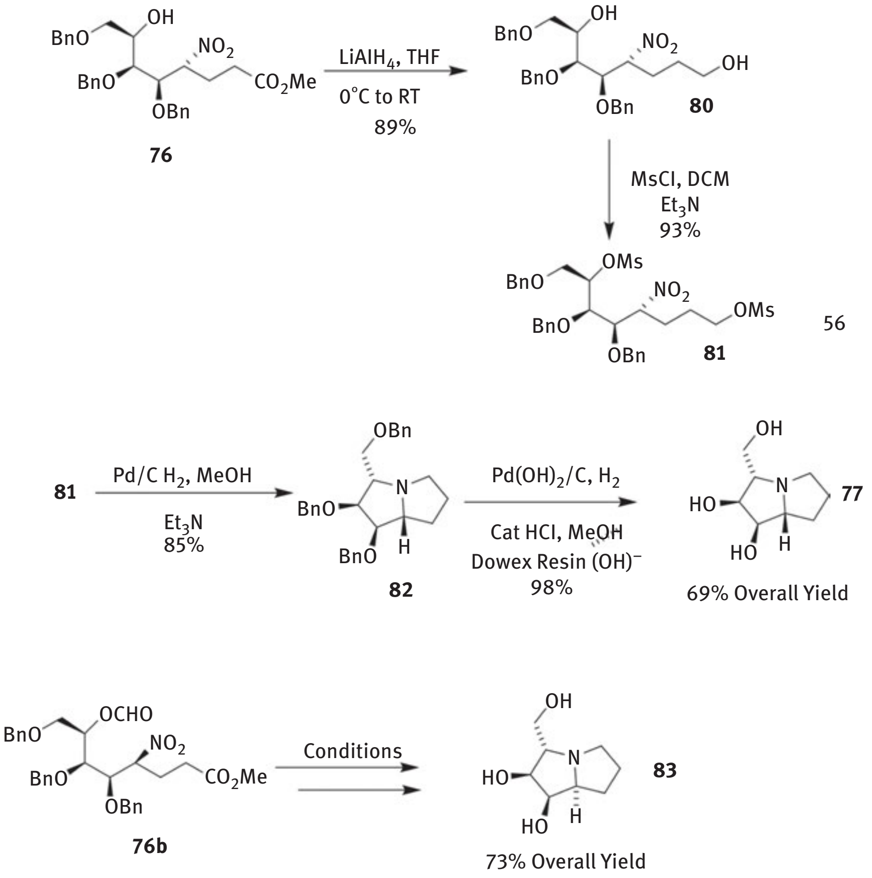


Figure 3.16: Synthesis of epi-(-)-hyacinthacine and (-)-hyacinthacine A1.

building block in its own right, but it can decompose to the pyrrole (**87**). GC analysis of the reaction mixture indicated that there were other nitrogen compounds present including pyrazine, Pyr, and amide derivatives. Overall this process to yield acetic acid and pyrrole will not be a viable industrial process until the extraction of chitin from crustacean shells can be done more efficiently, and the route does not provide substituted pyrroles, which are of far greater interest for the fine chemical industry.

A recent report from Huawu Shao does make substituted pyrroles from a carbohydrate derivative, however it uses a far more advanced intermediate: 1,2 cycloproponated sugars (still readily available from glycals) [74]. Donor-acceptor cyclopropanes are extremely useful synthons, and are reactive with a wide variety of nucleophiles and electrophiles. In the presence of Lewis acids they can be readily converted to a number of valuable heterocyclic scaffolds [75]. Specifically, Charette reported in 2005 that donor-acceptor cyclopropanes undergo reaction with amines to yield 4-pyrrole derivatives [76]. This carbohydrate variant involves a Zn(OTf)$_2$-mediated rearrangement of

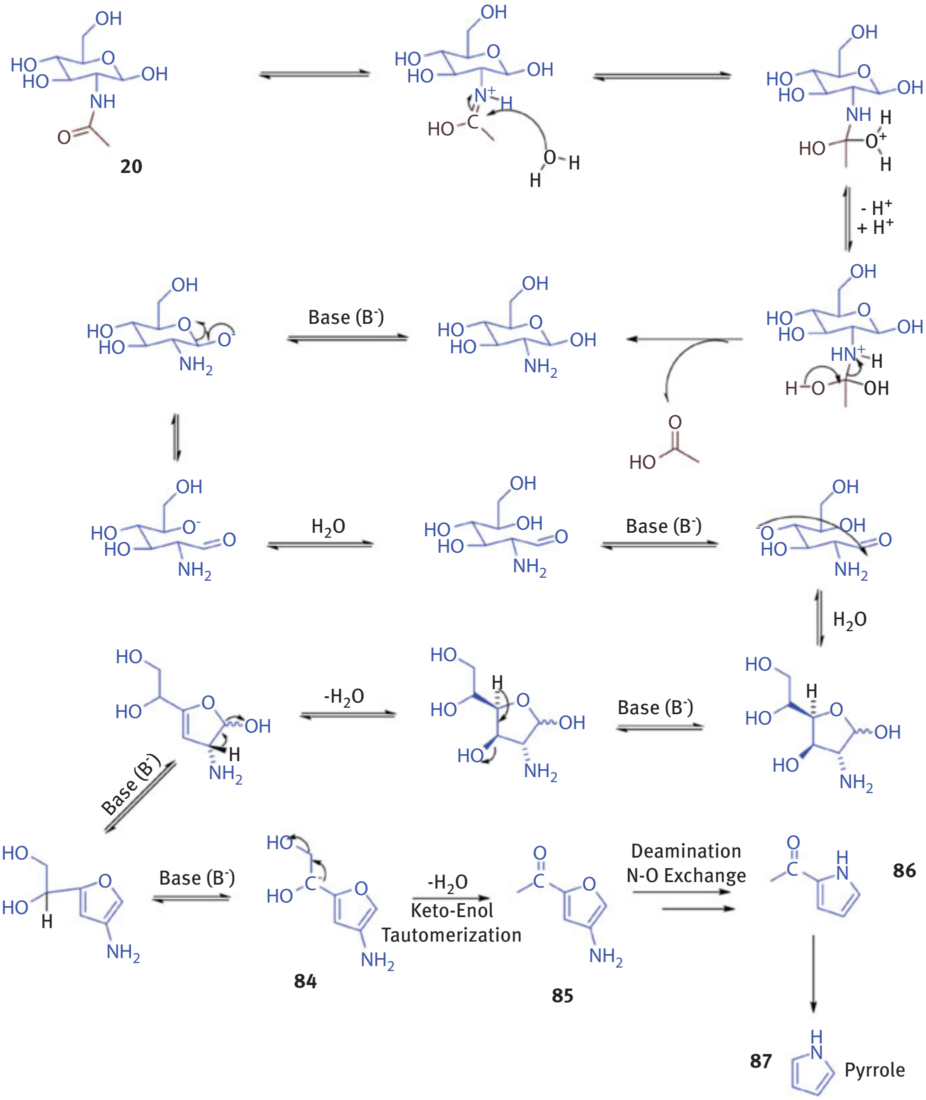


Figure 3.17: General mechanism for pyrrole formation.

1,2-cycloproponated sugars to afford 3-polyhydroxylalkyl-substituted pyrroles (other metals were far less efficient) [77]. The general reaction Figure outlining the Lewis acid mediated synthesis of polyhydroxyalkyl pyrroles is shown below in Figure 3.18.

With respect to the amine, the reaction appears tolerant of standard unhindered aliphatics (i. e., octyl, hexyl, butyl, allyl, propargyl, 77–84% yield), although a t-butyl group provides no conversion most likely due to high steric hinderance. Electron rich anilines work well, and ester, ether, and amide functionalities on the amines are also

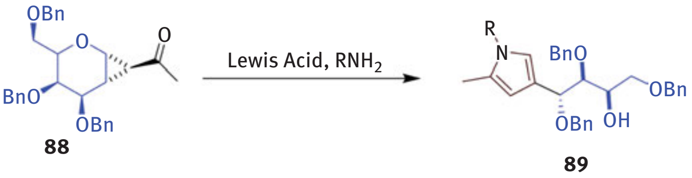


Figure 3.18: Lewis acid mediated donor-acceptor cyclopropanated sugars.

tolerated. Electron poor anilines do not fare so well, limiting access to this important class of pyrrole derivatives. In terms of the carbohydrate, the reaction works well with all examined cyclopropanated furanose and pyranose sugars (Figure 3.19). Additional synthetic complexity can be introduced by inverting the liberated C-5 hydroxyl group to access epimeric hydroxylated chains. These units could provide useful building blocks for drug-like molecules.

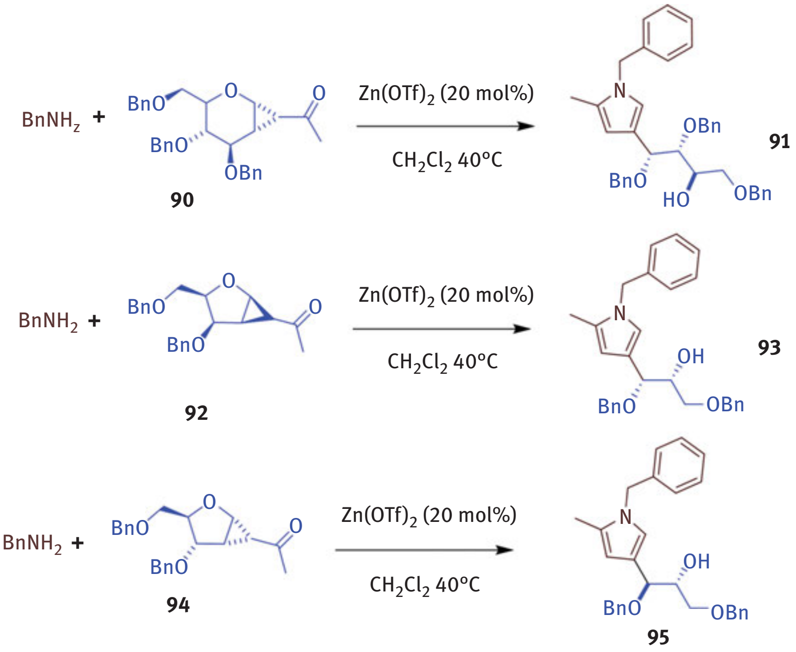


Figure 3.19: Lewis acid mediated donor-acceptor cyclopropanated sugars.

3.5.2.3 Synthesis of pyrazines

Pyrazines are another very useful bulk material, with the scaffold being used extensively in both flavouring agents and pharmaceuticals [78–80], and are produced during the cooking of carbohydrate-containing food from Maillard reactions [81].

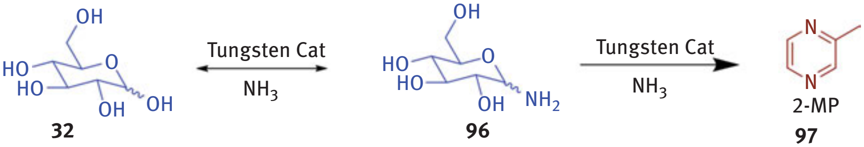


Figure 3.20: Generalized tungsten mediation of aminosugars.

Consequently, they should be accessible from carbohydrate-containing biomass. Yan an co-workers recently reported the use of tungsten-based catalysts to prepare 2-methyl pyrazine (**97**) from glucose (**32**), cleverly applying the chemistry developed by Tao Zhang to convert cellulose biomass to EG (Figure 3.20) [82].

The initial studies used glucose, ammonia, and tungsten-based catalysts (the best results were obtained using phosphotungstic acid, although most tungsten (VI) species performed well). The yields were temperature dependent with the best results obtained at 220ºC in the presence of 25 mass% ammonia and 150% w/w catalyst loading. The yield is also dependent on the stereochemistry of the sugar. Glucose, and its C-6 deoxy sugar, xylose, provided the best yields at 25% and 23%, respectively, while glucosamine and fructose generated 2 MP in approximately 20% yield. Excellent mechanistic studies demonstrate that the aldehyde is essential for conversion, sorbitol was unreactive, and 5-HMF also gave no conversion, suggesting that it is not an intermediate in the series. Consequently, they propose an oxidative cleavage reaction which requires the C2 and C3 fragments shown in Figure 3.21.

The proposed mechanism shows the conversion of glucose to the corresponding amino sugar which ring opens to form the isomeric imines **98** and **99** that interconvert under the reaction conditions. Based on DFT calculations, if the reaction progressed through path 1, the homolytic bond cleavage favours breaking the C-C bond between C-2 and C-3 through a retro-aldol mechanism to produce intermediates C2 and C4. Further retro-aldol reactions can either yield a C1 fragment and a C3 fragment which is in equilibrium with the fructose form or a C2 and a C3 fragment. If path 2 was followed that would mean fructose-based imine would be the reactive intermediate. Compound **99** was not detected even fructose was used as the starting material in place of glucose. This indicates that the retro-aldol of path 2 is fast so no accumulation of the fructose intermediate **99** occurs. Both pathways are accessible to glucose, and both lead to similar intermediated eventually becoming degenerated through the formation of **100**. When both C2 and C3 fragments have been formed, the final condensation reaction occurs followed by dehydration to give 2-methylpyrazine (2-MP).

Alternatively, Taylor and co-workers have very recently described the direct conversion of sugars into pyrazines using ammonium hydroxide, heat and L-leucine [83]. The reaction works well with a variety of carbohydrates: glucose, fructose or a combination of the two (typical of fruit extracts, or corn syrup, glucose-

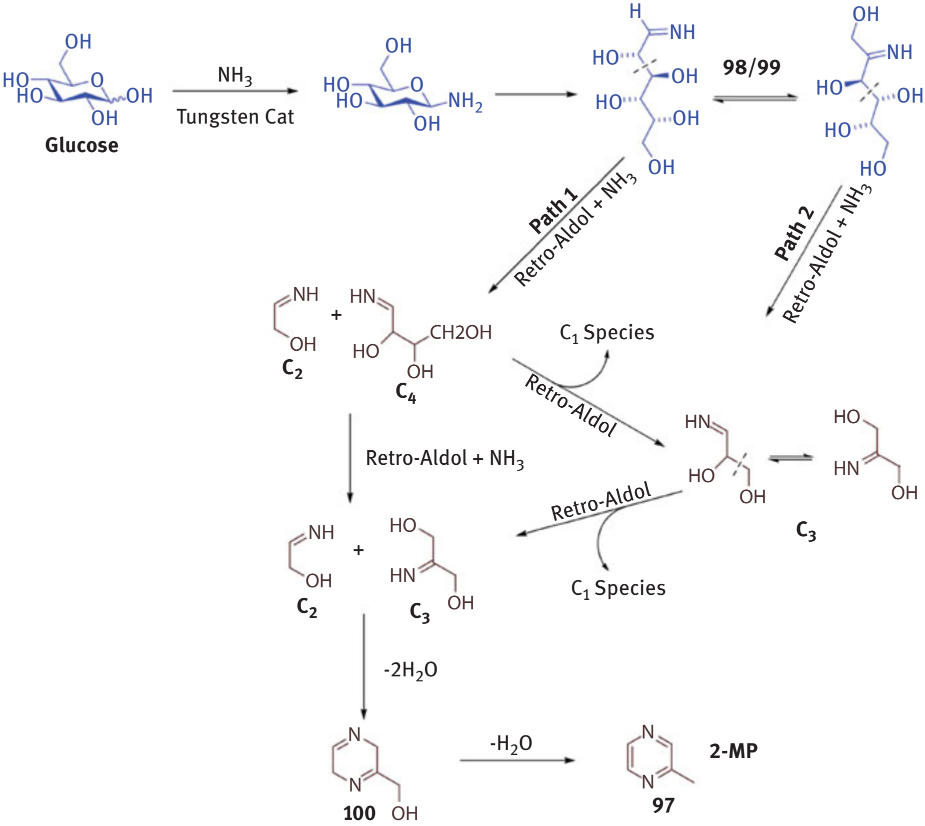


Figure 3.21: Proposed mechanism of 2-methylpyrazine using tungsten catalysts.

fructose) but only a few derivatives were synthesized. Rhamnose provided much lower chemical yields, but also provided a wider variety of pyrazine derivatives were detected including an interesting branched example: 2-isoamyl-6-methylpyrazine. The varying pyrazines were identified from the mixture using GC/MS (Figure 3.22).

This ratio of products is highly influenced by varying temperature, concentration of rhamnose, concentration of ammonium hydroxide and the concentration of the amino acid. Similar results were obtained regardless of the amino acid: L-threonine, L-valine and L-leucine were all screened, and all generated a mixture of pyrazines. The differences were comparably minor: L-valine gave the highest amount of total pyrazine mass, whereas L-leucine provided better selectivity with comparable recovery of pyrazine mass (primarily 2-methyl pyrazine and the 2,6-dimethyl derivative). Threonine provided the poorest mass recovery, although the

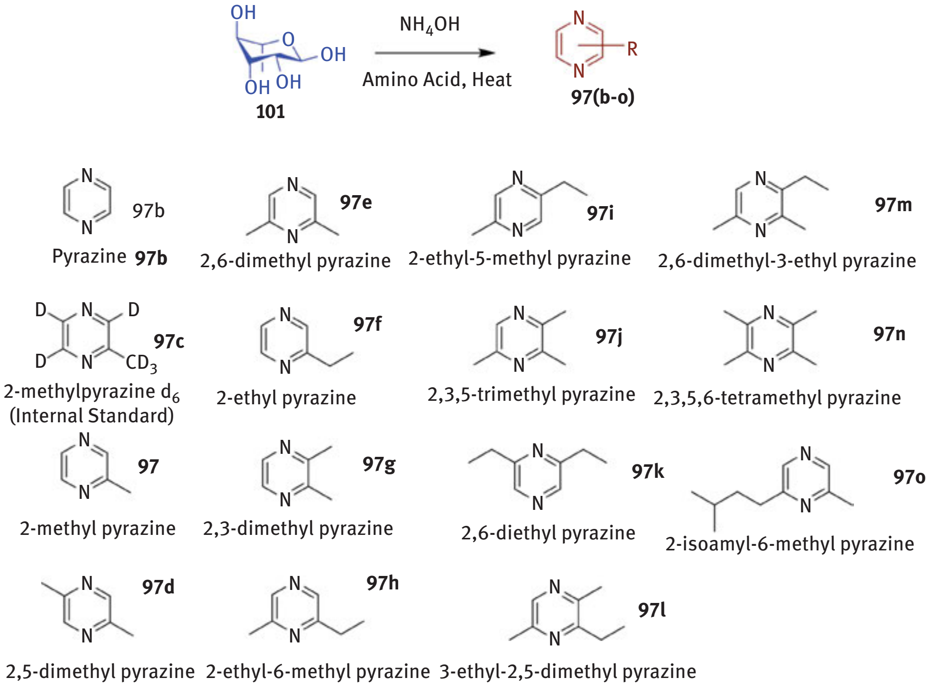


Figure 3.22: Derivatives of pyrazine recovered by GC/MS

reaction was cleaner: only 8 pyrazines were formed, compared to 11 with leucine and valine. Temperature and reaction time have the biggest influence on the reaction. At 90°C for 1 h, the conversion was very poor and many of the pyrazines were not formed. Increasing the temperature to 110°C for the same 1-h incubation yielded all 13 pyrazines, but again in low yield. However, heating to 110°C over 2 h provided 4.5 times the amount of total pyrazine content. The yields are still very low as a percent of the biomass, but this is plenty of material if flavouring agents are what is required. As the conditions of the reaction can be tightly controlled, this could provide access to flavour compounds and flavour mixtures relatively effectively and could be important for the flavouring industry going forward.

3.5.2.4 Synthesis of tetrahydropyrrole

Iminosugars form an important class of competitive inhibitors of glycosidase and glycosyltransferases, the mis-regulation of which is important in many diseases [84]. Consequently, they form the basis of a number of current pharmaceuticals including Glycet, Zavesca and celgosivir [84]. However, the syntheses have often been challenging and somewhat lengthy [85]. Venkateswara Rao and coworkers recently reported on the conversion of vinyl pyranosylamine and furanosylamines to 2,6- and 2,5-

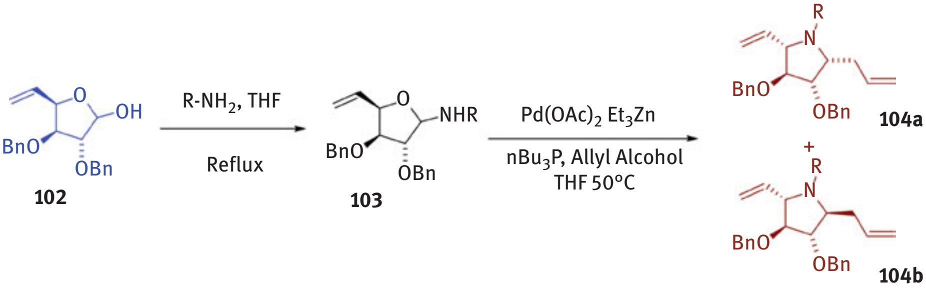


Figure 3.23: General allylation of iminosugars.

disubstituted pyrrolidine and piperidine iminosugars in a one-pot procedure (Figure 3.23) [86].

These iminosugars were then elaborated for the synthesis of polyhydroxylated piperazines, pyrrolidines and indolizidine compounds. The initial reactions used a protected free-reducing end sugar and a primary amine to generate the hemiaminal. Treatment using a palladium catalyst forces the rearrangement to the iminosugar in the presence of an allyl alcohol. In terms of aliphatic amines, only allyl amine (55% yield) provided moderate conversion with both hindered (cyclohexylamine) and unhindered (n-hexylamine) alkylamines providing only low conversion. Benzyl amine and electron-rich anilines were far more effective (60–72% yield). The reaction was far more tolerant in terms of the protecting group strategy and identity of the carbohydrate, and examples are provided below (Figure 3.24). These systems are perfectly positioned for ring closing metathesis to generate complex polycyclic systems. These pyrrolidines, piperazines and indolizidines are highly promising scaffolds for the development of carbohydrate-based glycosidase inhibitors.

3.6 Conclusion

There has been significant focus over the years on converting carbohydrate biomass to HMF, LA, and their derivatives including hydrocarbons for bio-derived fuels and building blocks for polymers. However, in very recent years, there has been excellent progress on derivatizing these same readily available building blocks into the complex heterocycles that form the basis of so many of the pharmaceutically active materials. The examples shown here are just the initial forays into this field of generating valuable fine chemicals from sustainable sources, and we can expect this field of research to continue to expand in the coming years and decades as the social, environmental, and economic cost differential between fossil fuels and biomass conversion continues to shift.

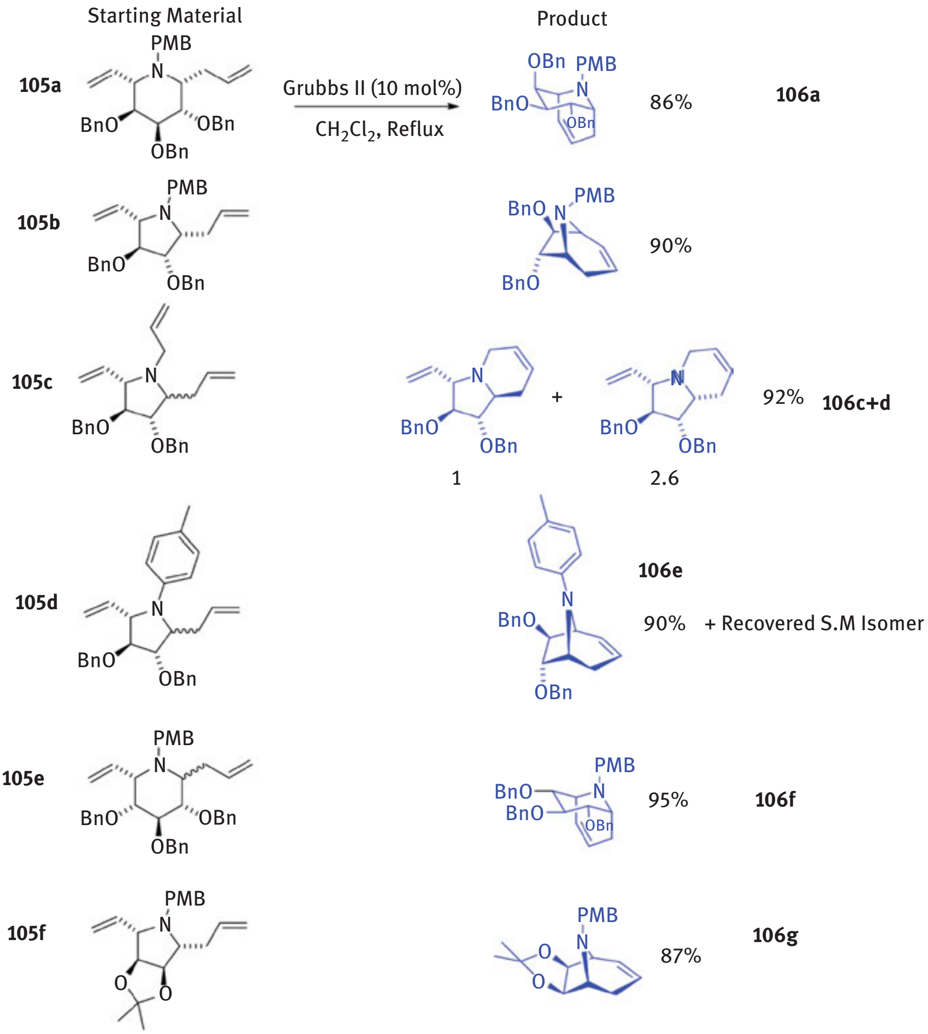


Figure 3.24: Yields of ring closing metathesis of N-containing heterocycles.

Abbreviations

3A5AF	3-acetamido-5-acetylfuran
AgOTf	Silver Triflate
$Cu(OTf)_2$	Copper triflate
DCE	1,2-dichloroethane
DCM	Dichloromethane
DFA	di-D-fructose dianhydrides
DMA	Dimethylacetamide

DMF	Dimethylformamide
DMSO	Dimethyl sulfoxide
dtbpy	4,4’-di tert butyl-2,2’-bipyridine
EG	Ethylene glycol
Fruf	Fructofuranosyl
Gal	Galactose
GC-MS	Gas chromatography–mass spectrometry
GPC	Gel permeation chromatography
GlcNAc	*N*-acetyl-2-deoxy-2-amino-D-glucose
Glcp	Glucopyranosyl
α-Gls	α-glucosidase
Gly	Glycerine
5-HMF	5-(hydroxymethyl)furfural
LA	Levulinic acid
LC-MS	Liquid Chromatography-Mass Spectrometry
2-MP	2-methyl pyrazine
Ms	Mesyl
MsCl	Mesyl Chloride
NAG	*N*-acetyl-2-deoxy-2-amino-D-glucose
NMP	N-methyl-2-pyrrolidone
PFH’s	Pyrimidine-fused Heterocycles
PHPFH	Polyhydroxylated pyrimidine-fused heterocycles
PTSA	p-toluenesulfonic acid
Pyr	Pyridine
RT	Room temperature
THF	Tetrahydrofuran
TMSOTf	Trimethylsilyl Trifluoromethanesulfonate
Tf_2O	Trifluoromethanesulfonic Anhydride
USD	United States Dollar

Acknowledgements: The authors would like to thank the University of Windsor for supporting the writing of this Chapter through Start-Up Funds to JFT. BSO would like to thank his supervisor, Prof. J. Green, for his support during the writing process.

References

[1] Jiménez-González C, Poechlauer P, Broxterman QB, Yang BS, am Ende D, Baird J et al. Key green engineering research areas for sustainable manufacturing: a perspective from pharmaceutical and fine chemicals manufacturers. Org Proc Res Dev. 2011;15:900–11
[2] Priddy RD. Sustainability: the train has left the station. MRS Energy Sustainability. 2017;4:E3.
[3] Krane J. Climate change and fossil fuel: an examination of risks for the energy industry and producer states. MRS Energy Sustainability. 2017;4:E2.

[4] Sheldon RA. Green chemistry and resource efficiency: towards a green economy. Green Chem. 2016;18:3180–3.

[5] Colmenares JC. Nanophotocatalysis in selective transformations of lignocellulose-derived molecules: a green approach for the synthesis of fuels, fine chemicals, and pharmaceuticals. RSC Green Chem Ser. 2016;42:168–201.

[6] Gandini A. Furans as offspring of sugars and polysaccharides and progenitors of a family of remarkable polymers: a review of recent progress. Polym Chem. 2010;1:245–51.

[7] Galbis JA, García-Martín MG. Synthetic polymers from readily available monosaccharides. In: Rauter AP, Vogel P, Queneau Y, editors. Carbohydrates in sustainable development II. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010:147–76.

[8] El Kadib A. Chitosan as a sustainable organocatalyst: a concise overview. ChemSusChem. 2015;8:217–44.

[9] Lichtenthaler FW, Mondel S. Perspectives in the use of low molecular weight carbohydrates as organic raw materials. Pure Appl Chem. 1997;69:1853–66.

[10] Mika LT, Cséfalvay E, Németh Á. Catalytic conversion of carbohydrates to initial platform chemicals: chemistry and sustainability. Chem Rev. 2018;118:505–613.

[11] Khoo HH, Ee WL, Isoni V. Bio-chemicals from lignocellulose feedstock: sustainability, LCA and the green conundrum. Green Chem. 2016;18:1912–22.

[12] Roy Goswami S, Dumont M-J, Raghavan V. Starch to value added biochemicals. Starch/Staerke. 2016;68:274–86.

[13] Isikgor FH, Becer CR. Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers. Polym Chem. 2015;6:4497–559.

[14] Holmberg AL, Reno KH, Wool RP, Epps IIITH. Biobased building blocks for the rational design of renewable block polymers. Soft Matter. 2014;10:7405–24.

[15] Lichtenthaler FW, Peters S. Carbohydrates as green raw materials for the chemical industry. C R Chim. 2004;7:65–90.

[16] Sheldon RA. Green and sustainable manufacture of chemicals from biomass: state of the art. Green Chem. 2014;16:950–63.

[17] Climent MJ, Corma A, Iborra S. Conversion of biomass platform molecules into fuel additives and liquid hydrocarbon fuels. Green Chem. 2014;16:516–47.

[18] Yan L, Yao Q, Fu Y. Conversion of levulinic acid and alkyl levulinates into biofuels and high-value chemicals. Green Chem. 2017;19:5527–47.

[19] Gao X, Chen X, Zhang J, Guo W, Jin F, Yan N. Transformation of chitin and waste shrimp shells into acetic acid and pyrrole. ACS Sustainable Chem Eng. 2016;4:3912–20.

[20] Jin F, Zhou Z, Moriya T, Kishida H, Higashijima H, Enomoto H. Controlling hydrothermal reaction pathways to improve acetic acid production from carbohydrate biomass. Environ Sci Technol. 2005;39:1893–902.

[21] Liguori F, Moreno-Marrodan C, Barbaro P. Environmentally friendly synthesis of γ-valerolactone by direct catalytic conversion of renewable sources. ACS Catalysis. 2015;5:1882–94.

[22] Szabolcs A, Molnar M, Dibo G, Mika LT. Microwave-assisted conversion of carbohydrates to levulinic acid: an essential step in biomass conversion. Green Chem. 2013;15:439–45.

[23] Bozell JJ, Moens L, Elliott DC, Wang Y, Neuenscwander GG, Fitzpatrick SW et al. Production of levulinic acid and use as a platform chemical for derived products. Resour, Conserv Recycl. 2000;28:227–39

[24] Werpy T, Petersen G Top Value Added Chemicals from Biomass: Volume I – Results of Screening for Potential Candidates from Sugars and Synthesis Gas: National Renewable Energy Lab., Golden, CO (US); 2004. Report No.: DOE/GO-102004-1992; TRN: US200427 United States.

[25] Lee AF. Catalysing sustainable fuel and chemical synthesis. Appl Petrochem Res. 2014;4:11–31.

[26] Kan T, Strezov V, Evans TJ. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renewable Sustainable Energy Rev. 2016;57:1126–40.

[27] Bond JQ, Upadhye AA, Olcay H, Tompsett GA, Jae J, Xing R et al. Production of renewable jet fuel range alkanes and commodity chemicals from integrated catalytic processing of biomass. Energy Environ Sci. 2014;7:1500–23

[28] Beerthuis R, Rothenberg G, Shiju NR. Catalytic routes towards acrylic acid, adipic acid and ?-caprolactam starting from biorenewables. Green Chem. 2015;17:1341–61.

[29] Chatzidimitriou A, Bond JQ. Oxidation of levulinic acid for the production of maleic anhydride: breathing new life into biochemicals. Green Chem. 2015;17:4367–76.

[30] Chen W-H, Lin B-J, Huang M-Y, Chang J-S. Thermochemical conversion of microalgal biomass into biofuels: A review. Bioresour Technol. 2015;184:314–27.

[31] Bicker M, Hirth J, Vogel H. Dehydration of fructose to 5-hydroxymethylfurfural in sub- and supercritical acetone. Green Chem. 2003;5:280–4.

[32] Caes BR, Teixeira RE, Knapp KG, Raines RT. Biomass to furanics: renewable routes to chemicals and fuels. ACS Sustainable Chem Eng. 2015;3:2591–605.

[33] Huang H, Denard CA, Alamillo R, Crisci AJ, Miao Y, Dumesic JA et al. Tandem catalytic conversion of Glucose to 5-Hydroxymethylfurfural with an immobilized Enzyme and a solid acid. ACS Catalysis. 2014;4:2165–8

[34] Luterbacher JS, Rand JM, Alonso DM, Han J, Youngquist JT, Maravelias CT et al. Nonenzymatic sugar production from biomass using biomass-derived γ-valerolactone. Science. 2014;343:277–80

[35] Chuntanapum A, Matsumura Y. Formation of tarry material from 5-HMF in subcritical and supercritical water. Ind Eng Chem Res. 2009;48:9837–46.

[36] Akien GR, Qi L, Horvath IT. Molecular mapping of the acid catalysed dehydration of fructose. Chem Commun. 2012;48:5850–2.

[37] Antal MJ, Mok WSL, Richards GN. Mechanism of formation of 5-(hydroxymethyl)-2-furaldehyde from d-fructose and sucrose. Carbohydr Res. 1990;199:91–109.

[38] Amarasekara AS, Williams LD, Ebede CC. Mechanism of the dehydration of d-fructose to 5-hydroxymethylfurfural in dimethyl sulfoxide at 150°C: an NMR study. Carbohydr Res. 2008;343:3021–4.

[39] Omari KW, Besaw JE, Kerton FM. Hydrolysis of chitosan to yield levulinic acid and 5-hydroxymethylfurfural in water under microwave irradiation. Green Chem. 2012;14:1480–7.

[40] Andrić P, Meyer AS, Jensen PA, Dam-Johansen K. Reactor design for minimizing product inhibition during enzymatic lignocellulose hydrolysis: I. Significance and mechanism of cellobiose and glucose inhibition on cellulolytic enzymes. Biotechnol Adv. 2010;28:308–24.

[41] Mascal M, Nikitin EB. Dramatic advancements in the saccharide to 5-(Chloromethyl)furfural conversion reaction. ChemSusChem. 2009;2:859–61.

[42] Ruppel JV, Snyder NL, Thompson AD, Farnsworth TW. Furans, benzofurans, thiophenes, and benzothiophenes. In: Li JJ, editor. Heterocyclic chemistry in drug discovery. Hoboken, N.J.: John Wiley & Sons, Inc., 2013:119–96.

[43] Sperry JB, Wright DL. Furans, thiophenes and related heterocycles in drug discovery. Curr Opin Drug Discovery Dev. 2005;8:723–40.

[44] Kerton FM, Marriot R. Chapter 7 room-temperature ionic liquids and eutectic mixtures. In: Alternative solvents for green chemistry. 2nd ed. London: The Royal Society of Chemistry, 2013:175–209.

[45] El Seoud OA, Koschella A, Fidale LC, Dorn S, Heinze T. Applications of ionic liquids in Carbohydrate chemistry: a window of opportunities. Biomacromolecules. 2007;8:2629–47.

[46] Benedetto A, Ballone P. Room temperature ionic liquids meet biomolecules: a microscopic view of structure and dynamics. ACS Sustainable Chem Eng. 2016;4:392–412.

[47] Buntara T, Noel S, Phua PH, Melián-Cabrera I, De Vries JG, Heeres HJ. Caprolactam from renewable resources: catalytic conversion of 5-Hydroxymethylfurfural into Caprolactone. Angew Chem Int Ed. 2011;50:7083–7.

[48] Drover MW, Omari KW, Murphy JN, Kerton FM. Formation of a renewable amide, 3-acetamido-5-acetylfuran, via direct conversion of N-acetyl-d-glucosamine. RSC Adv. 2012;2:4642–4.

[49] Franich RA, Goodin SJ, Wilkins AL. Acetamidofurans, acetamidopyrones, and acetamidoacetaldehyde from pyrolysis of chitin and n-acetylglucosamine. J Anal Appl Pyrolysis. 1984; 7:91–100.

[50] Chen J, Wang M, Ho C-T. Volatile compounds generated from thermal degradation of N-acetylglucosamine. J Agric Food Chem. 1998;46:3207–9.

[51] Chen X, Chew SL, Kerton FM, Yan N. Direct conversion of chitin into a N-containing furan derivative. Green Chem. 2014;16:2204–12.

[52] Einbu A, Varum KM. Characterization of Chitin and its Hydrolysis to GlcNAc and GlcN. Biomacromolecules. 2008;9:1870–5.

[53] Vaaje-Kolstad G, Westereng B, Horn SJ, Liu Z, Zhai H, Sorlie M et al. An Oxidative Enzyme boosting the enzymatic conversion of recalcitrant polysaccharides. Science. 2010;330:219–22

[54] Streith J, Boiron A, Frankowski A, Le Nouen D, Rudyk H, Tschamber T. On the way to glycoprocessing inhibitors: a general one-pot synthesis of Imidazolosugars. Synthesis. 1995;1995:944–6.

[55] Brust A, Cuny E. Conversion of reducing carbohydrates into hydrophilic substituted imidazoles. Green Chem. 2013;15:2993–98.

[56] Wrodnigg TM, Kartusch C, Illaszewicz C. The amadori rearrangement as key reaction for the synthesis of neoglycoconjugates. Carbohydr Res. 2008;343:2057–66.

[57] Brust A, Cuny E. Reducing disaccharides and their 1,2-dicarbonyl intermediates as building blocks for nitrogen heterocycles. RSC Adv. 2014;4:5759–67.

[58] Mohana Roopan S, Sompalle R. Synthetic chemistry of pyrimidines and fused pyrimidines: a review. Synth Commun. 2016;46:645–72.

[59] Gaurav J, Himanshu N, Jimi Marin A, Gajendra SV, Sunil M, Raj K. Pyrimidine-fused derivatives: synthetic strategies and medicinal attributes. Curr Top Med Chem ((Sharjah, United Arab Emirates)). 2016;16: 3175–210.

[60] Schenone S, Radi M, Musumeci F, Brullo C, Botta M. Biologically driven synthesis of Pyrazolo [3,4-d]pyrimidines as protein kinase inhibitors: an old scaffold as a new tool for medicinal chemistry and chemical biology studies. Chem Rev. 2014;114:7189–238.

[61] Bahashwan SA. Pharmacological studies of some pyrimidino derivatives. Afr J Pharm Pharmacol. 2011;5:527–31.

[62] Singh B, Maheshwari A, Dak G, Sharma K, Talesara GL. Studies of antimicrobial activities of some 4-Thiazolidinone Fused pyrimidines, [1,5]-Benzodiazepines and their Oxygen substituted Hydroxylamine derivatives. Indian J Pharm Sci. 2010;72:607–12.

[63] Mah R. Pyrimidine-based kinase inhibitors in cancer chemotherapy. In: Dinges J, Lamberth C, editors. Bioactive heterocyclic compound classes. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2012:257–71.

[64] Banday AH, Mir BP, Lone IH, Suri KA, Kumar HMS. Studies on novel D-ring substituted steroidal pyrazolines as potential anticancer agents. Steroids. 2010;75:805–09.

[65] Shamroukh AH, Zaki MEA, Morsy EMH, Abdel-Motti FM, Abdel-Megeid FME. Synthesis of Pyrazolo[4′,3′:5,6]pyrano[2,3-d]pyrimidine derivatives for antiviral evaluation. Arch Pharm. 2007;340:236–43.

[66] Amir M, Javed SA, Kumar H. Pyrimidine as antiinflammatory agent: a review. Indian J Pharm Sci. 2007;69:337–43.

[67] Yousefi R, M-M A-M, Mokhtari F, Panahi F, Mehraban MH, Khalafi-Nezhad A. Pyrimidine-fused heterocycle derivatives as a novel class of inhibitors for α-glucosidase. J Enzyme Inhib Med Chem. 2013;28:1228–35.

[68] Nourisefat M, Panahi F, Khalafi-Nezhad A. Carbohydrates as a reagent in multicomponent reactions: one-pot access to a new library of hydrophilic substituted pyrimidine-fused heterocycles. Org Biomol Chem. 2014;12:9419–26.

[69] Wang J, Xi J, Wang Y. Recent advances in the catalytic production of glucose from lignocellulosic biomass. Green Chem. 2015;17:737–51.

[70] Lahiri R, Ansari AA, Vankar YD. Recent developments in design and synthesis of bicyclic azasugars, carbasugars and related molecules as glycosidase inhibitors. Chem Soc Rev. 2013;42:5102–18.

[71] Robertson J, Stevens K. Pyrrolizidine alkaloids: occurrence, biology, and chemical synthesis. Nat Prod Rep. 2017;34:62–89.

[72] Dharuman S, Gupta P, Kancharla PK, Vankar YD. Synthesis of 2-Nitroglycals from Glycals using the Tetrabutylammonium Nitrate–trifluoroacetic Anhydride–triethylamine reagent system and base-catalyzed ferrier rearrangement of Acetylated 2-Nitroglycals. J Org Chem. 2013;78:8442–50.

[73] Ritthiwigrom T, Au CWG, Pyne SG. Structure, biological activities, and synthesis of hyacinthacine alkaloids and their stereoisomers. Curr Org Synth. 2012;9:583–612.

[74] Murali R, Ramana CV, Nagarajan M. Synthesis of 1,2-cyclopropanated sugars from glycals. J Chem Soc Chem Commun. 1995;1995:217–8.

[75] Reissig H-U ZR. Donor-acceptor-substituted Cyclopropane derivatives and their application in organic synthesis. Chem Rev (Washington, DC, U S). 2003;103:1151–96.

[76] Wurz RP, Charette AB. Doubly activated cyclopropanes as synthetic precursors for the preparation of 4-nitro- and 4-cyano-dihydropyrroles and pyrroles. Org Lett. 2005; 7:2313–6.

[77] Shen X, Xia J, Liang P, Ma X, Jiao W, Shao H. $Zn(OTf)_2$ promoted rearrangement of 1,2-cyclopropanated sugars with amines: a convenient method for the synthesis of 3-polyhydroxyalkyl-substituted pyrrole derivatives. Org Biomol Chem. 2015;13:10865–73.

[78] Masuda H, Mihara S. Olfactive properties of alkylpyrazines and 3-substituted 2-alkylpyrazines. J Agric Food Chem. 1988;36:584–7.

[79] Miniyar PB, Murumkar PR, Patil PS, Barmade MA, Bothara KG. Unequivocal role of Pyrazine ring in medicinally important compounds: a review. Mini-Rev Med Chem. 2013;13:1607–25.

[80] Ferreira SB, Kaiser CR. Pyrazine derivatives: a patent review (2008 – present). Expert Opin Ther Pat. 2012;22:1033–51.

[81] Fors SM, Olofsson BK. Alkylpyrazines, volatiles formed in the maillard reaction. i. determination of odour detection thresholds and odour intensity functions by dynamic olfactometry. Chem Senses. 1985;10:287–96.

[82] Wang A, Zhang T. One-pot conversion of cellulose to ethylene glycol with multifunctional tungsten-based catalysts. Acc Chem Res. 2013;46:1377–86.

[83] Ara KM, Taylor LT, Ashraf-Khorassani M, Coleman WM. Alkyl pyrazine synthesis via an open heated bath with variable sugars, ammonia, and various amino acids. J Sci Food Agric. 2017;97:2263–70.

[84] Horne G, Wilson FX, Tinsley J, Williams DH, Storer R. Iminosugars past, present and future: medicines for tomorrow. Drug Discovery Today. 2011;16:107–18.

[85] Asano N. Azaglycomimetics: natural occurrence, biological activity, and application. In: Fraser-Reid B, Tatsuta K, Thiem J, editors. Glycoscience. 2nd ed. Berlin: Springer-Verlag, 2008:1887–911.

[86] Naresh A, Marumudi K, Kunwar AC, Rao BV. Palladium-catalyzed double allylation of sugar-imines by employing tamaru-kimura’s protocol: access to unnatural iminosugars. Org Lett. 2017;19:1642–5.

Theodore Mill, Jay M. Patel and Caroline Tebes-Stevens

4 The environmental fate of synthetic organic chemicals

Abstract: This article focuses on the routes of transport and abiotic processes involved in the environmental transformation of synthetic organic chemicals and how molecular structure controls the products and lifetimes of several important classes of organic chemicals. The chapter also discusses the current methods to reliably determine the rates and products of degradation of new chemicals based on combinations of chemical structure and environmental processes as well as use of laboratory and field measurements. Methods are also discussed for use of structure activity relations for this purpose.

Keywords: synthetic organic chemicals, environmental fate, volatilization, adsorption, hydrolysis, photolysis, oxidation, reduction, transformations, predictive models, LFER, pH, cheminformatics

4.1 Introduction

Several hundred billion kilograms of synthetic organic chemicals are manufactured each year worldwide with over $3 trillion in sales. A small but significant fraction of these chemicals enters the environment through losses during manufacture, disposal, and use. Once chemicals arrive in the air, soil, or water, a variety of physical, chemical, and biochemical processes act on them to move and transform their molecular structures into new chemicals, and in some cases, to serially transform (degrade) organic compounds to CO_2 and water.

Implicit in the 12 principles of Green Chemistry is the requirement to avoid synthesis and disposal procedures that lead to increased environmental exposure to synthetic chemicals and their degradation products. Principle 10 is that chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment [1].

This chapter focuses on the routes of movement and abiotic processes involved in degradation and how molecular structure controls the products and lifetimes of several important classes of chemicals. The chapter also discusses the current methods to reliably predict rates and products of degradation based on the combination of

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Mill, T., Patel, J. M., Tebes-Stevens, C. The Environmental Fate of Synthetic Organic Chemicals. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0075

https://doi.org/10.1515/9783110566499-004

chemical structure and environmental processes. Methods for determining and estimating degradation rates of new chemicals by use of laboratory and field measurements and structure activity relations are discussed.

Of the five million unique chemical structures synthesized over the past 200 years [2], daily use of about 80,000 to 100,000 of these mostly organic chemicals presents a continuing source of concern about what effects the most persistent and abundant compounds might have on the environment, plant and animal life, and human health [3]. To mitigate the potential threat to human health and the environment, significant efforts are being made to understand and control the degradation of synthetic chemicals as well as their degradation products.

When released from various sources (e. g. industrial outflow, stacks, water treatment effluent, and runoff), chemicals move in and between water, air, or soil, and structural transformations take place through specific actions of physical, chemical, photochemical, and microbial processes. Both a chemical's concentration and molecular structure, as well the concentration/intensity of the environmental change agent (e. g. wind, current, or reactant) and the ambient environmental conditions, such as temperature and pH, determine the rate of change in location or chemical structure.

Laboratory test methods have been developed to measure specific rates of movement and degradation in environments that are controlled with respect to air or water movement, light sources, concentrations of reactants, temperature, and pH. Useful predictive methods to estimate rates of change as well as products critically depend on detailed understanding of the key factors controlling chemical, physical, and biological changes. This chapter focuses on these factors in abiotic degradation processes and newer approaches being developed to improve reliability of predictions based on this understanding.

4.2 Transport and transformation of synthetic chemicals in the environment

4.2.1 Physical movement

Losses of synthetic chemicals from manufacturing facilities are estimated at less than 1% of total production in many cases, reflecting high efficiencies of most modern facilities [4], and monitoring of nearby river/marine locations of many large manufacturing sites points to likely losses directly into those waters. Once in an aquatic compartment, chemicals can mix through advective (water movement) and diffusive (molecular) processes and undergo intercompartmental transfer through volatilization to the troposphere and adsorption to bottom sediments or suspended particles. For example, in just over a year, several thousand tons of a nearly insoluble, highly volatile compound can dissolve from the air and then further mix into lake or ocean water. Figure 4.1 illustrates the multiple physical processes at work in the water,

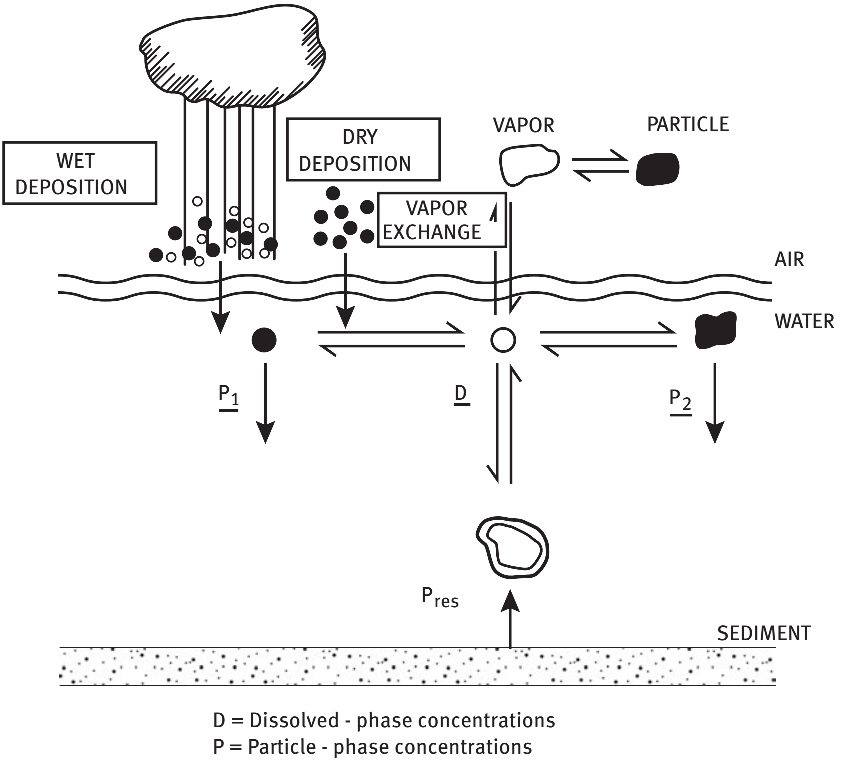


Figure 4.1: A scenario for air–water exchange for polychlorobiphenyls in Lake Superior. Reprinted with permission from [6], Copyright (1987) American Chemical Society.

sediment, and air above the water. Airborne vapor, aerosols, and particles all contribute to land/air exchange of large amounts of organic compounds, including terpenes wafted into the air from forest and land plants every year [5].

Studies of movement of polychlorobiphenyls (PCB)s in Lake Superior (the largest of the Great Lakes) revealed that despite extremely low water solubility of <1 ng/L, total PCBs deposited in the lake ranged from 5,000 to 40,000 kg in the period around 1980. The majority (75 %) of the PCB burden is believed to originate through air–water transfer [6]. If the Lake Superior processes apply to the World Ocean, with a surface area a thousand times greater than that of the lake, large burdens of low-solubility, low-volatility chemicals are now present there as well [7, 8].

4.2.1.1 Volatilization

Volatilization of nonpolar organic compounds from water to air (and the reverse) iswell studied [9, 10]. Both theoretical and empirical treatments of specific situations reveal a variety of complex relationships thoroughly reviewed by Schwarzenbach et al. [9]. To estimate the rate of transfer from water to air for nonpolar compounds, a double-layer model for transfer that includes variable wind velocity and water flow rates in the field as opposed to fixed water/air parameters found in the laboratory is described by Smith et al. [11]. Volatilization rates in aquatic systems use the equation [12, 13]:

$$k_v = V/A\left[(1/k_L) + \left(RT/H_c k_g\right)\right]^{-1} \tag{4.1}$$

where k_v is the rate constant for volatilization, V/A is the mean aquatic depth, k_L and k_g are liquid- and gas-phase transfer coefficients, and H_c is the Henry's law constant. Smith et al. [11] showed that liquid-phase control requires H_c values >3,500 torr L/mol, whereas gas-phase control applies when H_c values are <10 torr L/mol.

H_c values are readily estimated from the ratio of vapor pressure/water solubility for the pure compound. Compilations of measured values of vapor pressure, water solubility, and Henry's law constant are readily available in online databases for many synthetic organic chemicals [14, 15]. If measured values are not available for a compound of interest, software tools are available to estimate these physicochemical properties from the molecular structure of the compound [14, 16, 17]. Simple, low-molecular-weight aromatic compounds are examples of high-volatility compounds, as are PCBs with high molecular weights, very low vapor pressures, but extremely low water solubilities of the order of 10^{-9} g/L.

Smith et al. [11] proposed a simpler procedure avoiding the need for eq. (4.1) by measuring the ratio of the volatilization rate of oxygen to that of the chemical of interest ($k_\mathrm{v}(\mathrm{O_2})/k_\mathrm{v}(\mathrm{C})$) in the laboratory and $k_\mathrm{v}(\mathrm{O_2})$ in a natural water site. Since the ratio is relatively unchanged over a range of turbulent conditions, measuring a value for $k_\mathrm{v}(\mathrm{O_2})_\mathrm{env}$ provides the value for $k_\mathrm{v}(\mathrm{C})_\mathrm{env}$ and k_v through eq. (4.2).

$$k_v(\mathrm{C})_{env} = [k_v\,(\mathrm{O_2})/k_v\,(\mathrm{C})]_\mathrm{lab}/k_v(\mathrm{O_2})_\mathrm{env} \tag{4.2}$$

Re-aeration constants for oxygen in rivers, lakes, and ponds range from 0.10 to 0.30 day^{-1}, with equivalent half-lives of 7 to 2.3 days.

4.2.1.2 Sorption to sediments and soils

Sediments and soils are complex mixtures of clays, minerals, and organic material. The proportions of these components, as well as particle size distribution, vary widely from one source to another. Many nonpolar organic compounds, with low water solubility, sorb strongly to sediments and soils by a variety of pathways. Sorption of a large fraction of a specific chemical in contact with sediment leads to an overall loss of the aqueous portion of the chemical and, in turn, slowing of other aquatic processes; in effect, sorption buffers the concentration of chemical present in the aqueous phase.

The ratio of sorbed to nonsorbed chemical on a sediment at equilibrium may be expressed as an equilibrium constant:

$$K_S = [C]_S / [C]_w \qquad (4.3)$$

where $[C]_S$ and $[C]_w$ are the concentrations sorbed on the sediment and dissolved in water, respectively. Strongly sorbed chemicals such as PAHs or PCBs have $K_S > 10^5$ compared with weakly sorbed chemicals such as halo- or nitroaromatics with $K_S < 10^2$. K_S values for a single chemical vary with the composition of the soil because the values are largely controlled by the organic carbon content of the soil [18]. To adjust for the variation in organic carbon content of soils or sediments, the value K_S is expressed as

$$K_S = f_{org} K_{SC} \qquad (4.4)$$

where f_{org} is the fraction of organic content; thus, K_{SC} is a sorption constant corrected for the organic content. It follows from eq. (4.4) that if $f_{org} = 1$, then K_S is equivalent to a partition coefficient such as the octanol–water coefficient, K_{ow}, which is another measure of a compound's tendency to partition into the organic or humic fraction of soil and, along with $K_{S,}$ provides a readily measured chemical property. K_{ow} values have been compiled by Chiou et al. [18, 19] and for most nonpolymeric organic compounds can be found in chemistry texts and online [15, 20, 21]. Additionally, numerous software tools are available for the estimation of K_{ow} from molecular structure [14, 16, 17, 21]. Smith and Bomberger [22] have taken the sorption data of Karickoff et al. [23] and Smith et al. [24], rescaled the data to one coordinate set, and developed the following regression relation plotted in Figure 4.2.

$$\log K_{oc} = -0.782 \log [C] - 0.27 \qquad (4.5)$$

Although scatter in the plot increases significantly for low-solubility compounds, the linear relation extends over almost nine powers of ten. Thus, eq. (4.5) and the measured solubility of a chemical in water can be used to reliably estimate K_{SC} within a power of ten for most nonpolar chemicals, which in many cases is sufficient for screening purposes.

4.2.2 Abiotic chemical transformations

For many chemical transformation processes, we can formulate simple kinetic relationships of the form:

$$\text{Rate} = k_n [C] [P_n] \qquad (4.6)$$

where k_n is the rate constant for the nth process in units of M/sec or M/h; [C] is the molar concentration of chemical C and $[P_n]$ is a measure of the amount of an

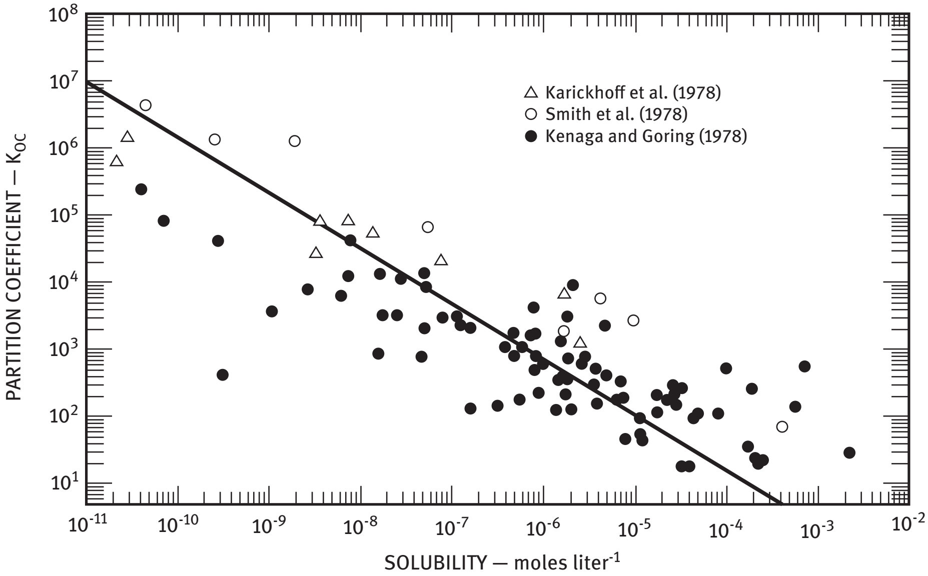


Figure 4.2: The combined data for log *K*oc are plotted vs. log ((solubilityC) using eq. (4.5) with the regression line.

environmental agent (e. g. concentration of H^+ or sunlight intensity) for the *n*th process. Values of k_n are temperature dependent for ground-state molecules, with close to twofold increases for every ten-degree increase in temperature [25]. For water-dependent reactions, formation of ice usually stops those reactions; effectively, $k_n \sim 0$. The following sections examine the detailed processes for several classes of compounds, the effects of environmental variables on those processes, and some methods for predicting rate constants based on molecular structure and values for $[P_n]$.

4.2.2.1 Hydrolysis

Water occupies about 70 % of the earth's surface, so it is no surprise that hydrolysis is an important process for transforming many kinds of organic compounds. Hydrolysis usually results in substitution by a hydroxyl function (–OH) for a wide variety of other molecular units, *X*, in the molecule, such as alkoxy, halide, epoxy, carboxy, and amide [25].

$$RX + H_2O \rightarrow ROH + HX \tag{4.7}$$

In liquid water, hydrolysis is catalyzed mainly by hydronium (H^+) and hydroxyl (HO^-) ions. Loosely complexed metal ions such as copper and clay surfaces may also serve as catalysts, but in natural settings, these metals are usually present in complexed form and ordinarily are unavailable as catalysts [9, 25].

The general rate equation for hydrolysis of compound C in water is

$$R_h = k_h[C] = k_A[H^+][C] + k_B[HO^-][C] + k_N[H_2O][C] \tag{4.8}$$

where k_h is the rate constant in units of time^{-1} at a fixed pH and k_A, k_B, and k_N, respectively, are defined as specific rate constants for the acid, base, and water (neutral) processes, respectively. This relation can be simplified to

$$R_h = k_h[C] = \{k_A[H^+] + k_B[HO^-] + k_N[H_2O]\}[C] \tag{4.9}$$

and further simplifies by adding the fixed concentration of water at 55 M with k_N

$$R_h = k_h[C] = \{k_A[H^+] + k_B[HO^-] + k'_N\}[C] \tag{4.10}$$

From eq. (4.10) and measured values of the acid, base, and neutral rate constants, a plot of log k_h for hydrolysis of phenyl acetate at 25 °C versus pH (Figure 4.3) provides a graphical picture of the effect of pH on the hydrolysis rate at any fixed temperature. As pH increases from 1 to 7, the rate of the acid-catalyzed reaction slows; beyond 7, the rate again increases, owing to the base-promoted process. If no water-promoted reaction is important, the combined acid and base curves meet at a pH point where their values are equal [25, 26].

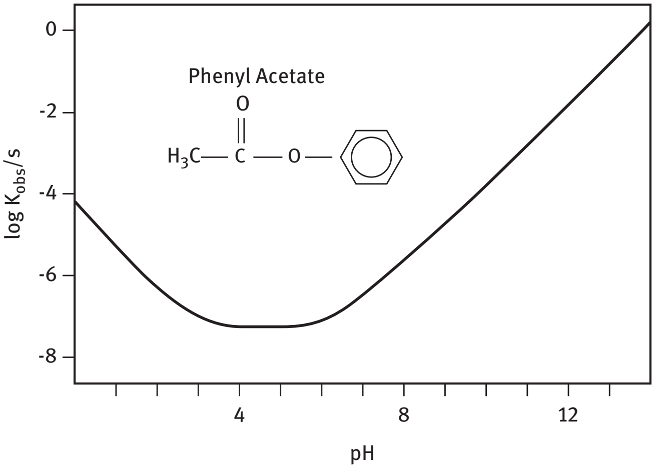


Figure 4.3: Hydrolysis of phenyl acetate. Reprinted with permission from [26]. Copyright (2007) Springer.

Organic chemicals can hydrolyze by a variety of pathways, including both solvolytic and substitution mechanisms catalyzed by H^+ and HO^-. Briefly, a solvolytic process implies a transition state for the reaction of RX as a precursor of the R^+ carbonium ion, which is captured either by water or by other nucleophilic species (N^-) present in water, including X^- to reform the starting compound by cage recombination eq. (4.11)-(4.15)

$$RX \rightarrow R^+ + X^- \tag{4.11}$$

$$R^+ + X^- \rightarrow RX \tag{4.12}$$

$$R^+ + N^{-\,-} \rightarrow RN \tag{4.13}$$

The solvolytic reaction is promoted by polar media such as water but not by acid or base and therefore is pH independent. t-Alkyl and benzyl halides can efficiently stabilize transient carbonium ions to exhibit this pH-independent process.

4.2.2.1.1 Hydrolysis of carbonyl compounds

where R1 is any alkyl group; and Q = –OR2 for carboxylic acid ester, $-NR_2R_3$ for amide, $-OOCR_2$ for anhydride, and –Cl, –Br, –I for acid halides.

As shown in Figure 4.4, acid halides and anhydrides have the shortest hydrolysis half-lives (and corresponding fastest reaction rates) at pH 7, followed by intermediate half-life values for carboxylic acid esters and longest half-lives for amides. This trend in relative reactivity is inversely correlated with the basicity of the leaving group.

4.2.2.1.2 Hydrolysis of esters

$$\mathbf{R_1C(O) - OR_2 + H_2O \rightarrow R_1C(O) - OH + R_2OH}$$

Esters constitute a major segment of the chemical market with applications in coatings, polymer, agricultural products, and pharmaceuticals. Hydrolysis of esters is promoted both by acid (protons) and base (HO^-) as well as water alone to give the alcohol and free acid anion (above pH 5).

$$R_1C(O) - OR_2 + H_2O(HO^-, H^+) \rightarrow R_1C(O) - OH + R_2OH \tag{4.14}$$

$$R_1C(O) - OH + H_2O \rightarrow R_1C(O) - O^- + H_3O^+ \tag{4.15}$$

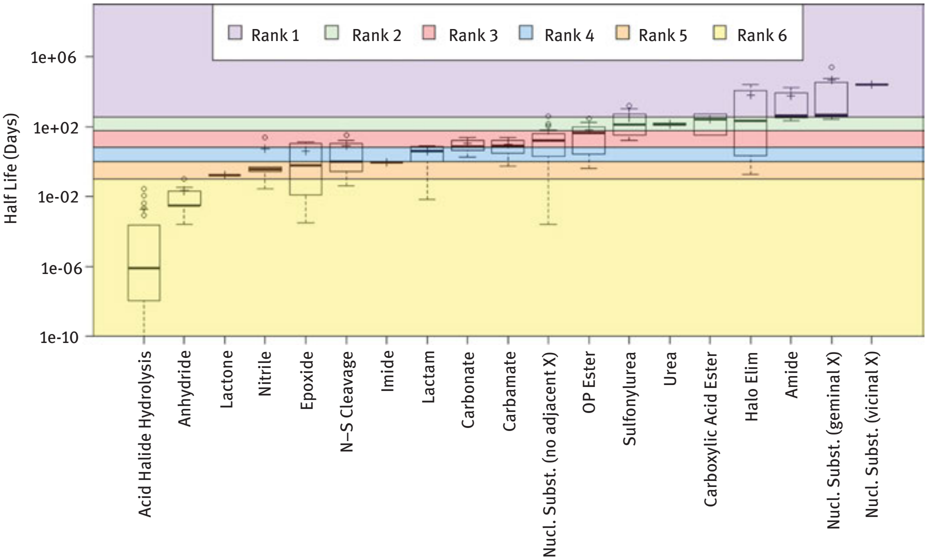


Figure 4.4: Box-and-whisker plots showing the distribution of 25 °C corrected half-lives at neutral pH for hydrolysis of various chemical classes (bottom and top of the box are first and third quartiles, respectively; band inside the box is the median; whiskers are maximum/minimum values, excluding outliers; + is the mean and O is an outlier). Half-lives are shaded according to ranks, as defined in Table 4.1. Reprinted with permission from [27]. Copyright (2017) American Chemical Society.

Table 4.1: Rank assignments for hydrolysis schemes according to median half-lives for hydrolytic transformation of organic chemicals in the environment. Reprinted with permission from [27]. Copyright (2017) American Chemical Society.

Rank	Range of median hydrolysis half-life
6	Less than 2.4 h
5	2.4 h to 24 h
4	24 hours to 7 days
3	7 days to 60 days
2	60 days to 1 year
1	Greater than 1 year

Hydrolysis of esters through acid and/or base catalysis is the subject of several comprehensive reviews [25, 28–31]. For most esters, the acid process constant $k_A = (1 \pm 0.5) \times 10^{-4}\ s^{-1}$ at 298 K and is little affected by steric or electronic effects in the acyl linkage. However, k_A for *t*-butyl acetate is one hundred times smaller than for methyl acetate owing to steric hindrance. Ethyl acetate has a half-life at pH 7 of 2 years due entirely to the base-promoted reaction and the half-life for the acid-catalyzed reaction is 1,000 times longer [25].

Table 4.2 lists a variety of aliphatic and aromatic esters that illustrate the effects of molecular structure on the value of k_B. Besides the steric effect, electron-withdrawing groups such as phenyl, nitro, and chlorine on either the acyl or alkyl ester fragments significantly increase the rate of the base-promoted reaction by increasing the polarization of the carbonyl. In the acetate series from CH_3–, $ClCH_2$–, Cl_2CH–, $t_{1/2}$ values at pH 7 decreased by a factor of 28,000 [25].

Table 4.2: Ester hydrolysis: Effects of molecular structure on half-lives at pH 7[a] [25].

$R_1C(O)OR_2$	$R_1C(O)OR_2$	k_h/s^{-1a}	$t_{1/2}$
Me	Et	1.1(−8)	2.0 year
Me	i-Pr	2.6(−9)	8.4 year
Me	t-Bu	1.6(−10)	140 year
Me	C6H5	2.1(−7)	40 days
Me	2,4-$diNO_2C_6H_3$	2.1(−5)	9.6 h
$ClCH_2$	Me	1.4(−5)	14 h
Cl_2CH	Me	3.0(−4)	38 min
Cl_2CH	C_6H_5	3.1(−3)	3.8 min

[a] 1.1(−8) corresponds to 1.1×10^{-8}

The slow or rate-controlling step in ester hydrolysis determines the magnitude of both steric and electronic effects. Johnson accounted for 18 different intermediate equilibria in acid-catalyzed ester hydrolysis [31]. Most of these intermediates have millisecond lifetimes, frustrating efforts to develop more robust structure-activity correlations (see below). Figure 4.5 illustrates the multiple reaction steps involved in hydrolysis of many carbonyl compounds.

Similar sequences exist for the other carbonyl systems including amides and carbamates. Amides also hydrolyze by acid- and base-catalyzed processes to carboxylic acids and amines by a process identical for the most part with that for esters. However, simple amides are about 1,000 times less reactive than simple esters in the base-catalyzed process. This reactivity pattern reflects the relative ease of removal of −OR, $-NR_2$, and −HNR [26].

Structure-reactivity patterns for the alkyl amides are much like those of esters where electrophilic substituents accelerate the reaction, but have no effect on the acid-catalyzed process. Half-lives for alkyl amides at or near pH 7 are mostly hundreds or thousands of years and can be considered as persistent in the environment, except in soils where biodegradation via microbially generated enzyme-catalyzed reactions likely occur [25].

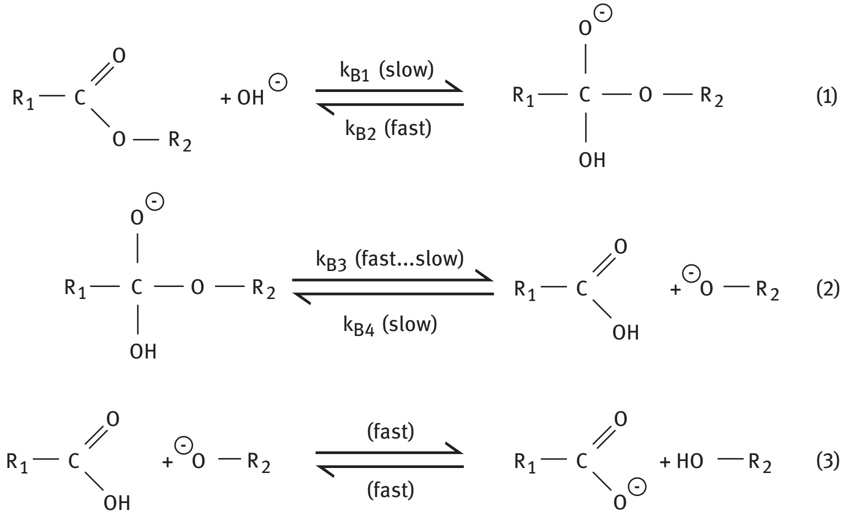


Figure 4.5: Illustrates the multiple reaction steps involved in hydrolysis of many carbonyl compounds.

Carbamates are carbonyls which find wide use as polymer precursors via the isocyanate intermediate, which reacts with alcohols to produce polyurethane polymers, important components of foams, thermoplastic elastomers, and paints. The carbamates hydrolyze to alcohols, amines, and CO_2, probably via the intermediate carbamic acids. Although some carbamates are moderately reactive at 298 K, overall, they have values for k_B that span s 5 orders of magnitude [25].

The exceptions are carbamates with –NHR instead of NR_2 where reactivity toward HO^- (k_B) increases by factors of 10 to 1,000 because pathways change to form intermediate isocyanates (RNCO), which rapidly decompose in water to CO_2 and amines eq. (4.16)–(4.18) [25].

$$R_1OC(O)NHR + HO^- \rightarrow ROC(O)NR^- + H_2O \tag{4.16}$$

$$ROC(O)NR^- \rightarrow RNCO + RO^- \tag{4.17}$$

$$RNCO + H_2O \rightarrow RNH_2 + CO_2 \tag{4.18}$$

4.2.2.1.3 Hydrolysis of alkyl and aromatic halides and polyhaloalkanes

$$R - X + HO - \rightarrow R - OH + HX$$

Alkyl and allylic halides hydrolyze by water and hydroxide ion pathways with displacement of the halide ion and formation of alcohols; no acid-catalyzed process has been observed. Although the span of half-lives ranges over 11 orders of magnitude, most of the alkyl, allyl, and benzyl halides have half-lives of less than 150 days; benzotrichloride ($C_6H_5CCl_3$) has a 3-min half-life, whereas the half-life for $HCCl_3$ is over 3,000 years, both at neutral pH [25, 31].

Table 4.3: Half-lives for hydrolysis of halogenated alkanes and aromatics [25].

R-X	k_H/s^{-1a}	$t_{1/2}$
MeCl	2.8(−8)	300 days
MeBr	4.0(−7)	19 days
CH_2Cl_2	3.2(−11)	690 years
$HCCl_3$	6.9(−12)	3,200 years
EtCl	2.1(−7)	38 days
EtBr	2.6(−7)	31 days
i-PrCl	2.6(−7)	31 days
t-BuCl	3.0(−2)	23 s
$PhCH_2Cl$	1.3(−5)	15 h
$PhCHCl_2$	1.6(−3)	7 min
PhCCl3	6.3(−2)	11 s

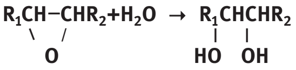
[a] $2.8(-8) = 2.8 \times 10^{-8}$

For many polyhaloalkanes, there are two reaction paths available owing to the combined inductive and steric effects of the polyhalo groups to increase the acidity of adjacent C-H bonds and as well as to pose a steric barrier to HO^- displacement of a halide, thus facilitating β elimination of HX with the formation of vinyl halides as well as aldehydes rather than alcohols (eqs. (4.19), (4.20). These are the rare examples of a degrading pathway that produces daughter products more toxic than the parent compounds.

$$R'CH_2CHCl_2 \rightarrow R'CH=CHCl + R'CH_2CH(OH)Cl + HX \tag{4.19}$$

$$R'CH_2CH(OH)Cl \rightarrow R'CH_2CH=O + HCl \tag{4.20}$$

4.2.2.1.4 Hydrolysis of epoxides



$$R_1CH{-}CHR_2 (\text{-O-}) + H_2O \rightarrow R_1CH(OH)CH(OH)R_2$$

Epoxides hydrolyze mainly by acid-catalyzed and water-promoted reactions to give 1,2-diols. For terminal epoxides, those without primary carbon attachments, there is little effect on k_N or k_B values by substitution at secondary carbon: $10^7 k_N = 5.7 \pm 3$ and $10^4 k_B = 0.85 \pm 0.3$. However, with attachment of alkyl groups to beta positions, k_A values increase dramatically to stabilize incipient carbonium ions, with the result that even at pH 7, the acid-catalyzed process dominates. Half-lives for these epoxides are about 10 ± 5 days. Aromatic epoxides have half-lives close to 6 min, about a 1,000-fold increase [25].

4.2.2.2 Photochemical and redox transformations

The earth's surface is bathed in sunlight 24 h/day, but not uniformly in place, time or always under clear skies. Sunlight is limited to wavelengths above 290 nm, meaning that compounds absorbing weakly or not at all above 290 nm are not subject to direct photolysis, but still may undergo reactions initiated with sunlight through one of several indirect photolysis routes.

Absorption of energetic sunlight photons, with energies >60 kcal/mol, can initiate a wide range of reactions involving fragmentation of C-X, C = O or C-C bonds to free radicals, rearrangements, ring closures, or isomerizations [32]. In air, radicals combined with oxygen lead to destruction of aromatic rings such as toluene, but in surface waters where oxygen is only slightly soluble, solvated cations often form in preference. For example, photolysis of aqueous chlorobenzene under a headspace of air or nitrogen produced only phenol, indicative of formation of a phenyl cation [33].

Indirect photochemical reactions result when one molecule absorbs solar photons and transfers the energy to another molecule that then decomposes. Often, the absorbing species is a natural humic material. Unlike hydrolysis or other thermal reactions of ground-state molecules, photoprocesses are controlled by quantum chemical rules governing formation and decay of high-energy intermediates capable of multiple and competing reactions. The complexity of these excited-state kinetic processes has inhibited the development of reactivity rules similar to those associated with thermal reactions of ground-state species (see Section 3.3). Below we discuss the kinetic features of both direct and indirect photoprocesses.

4.2.2.2.1 Direct photolysis kinetics – measurements in the laboratory

Photochemical kinetics for direct photoreactions reflects the need to determine only the number of photons absorbed by a compound per unit time (k_p in Einsteins-volume/time) at each frequency (λ) as measured by light intensity in the compound's absorption spectrum, as well as the quantum yield (Φ), which measures the efficiency with which the absorbed photons are used to effect chemical change. The photolysis rate R_p is

$$R_p = d[C]/dt = \Phi \times \text{photonsabsorbed}/\text{time} \tag{4.22}$$

$$d[C]/dt = \text{rate} = \Phi k_p \tag{4.23}$$

Quantum yields in the environment rarely exceed 0.1 (10 % efficient) and often are <0.01. To determine k_p, the rate constant for direct photolysis, requires experimental measurements because neither quantum yields nor absorption spectra can be computed with the required accuracy. However, by setting $\Phi = 1$ and measuring just the UV/Vis spectrum, the maximum value of k_p that results will indicate if the compound is persistent or significantly affected by sunlight [34, 35]. Since the true value of k_p almost always must be smaller, making the compound still more persistent, this calculation is a conservative estimation procedure.

Haag, Mill and co-authors [34] describe a method for measuring quantum yields applicable to laboratory experiments using a narrow-spectrum light source or to field conditions where sunlight intensity changes with time and cloud cover. The aqueous UV spectrum of nitroquanidine (NQ) was shown to absorb sunlight strongly between 300 and 400 nm. Kinetic experiments were conducted in the surface water of a local lake to measure changes in concentrations of NQ in sunlight and with *p*-nitroacetophenone (PNAP) as an actinometer to monitor sunlight intensity. Slopes from plots of $\ln\{[NQ_t]/[NQ]_0]\}$ vs. $\ln\{[PNAP_t]/[PNAP]_0]\}$ were used to determine the quantum yield (Φ) for NQ using eq. (4.24), where the $L\varepsilon_\lambda$ values are the day/night-averaged solar intensity data for spring and summer summed over all wavelengths from 290 to 400 nm at 40° N Lat [35].

$$\Phi_{NB} = \Phi_{PNAP} S \frac{\sum_{\varepsilon\lambda}^{PNAP} L_{\varepsilon\lambda}}{\sum_{\varepsilon\lambda}^{NQ} L_{\varepsilon\lambda}} \tag{4.24}$$

The summation symbol (${}^{NQ}\Sigma_\varepsilon L_{\varepsilon\lambda}$) in eq. (4.25) provides the sunlight absorption rate constant for NQ, which when multiplied by Φ from eq. (4.24) gives the photolysis rate constant (k_{pNQ}) in eq. (4.25).

$$k_{pNQ} = \Phi_{NQ} \sum^{NQ} L_{\varepsilon\lambda} \tag{4.25}$$

Applying eq. (4.25) to NQ gave k_p values of 0.9, 1.1, 0.5, and 0.3 days^{-1} for spring, summer, fall, and winter, respectively, corresponding to half-lives of NQ of 0.8, 0.6, 1.3, and 2.3 days in near-surface water at 40°N latitude. $L_{\varepsilon\lambda}$ values are tabulated for the four seasons at each decadic latitude from 0° to 50° for clear sky conditions. The PNAP/pyr binary actinometer is widely used to measure quantum yields in the field for several days to several weeks of exposure [35, 36].

4.2.2.2.2 Direct photolysis kinetics – measurements in natural waterways

Sunlight optics in a natural waterway (river, lake, or ocean) is much more complicated than the collimated, filtered light used for measuring quantum yields in the laboratory. Figure 4.6 illustrates the complex light paths associated with multispectral sunlight (290–600 nm) impinging on surface waters. The effects of refraction, reflection, absorption, and angular light entry into water lead to path lengths longer than water depth, plus a limited photic zone, below which <1% of light is available. Exact treatment of the rate equations for photolysis under these conditions is not only complicated, but also not subject to a single general rate expression. See Schwarzenbach et al. [9] and Leifer [35] who provide detailed analyses and Winterle et al. [37] who describe experimental procedures to measure light intensity at depth in waterways.

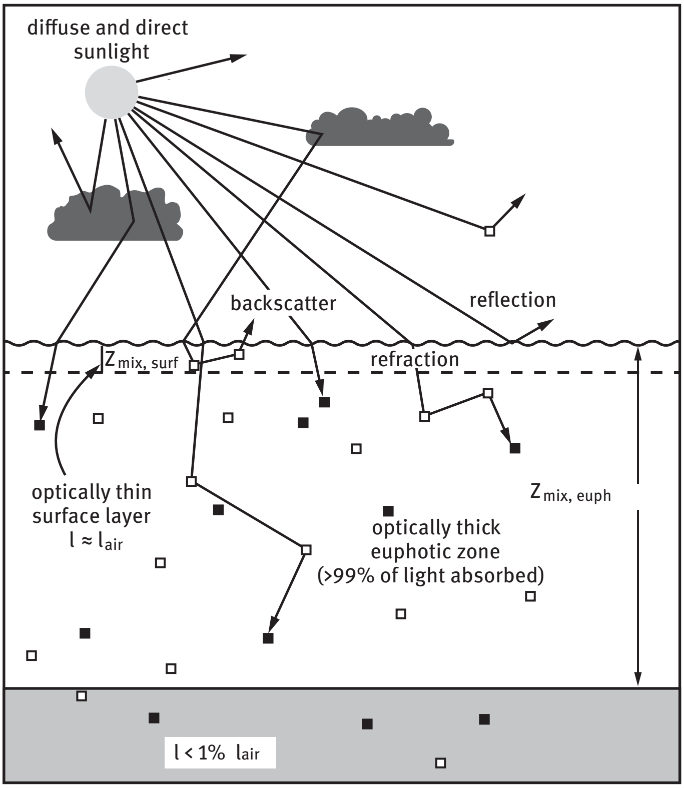


Figure 4.6: Show multiple light paths in sunlit natural water resulting from absorption, reflection, refraction and scattering in and on the water.

4.2.2.2.3 Indirect photolysis

Indirect photolysis, driven by sunlight, occurs in surface waters, on soil, and in the atmosphere at rates that often make this transformation process the most important one for many classes of organic compounds that otherwise do not photolyze directly.

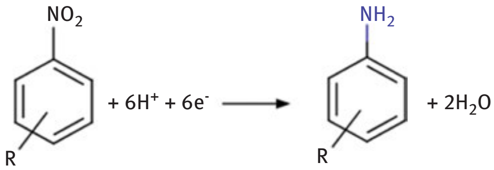
Indeed, more than 90 % of the organic compounds present in the troposphere are transformed more rapidly by HO’ radical than by any other atmospheric process [38].

Humic and fulvic acids are important natural polymers that absorb sunlight and generate a suite of oxyradicals including RO’ and RO_2’ radicals, $^1O_2$, and HO’ radical. Sunlight photolysis of atmospheric ozone generates HO’ radical in concentrations high enough to account for a majority of the volatile organics entering the atmosphere to undergo oxidative destruction. Although good experimental evidence has been found for all of these oxidants forming in insolated surface waters and on mineral surfaces, their concentrations are generally too low (in the range of 10^{-13} to 10^{-16} M) to have importance for any but a few highly reactive organic compounds including polyenes, hydrazines, furans, and sulfides [39, 40].

4.2.2.2.4 Redox transformations

Depletion of oxygen in environmental compartments that are not in direct contact with air, such as groundwater, benthic sediments, and deep layers of stratified lakes, can lead to conditions that are favorable for the reduction of organic chemicals. Reductive transformation of an organic molecule requires the transfer of electrons from a reductant (also known as an electron donor) to the organic molecule, which plays the role of the oxidant (or electron acceptor) in the redox reaction. In natural anoxic environments, the most abundant reductants are reduced iron or sulfur species formed from the dissolution of minerals. Both the depletion of oxygen and the dissolution of iron- or sulfur-bearing minerals occur due to microbial oxidation of organic matter; thus, the activity of microorganisms creates the conditions that make abiotic reduction possible [9].

There are a limited number of functional groups on organic molecules that are susceptible to abiotic reductions [9, 41, 42]; however, these functional groups are present in a number of environmentally relevant organic chemical classes, including agrochemicals, textile dyes, solvents, and explosives. For example, the abiotic reduction of the nitro group ($-NO_2$) to an amino group ($-NH_2$) has been found to be a significant process for the environmental fate of nitroaromatic compounds, such as 2,4,6-trinitrotoluene (TNT) (reaction 27) and methyl parathion [9, 41]:



From an ecotoxicological perspective, the aromatic amines formed from nitroaromatic reduction are generally of greater concern for toxicity than the corresponding parent molecules [9].

Abiotic reductive transformations pathways for synthetic organic chemicals usually involve multiple electron steps, and in some cases, may involve electron transfer mediators, such as natural organic matter or iron porphyrins [9, 41]. A detailed characterization of reduction mechanisms for synthetic organic chemicals is outside the scope of this chapter; however, the pathways, kinetics, and thermodynamic considerations for abiotic reductive transformations have been described in comprehensive reviews by Schwarzenbach et al. [9], Larson and Weber [41], and Macalady et al. [42].

4.2.2.3 Biotransformations

Biotranformation of organic molecules is a major environmental process for removing not only natural compounds, but also many newer synthetic ones, as well as several generations of daughter products from the environment. Hundreds of millions of years of biological activity have provided an enormous variety of bacterial and fungal species needed to degrade natural organic molecules. Synthetic chemicals are newcomers for which biological adaptations evolve slowly. But, in a number of cases, enzymes used to transform natural products can also be effective for some synthetic molecules. So far though, many polymers and perfluorinated compounds defy biotic and abiotic transformation processes alike owing either to low solubility, thermodynamic factors (i. e. high bond strengths) or kinetic limitations.

Descriptions of biotransformation processes are plentiful and are not a detailed subject for this chapter. Modern analytical, biologic, and computer modeling advances provide new insight into the biotic chain of events starting with, for example, a parent herbicide on soil, leading to intermediates and culminating with CO_2 and water plus hetero-oxides (nitrate, sulfate, etc.) for the fast aerobic processes, or methane, ammonia, and sulfide in the usually slower anaerobic pathways. Once again, Schwarzenbach et al. [9] provide us with incisive descriptions of biotransformations as shown in Figure 4.7; Boxall et al. [43] have summarized many product studies describing the degradation pathways of agricultural products on soil, where microorganisms are most plentiful. In aquatic compartments, hydrolysis and photolysis compete with biodegradation, but in the atmosphere, oxidation via the photolytically generated $HO^{\cdot}$ radical dominates in most circumstances.

An important takeaway lesson, then, is that multiple abiotic and biotic processes do compete over time and local circumstances in many environmental compartments in controlling the fate of the organic compounds found therein. It should be clear that direct characterization of the compartments of interest with respect to all of the reactions described here is an essential component of reliable modeling efforts to describe the current or future fate of the many organic compounds that continue to pollute the planet.

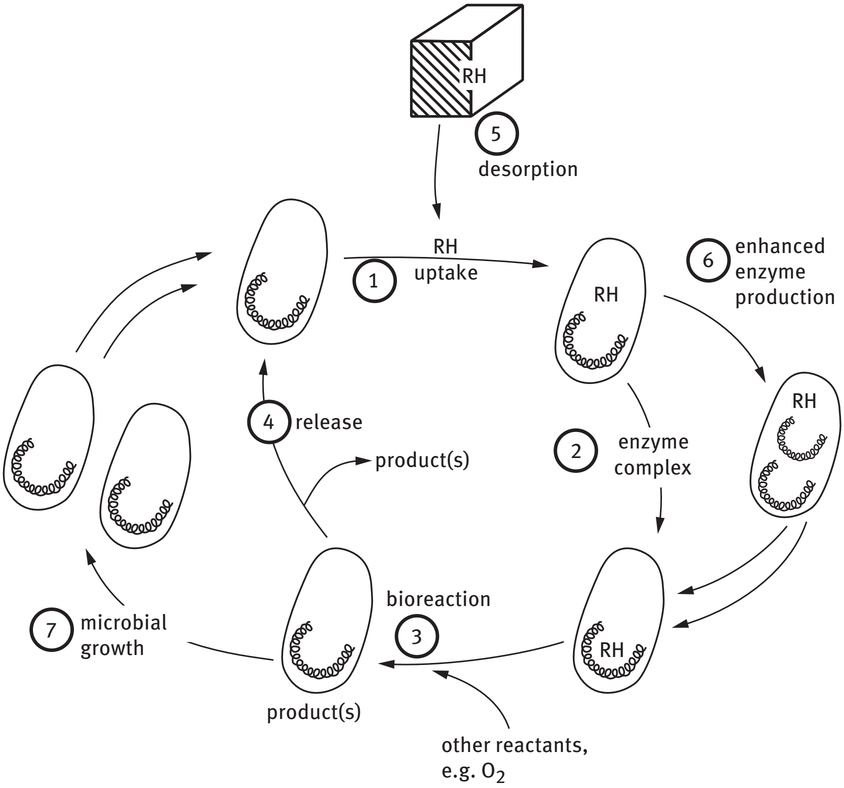


Figure 4.7: Sequence of events in overall process of biotransformations. Reprinted with permission from [9], Copyright (2003) Wiley.

4.3 Prediction of chemical transformation products and rates in the environment

4.3.1 Predicting environmental transformation products

4.3.1.1 Software tools for prediction of environmental transformation products

There are three fundamental components of any software application for the prediction of transformation products: (i) it needs to understand the basic rules about chemical structures (“cheminformatics layer”) by encoding them in a computer-readable format; (ii) it needs a curated database of known transformation pathways, products, and half-lives as a training dataset to develop a knowledge base of generalized reaction schemes which serve as the prediction engine of the software; and (iii) it needs a logic layer to prioritize predicted products from multiple pathways under user-specified experimental conditions to increase sensitivity and selectivity. We will discuss each of the components in greater detail in the next sections.

When a user enters a chemical of interest, the molecule is converted into machine-readable format using the cheminformatics layer, and all the structural features are compared to the encoded reaction schemes. When a positive match is made using conditions specified in logic layer, the scheme is executed and a predicted product is generated. This is applied iteratively to obtain subsequent generations of predicted products.

Examples of software tools designed for prediction of environmental fate include the META expert system [44], enviPath [45, 46], and the chemical transformation simulator (CTS, under development at US EPA [27, 47]).

4.3.1.2 Cheminformatics layer

Cheminformatics may be defined as the generation, storage, indexing, and search of information relating to chemical structure and chemical processes. One of the most basic cheminformatics applications is encoding chemical structures and reactions in a computer-parsable form. Simplified molecular-input line-entry system (SMILES) language, developed by David Weininger in 1980s [48] at the Environmental Research Laboratory, US EPA, Duluth, MN and later at Pomona College in Claremont, CA, is a very popular language which represents chemical structures as alphanumeric characters (Table 4.4). Due to its simplicity, SMILES language does not allow for substructure searching, i. e. finding a particular pattern of atoms in a molecule, or formulating generic reaction schemes; SMARTS [49] and SMIRKS [50] were created, respectively, to fill these gaps.

Table 4.4: Example IUPAC names and SMILES representations for common chemicals.

IUPAC Name	SMILES	Structure
Propane	CCC	
prop-1-ene	C = CC	
Benzene	c1ccccc1	

In addition to a string-based structural representation of molecular structure, other descriptors such as pK_a, log K_{ow}, partial charge distribution, Hückel localization energy, etc. may be needed to correctly predict chemical transformations in a software system. An XML-based language like chemical markup language (CML) [51] can be used to encode these property descriptors along with structural information. CML still needs external software libraries such as CDK or AMBIT, both developed by the Blue Obelisk community [52], to calculate the physicochemical properties. These cheminformatics toolkits are freely available and their source code is open source; however, building a transformation prediction model solely from these open-source toolkits requires some software engineering background. Conversely, the commercially available reactor and metabolizer applications from ChemAxon are more user-friendly alternatives based on a proprietary cheminformatics language called chemical terms language (CTL) [53] which, unlike the open source alternatives, tightly integrates arithmetic and logic operators, similarity and substructure matching, and physicochemical property calculators, with the syntax for encoding reaction schemes.

4.3.1.3 Knowledge base

To develop a system like enviPath (and its predecessor EAWAG-PPS/BBD) or CTS, a group of experts compiles and curates a database of known chemical transformation pathways, reaction rates, and major degradation products. Using this database, frequently referred to as a knowledge base, generalized reaction schemes are developed and encoded based on structural descriptors in machine-readable formats such as SMIRKS, CTL etc., which are then used for the prediction of pathways. These reaction schemes have a mechanistic basis and correspond to specific reaction mechanisms already documented in the scientific literature.

In some cases, criteria must be explicitly specified to ensure that the encoded reaction schemes do not overlap with other reaction schemes for structurally similar functional groups. For example, in CTS's carboxylic acid ester hydrolysis reaction scheme (Figure 4.8), the first reactivity rule specifies that atom 3 is not part of an anhydride structure to distinguish it from the scheme for anhydride hydrolysis and the second rule distinguishes it from the lactone scheme by explicitly specifying that if atom 3 is part of a ring, then the lactone scheme should be triggered instead. Figure 4.10 shows an output of predicted hydrolysis products of metsulfuron-methyl from CTS; products 1.1, 1.2, 1.3.1, 1.3.2 are from the sulfonylurea hydrolysis scheme (Figure 4.9) and 1.3, 1.4, 1.1.1, and 1.1.2 are from carboxylic acid ester hydrolysis (Figure 4.8). These predicted products are in agreement with laboratory studies conducted at pH 7 and 65 °C, which indicated that the dominant hydrolysis products of metsulfuron-methyl were 2-(aminosulfonyl)benzoic acid (products 1.1.1 and 1.3.2) and 4-methoxy-6-methyl-1,3,5-triazin-2-amine (products 1.2 and 1.3.1) [54].

4.3.1.4 Logic layer

The goal of the logic layer is to increase the selectivity and sensitivity of a prediction model. Sensitivity is defined as number of correctly predicted transformation

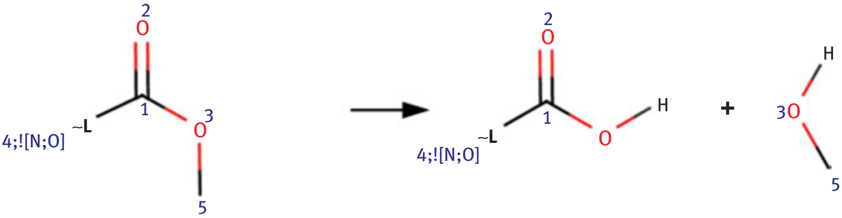


Figure 4.8: Generalized reaction scheme encoded in CTL for carboxylic acid ester hydrolysis where *L* is any atom except N or O.

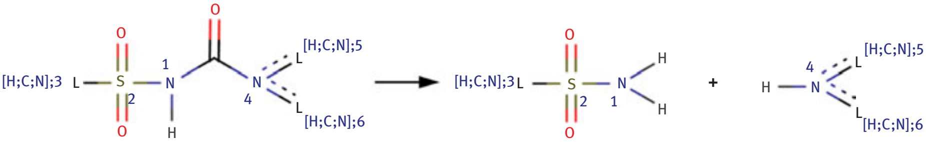


Figure 4.9: Generalized reaction scheme encoded in CTL for sulfonylurea hydrolysis, where *L* is a H, N, an aromatic or aliphatic C.

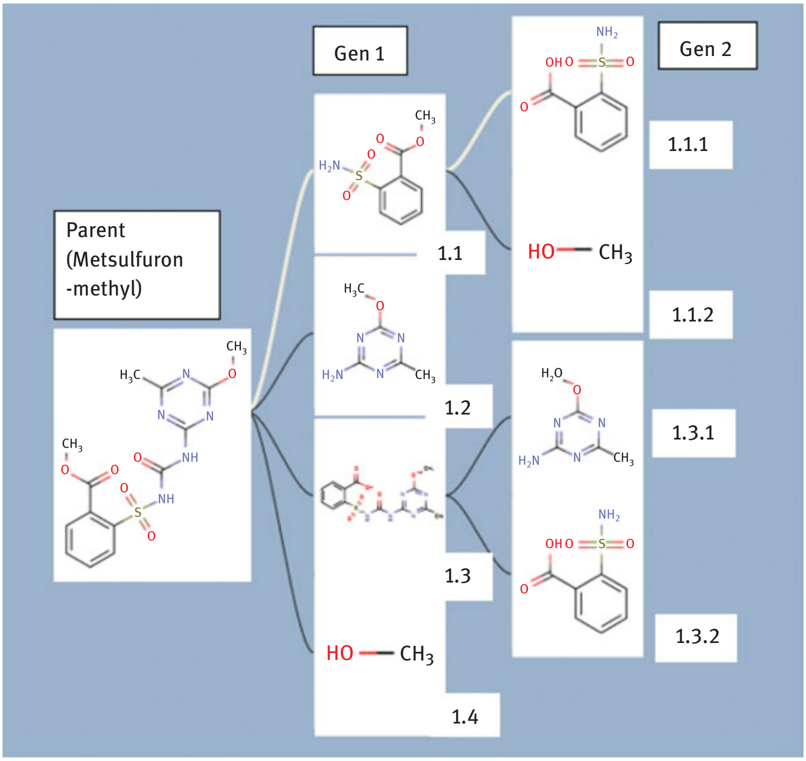


Figure 4.10: Transformation product prediction from CTS for hydrolysis of the sulfonylurea pesticide metsulfuron-methyl.

products (N_{TP}, also known as true positives) divided by the total number of observed transformation products (N_{obs}) in laboratory studies.

$$\mathrm{Sensitivity} = N_{\mathrm{TP}}/N_{\mathrm{obs}} = N_{TP}/(N_{\mathrm{TP}} + N_{\mathrm{FN}}) \tag{4.27}$$

where N_{FN} is the number of false negatives, or transformation products that were observed, but not predicted.

Selectivity is defined as the number of correctly predicted transformation products divided by the total number of predicted products (N_{pred}):

$$\mathrm{Selectivity} = N_{\mathrm{TP}}/N_{\mathrm{pred}} = N_{\mathrm{TP}}/(N_{\mathrm{TP}} + N_{\mathrm{FP}}) \tag{4.28}$$

where N_{FP} is the number of false positives, or transformation products that were predicted, but not observed.

If the prediction model was perfectly correct, there would be no false negatives or false positives, and both sensitivity and selectivity would be equal to one. In practice, selectivity and sensitivity are generally not equal to one. A sensitivity value less than one means that either there was no reaction scheme in the knowledge base which predicted the observed metabolite or it may simply be that more generations of predicted products are needed before the product is predicted to form. On the other hand, a selectivity value less than one indicates that the model has predicted one or more products that were not observed in laboratory studies. Selectivity will be negatively impacted by the fact that not all transformation products may be observed in laboratory studies at a given experimental pH and temperature. Prediction of irrelevant transformation products under user-specified experimental conditions can become a major problem when reaction schemes are iteratively applied to predict consecutive reactions. This is commonly referred to as combinatorial explosion [44, 55].

In general, most rule-based prediction systems show higher sensitivity than selectivity. Various approaches to increase selectivity and to estimate proportions of each predicted product are described below.

4.3.1.4.1 Ranking

In order to prioritize the likelihood of formation of multiple predicted products, schemes within a knowledge base are often ranked based on their rates or likelihood of occurrence. Reaction schemes within UM-BBD/PPS [56] were classified into ranking tiers (very likely; likely, neutral; unlikely, very unlikely) for biodegradation under environmental conditions (neutral pH, 25 °C) by consensus of a group of experts (two or more) at a workshop. CTS employs a more quantitative approach to arrive at a ranking. The knowledge base database contains experimentally verified hydrolysis products and measured rate constants at pH 5, 7, and 9. Median half-lives from this database were used to classify reaction pathways into ranks as shown in Table 4.1. These ranks were used as the inputs to calculate the approximate percentage formation of each predicted transformation product using ChemAxon's metabolizer's prepackaged algorithm.

A more quantitative assessment of the relative likelihood of formation of multiple predicted products can be obtained through the estimation of transformation rate constants using LFER-based approaches, which are described in Section 3.2. For example, SPARC [57–59], HYDROWIN [16], and more recently developed QSARs [60] provide estimated hydrolysis transformation rate constants for various functional groups that are subject to hydrolysis. If equations are available to estimate the rate constants for all possible transformation schemes affecting a chemical of interest, the fractional formation of a given product is given by the ratio of the corresponding transformation rate constant over the sum of rate constants of all transformation processes affecting the parent compound.

4.3.2 Structure activity and linear free energy relations (SARs and LFERs): predicting transformation rate constants

A systematic approach for predicting rate constants for hydrolysis- or oxidation-induced transformations takes advantage of the fact that despite almost limitless diversity among chemical structures, most organic compounds share some common transformation pathways with other structurally similar compounds. Hydrolysis is one of the most familiar and well-studied reactions for which SARs and LFERs have been developed. For hydrolysis of carbonyl compounds (excluding ketones and aldehydes) or epoxides, measured rate constants for known carbonyl compounds similar to new, but unmeasured ones, provide a semiquantitative estimate of k_B or k_A.

LFER estimates are based on combinations of kinetic and thermodynamic parameters trained by fitting to measured values. An early example is the Hammett equation (eq. (4.29)), which was developed to compare the effects of substituents on the phenyl group on the acidity of substituted benzoic acids [61], which was further expanded to apply to a variety of reactions of both aromatic and aliphatic compounds (e. g. hydrolysis, oxidation, halogenation). Along with the later Taft, Swain, and Bronstead equations, the Hammett equation is linear in log k_x, and free energy, thus linear in free energy.

$$\log k_X = \rho\sigma_X + \log k_H \tag{4.29}$$

where k_H is for a compound with a known value and k_X is for the unknown value; σ_X is a portable substituent parameter that measures the sum of the electronic effects expressed by substituent X (inductive, mesomeric, and polar), independent of the reaction type, and ρ is a measure of the sensitivity of a specific reaction to changes in the electronic properties of a series of X's.

The key features of the Hammett equation are that (a) X, as a para- or meta-substituent, is remote from the reaction center, thus divorced from steric effects: only electronic effects need to be accounted for and (b) σ is independent of reaction type. A negative value for ρ indicates an electron-deficient reaction center stabilized by electron-donating groups, the most common situation for an oxidation reaction. Over the years, ρ and σ constants have been determined for many reaction types and for 50+ substituents on aromatic, bicyclic, and aliphatic systems as well [62, 63].

Taft developed an analogous equation (eq. (4.29)) for reactions of aliphatic systems in which both steric and electronic effects often are important:

$$\log k_X = \rho\sigma^\star + \delta E_s + \log k_H \tag{4.30}$$

In eq. (4.30), $\sigma^\star$ has the same meaning as in the Hammett equation (with different numerical values), E_s is the steric parameter for substituent X, and δ is a measure of the sensitivity of the reaction to changes in steric properties near the reaction center. The great advantage of these LFER is their relative simplicity and applicability to a wide range of reaction types yielding accurate value within factors of +/− 2 in many cases.

An example of the use of a LFER, incorporating not only Hammett, but also Taft (steric, electronic) parameters, is shown for the master eq. (4.31) for hydrolysis of 103 aromatic and aliphatic esters for which measured values of k_B are available and correlated using multivariate analysis for a broad range of structures fitting the form XRC(O)OR'X' [64].

$$\begin{aligned}\log k_B = 0.92E_{sR} + 0.36E_{sR'} + 2.14\sigma_{\star R} + 2.27\sigma_{\star R}{}_{+}\, 1.81\sigma_X \\ + 1.30\sigma_{X'} - 0.84\log k_{B0} + 1.13\,(\text{solvent corr})\; r^2 = 0.96, n = 103\end{aligned} \tag{4.31}$$

Equation 4.31 covers a reactivity range of almost 10^{10} for esters. The relatively good fit of the data shown in Figure 4.11 illustrates the value of using combined Hammett and Taft correlation constants to account for inductive, mesomeric, and steric effects. Updated values of σ and ρ are found in many chemistry texts and online, as well as in Hansch and Leo [62] and Todeschini et al. [63].

US EPA's EPI Suite [16] contains a plugin called HYDROWIN which uses Hammett–Taft sigma-based LFER approaches to predict hydrolysis rates for functional groups such as epoxides, carboxylic acid esters, and alkyl halides. Alternatively, the web-based calculator SPARC uses a mechanistic perturbation-based QSAR model to predict reaction rates of hydrolysis of carboxylic acid and phosphate esters [57–59].

4.3.3 Structure activity and linear free energy relations: predicting photolysis rate constants

Direct photolysis rate constants depend on the rate of light absorption coupled with the efficiency factor (quantum yield) – parameters not generally amenable to SAR/LFER estimation methods.

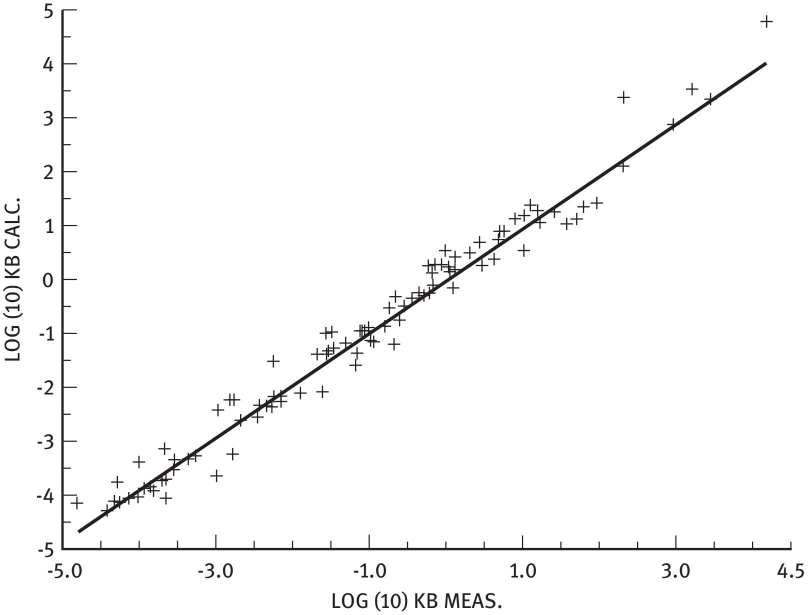


Figure 4.11: Plot of log k_B calculated versus log k_B measured for hydrolysis of aliphatic and aromatic esters from eq. (4.31). Reproduced with permission from [64] Copyright Elsevier 1988.

4.3.3.1 Indirect photolysis – oxyradicals

Indirect photolysis LFERs have been well-developed for estimating reactivities of oxyradicals. Rate constants for the addition of $HO^{\cdot}$ radical to aromatic bonds in substituted benzenes are well-correlated with the Hammett relation [37, 38] using the σ^+ parameter that reflects positive charge in the side chain:

$$k_A = -1.35 \sum \sigma^+ - 11.69 \tag{4.32}$$

where σ^+ ortho = σ^+ para.

An error plot (not shown) of calculated versus estimated values for k_{HO} for more than 100 compounds using eq. (4.31) shows that more than 80 % of the estimated values lie within a factor of 3 or better of the measured values [38].

Equation (4.32) for $HO^{\cdot}$ radical reactivity was developed for volatile, nonpolar chemicals, but the additivity for reactivity of the molecular fragments and the range of structures make possible reliable estimates of k_{HO} for much more complex, low-volatility compounds such as polychlorinated biphenyls and chlorodioxins.

Rate constants for addition of atmospheric ozone to double bonds follow additivity rules similar to those for the $HO^{\cdot}$ radical [38]:

$$k_{O3} = \sum \alpha k_{O3} \tag{4.33}$$

where α measures the modifying effect of double-bond substituents on the rate constant k_{O3}. About 80 % of the estimated values for k_{O3} are within a factor of 5 of the measured values [38].

Alkoxy and peroxy radicals ($RO^{\cdot}$ and $RO_2^{\cdot}$) are major oxidants in surface waters, but their low concentration in most bulk waters restricts their importance to only those reactions for which k_{ROn} is larger than 10^8 M^{-1} s^{-1} for $RO^{\cdot}$ or $RO_2^{\cdot}$ radicals. This limits oxy radical reactions to oxidation of phenols, aromatic amines, hydrazines, and possibly some activated dienes and enamines [38, 65].

4.3.3.2 Indirect photolysis – singlet oxygen

For similar reasons, the reactivity for singlet oxygen combined with its surface water concentrations of about 10^{-13} M [66] limits reactions to those involving furans, dialkyl sulfides, and phenolate anions [39]. For ionizable azo dyes, the LFER is of the form developed by Scully and Hoigne [66] for phenol oxidation:

$$k_{ox} = 1.3 \times 10^7 (1 - \alpha) + 1.8 \times 10^8 \alpha [O_x] \tag{4.34}$$

in which α, the fraction of the dye ionized, depends on the dye pK_a, and $[O_x]$ refers to the concentrations of mixed oxidants, as measured by the rate of oxidation of furfuryl alcohol, a probe molecule that is rapidly oxidized by both $RO_n^{\cdot}$ and $^1O_2$. Steric effects also can be important for $^1O_2$ reactions. In the series of dialkyl sulfides, R_2S, where R varies from Me to *t*-Bu and Ph, reactivity decreased by a factor 300 [39].

Acknowledgements: Stanford Research Institute colleagues of one author who made material contributions to this chapter are Letty Elgincolin, Lee Gerrans, and Jean Graham. The views expressed in this article are those of the author(s) and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. Any mention of trade names or products does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. This research was supported in part by an appointment to the Internship/Research Participation Program at the National Exposure Research Laboratory administered by the Oak Ridge Institute for Science and Education through Interagency Agreement No. DW-922983301-01 between the U.S. Department of Energy and the U.S. EPA.

References

[1] Grossman E. Chasing molecules. Washington DC, USA: Island Press, 2010.
[2] Chemical abstract content services. Available at: http://www.cas.org/services/content. Accessed: 10 Jan 2018.
[3] Estimates of total number of synthetic chemicals now in use range from 80,000 to 100,000. Available at: https://phys.org/news/2017-01-synthetic-chemicals-agents-global.html.

Accessed: 12 Jan 2017. Countable chemicals in use in the US is close to 24000: Chem Eng News Jan 2017, pg 23.

[4] EPA website for toxic chemicals. Available at:www.epa.gov/environmental topics/chemicals-and-toxic-topics. Accessed: 12 Jan 2018.

[5] Koppman R, editor. Volatile organic compounds in the atmosphere. New York, USA: John Wiley & Sons, Inc, 2007.

[6] Eisenreich SJ. Polychlorinated biphenyls in lake superior. In: Hites RA and Eisenreich SJ, editors. Sources and fates of aquatic pollutants. Washington, DC, USA: Amer Chem Soc. Adv Chem Ser 216, 1987:393–469.

[7] World Ocean Review. 2010. wor.com/en/wor-1/pollution/organic-pollutants. Accessed: 10 Jan 2018.

[8] Moore MQ, Vette W, Oaus C, Shaw CR, Miller JF. Trace organic compounds in the marine environment. Marine Pollut Bull. 2002;45:62–8.

[9] Schwarzenbach RR, Gschwend PM, Imboden DM. Environmental organic chemistry. 2nd ed. New York, USA: Wiley Interscience Publication, 2003.

[10] Mackay D, Leinonen PJ . Rate of evaporation of low solubility contaminants from water to atmosphere. Environ Sci Technol. 1975;9:1178–80.

[11] Smith JH, Bomberger DC, Haynes DL. Prediction of the volatilization rates of high volume chemicals in natural water bodies. Environ Sci Technol. 1980;14:332–7.

[12] Dilling WL. Interphase transfer processes II. Evaporative rates of volatile alkanes from dilute aqueous solution. Environ Sci Technol. 1977;11:405–9.

[13] Liss PS, Slater PG. Flux of gases across the air-sea interface. Nature. 1974;181–4. (London).

[14] Boethling RS, Howard PH, Meylan WM. Finding and estimating chemical property data for environmental assessment. Environ Toxicol Chem. 2004;23:2290–308.

[15] Williams AJ, Grulke CM, Edwards J, McEachran AD, Mansouri K, Baker NC, et al. The comptox chemistry dashboard: A community data resource for environmental chemistry. J Cheminform. 2017;9:61.

[16] Card ML, Gomez-Alvarez V, Lee W-H, Lynch DG, Orentas NS, Lee MT, et al. History of EPI Suite™ and future perspectives on chemical property estimation in US Toxic Substances Control Act new chemical risk assessments. Environ Sci Process Impacts. 2017;19:203–12.

[17] Tebes-Stevens C, Patel JM, Koopmans M, Olmstead J, Hilal SH, Pope N, et al. Demonstration of a consensus approach for the calculation of physicochemical properties required for environmental fate assessments. Chemosphere. 2018;194:94–106.

[18] Chiou CT, Porter PE, Schmedding DW. Partition equilibrium of nonionic organic compounds between soil organic matter and water. Environ Sci Technol. 1983;17:227–31.

[19] Chiou CT, Porter PE, Schmedding DW, Manes M. Partitioning of organic compounds in the octanol-water system. Environ Sci Technol. 1982;16:4–10.

[20] Online listing of K_{ow} values for organic compounds. Available at: https://www.nist.gov/sites/default/files/documents/srd/jpcrd367.pdf. Accessed:12 Jan 2018.

[21] Mannhold R, Poda GI, Ostermann C, Tetko IV. Calculation of molecular lipophilicity: state-of-the-art and comparison of log P methods on more than 96,000 compounds. J Pharm Sci. 2009;98:861–93.

[22] Smith J, Bomberger D. Unpublished work. 1979 (taken from structure reactivity correlations for environmental reactions, Mill T.). EPA Final Report, EPA –560/11-79-012.

[23] Karickoff SW, Brown DS, Scott TA Sorption of hydrophobic pollutants to natural sediments. Internal EPA report, 1978.

[24] Smith JH, Mabey WH, Bomberger DH, Mill T Environmental pathways of selected chemicals in freshwater systems. Part I. EPA Report 600/7-77-113, 1978.

[25] Mabey WH, Mill T. Critical review of hydrolysis of organic compounds in water under environmental conditions. J Phys Chem Data. 1978;7:383–413.

[26] Sum DT, Rikken, MG, Rorije, E, Traas, TP, McLachlan, MS, Peijenburg, WJ. Transport, Accumulation and Transport, Chapter 3. In: Van Leeuwen CJ, Vermeire TG, editors. Risk assessment of chemicals: an introduction. Springer, 2007.

[27] Tebes-Stevens C, Patel JM, Jones WJ, Weber EJ. Prediction of hydrolysis products of organic chemicals under environmental pH conditions.Environ Sci Technol. 2017;51:5008–16.

[28] Moelwyn Hughes EA. The chemical statics and kinetics of solutions. London Academic Press, 1971.

[29] Euranto EK. Chemistry of carboxylic esters. Patel S, editor. New York, NY USA: Academic Press, 1969.

[30] Klausen J, Meir MA, Schwarzenbach RP. Mechanism and kinetics of hydrolysis of a carboxylic ester. J Chem Educ. 1997;74:1440–4.

[31] Johnson SL. General base and nucleophilic catalysis of ester hydrolysis and related reactions. Adv Phys Org Chem. 1967;5:237–325.

[32] Klán PP, Wirz J. Photochemistry of organic compounds: from concepts to practice. Chichester: Wiley, 2009.

[33] Dulin D, Drossman H, Mill T. Products and quantum yields for photolysis of chloroaromatics in water. Environ Sci Technol. 1986;20:72–7.

[34] Haag WR, Spanggord R, Mill T, Podoll RT, Chou T-W, Tse D, et al. Aquatic environmental fate of nitroguanidine. Environ Toxicol Chem. 1990;9:1359–67.

[35] Leifer A. The kinetics of environmental aquatic photochemistry. Washington DC, USA: American Chemical Society, 1988. ACS Professional Reference Book.

[36] Dulin D, Mill T. Development and evaluation of sunlight actinometers. Environ Sci Technol. 1982;16:815–20.

[37] Winterle JS, Tse D, Mabey WR. Measurement of attenuation coefficients in natural water columns. Environ Toxicol Chem. 1987;6:663–72.

[38] Atkinson R. Gas-phase tropospheric chemistry of organic compounds. J Phys Chem Refer Data. 1994;1–216. Monograph no.2.

[39] Mill T. Structure-activity relationships for photooxidation processes in the environment. Environ Toxicol Chem. 1989;8:31–43.

[40] Haag WR, Hoigne J. Singlet oxygen in surface waters 3. Photochemical formation and typical concentrations in various waters. Environ Sci Technol. 1986;20:341–8.

[41] Larson RA, Weber EJ. Reaction mechanisms in environmental organic chemistry. Boca Raton, FL, USA: CRC Press, 1994.

[42] Macalady DL, Tratnyek PG, Grundl TJ. Abiotic reactions of anthropogenic organic chemicals in anaerobic systems: A critical review. J Contam Hydrol. 1986;1:1–28.

[43] Boxall AB, Sinclair CI, Fenner K, Kolpin D, Maund SI. When synthetic chemicals degrade in the environment. Env Sci Technol. 2004;39:368A-375A.

[44] Sedykh A, Saiakhov R, Klopman G, Meta V. A model of photodegradation for the prediction of photoproducts of chemicals under natural-like conditions. Chemosphere. 2001;45:971–81.

[45] Wicker J, Lorsbach T, Gütlein M, Schmid E, Latino D, Kramer S, et al. enviPath – the environmental contaminant biotransformation pathway resource. Nucl Acids Res. 2016;44:D502–D508.

[46] Latino DA, Wicker J, Gütlein M, Schmid E, Kramer S, Fenner K. Eawag-Soil in enviPath: a new resource for exploring regulatory pesticide soil biodegradation pathways and half-life data. Environ Sci Proc Imp. 2017;19:449–64.

[47] Wolfe K, Pope N, Parmar R, Galvin M, Stevens C, Weber E, et al. Chemical transformation system: cloud based cheminformatic services to support integrated environmental modeling.

In: Sauvage S, Sánchez-Pérez JM and Rizzoli AE, editors. Proceedings of the 8th international congress on environmental modelling and software. Toulouse, France, July10–142016.

[48] Weininger D. SMILES, a chemical language and information system. 1. introduction to methodology and encoding rules. J Chem Inj Comput Sci. 1988;28:31–6.

[49] SMARTS - A Language for Describing Molecular Patterns. Available at: http://www.daylight.com/dayhtml/doc/theory/theory.smarts.html. Accessed: 26 Jan 2018.

[50] SMIRKS - A Reaction Transform Language. Available at: http://www.daylight.com/dayhtml/doc/theory/theory.smirks.html. Accessed: 26 Jan 2018.

[51] Murray-Rust P, Rzepa HS. Chemical markup, XML, and the Worldwide Web. 1. Basic principles. J Chem Info Comp Sci. 1999;39:928–42.

[52] O'Boyle NM, Guha R, Willighagen EL, Adams SE, Alvarsson J, Bradley JC, et al. Open data, open source and open standards in chemistry: the blue obelisk five years on. J Cheminform. 2011;3:1–16.

[53] Pirok G, Máté N, Varga J, Szegezdi J, Vargyas M, Dóránt S, et al. “real” molecules in virtual space. J Chem Inf Model. 2006;46:563–8.

[54] EFSA (European Food Safety Authority). Renewal assessment report (RAR): draft re-assessment report review provided by the member state Slovenia and the co-rapporteur member state Sweden for the existing active substance metsulfuron-methyl of annex i inclusion under regulation (EC) 1107/2009, Volume 3, Annex B, B.8, 2013. Available at: http://dar.efsa.europa.eu/dar-web/provision.

[55] Ellis LB, Gao J, Fenner K, Wackett LP. The university of Minnesota pathway prediction system: predicting metabolic logic. Nuc Acids Res. 2008;36:W427–W432.

[56] Ellis LB, Roe D, Wackett LP. The university of Minnesota biocatalysis/biodegradation database: the first decade. Nuc Acids Res. 2006;34:D517–D521.

[57] Hilal SH, Karickhoff SW, Carreira LA, Shrestha BP. Estimation of carboxylic acid ester hydrolysis rate constants. Mol Inform. 2003;22:917–25.

[58] Whiteside T, Hilal SH, Carreira LA. Estimation of phosphate ester hydrolysis rate constants. I. Alkaline hydrolysis. Mol Inform. 2006;25:123–33.

[59] Whiteside T, Carreira L, Hilal S. Estimation of phosphate ester hydrolysis rate constants. II. Acid and general base catalyzed hydrolysis. Mol Inform. 2007;26:587–95.

[60] Patel JM, Stevens C, Weber E. Estimation of hydrolysis rate constants for carbamates. ACS 2017 Annual Spring Meeting. San Francisco, CA, April 02–06, 2017.

[61] Exner O. The Hammett equation –the present position. In: Chapman NB and Shorter J, editors. Advances in linear free energy relationships. London UK: Plenum Press, 1972:1–69.

[62] Hansch C, Leo A. Exploring QSAR volume 1: fundamentals and applications in chemistry and biology. Washington D.C.: American Chemical Society, 1995.

[63] Todeschini R, Consonni V, Mannhold R, Kubinyi H, Timmerman H. Handbook of molecular descriptors, methods and principles in medicinal chemistry. New York, NY, US: John Wiley & Sons11, 2008:, 144–57.

[64] Drossman H, Johnson H, Mill T. Structure activity relationships for environmental processes I. Esters Carbamates Chemosphere. 1988;17:1509–30.

[65] Hendry DG, Mill T, Piszkiewicz L, Howard JA, Eigenmann HK. A critical review of H-atom transfer in the liquid phase. J Phys Chem Ref Data. 1974;3:937–78.

[66] Scully FE, Hoigne J. Rate constants for reactions of singlet oxygen and phenols in water. Chemosphere. 1987;16:681–94.

Justin Pothoof, Michal Ruprecht, Ben D. Sliwinski,
Ben M. Sosnowski, Polly R. Fitzgerald, Steven Kosmas
and Mark A. Benvenuto

5 Synthesis of "three-legged" tri-dentate podand ligands incorporating long-chain aliphatic moieties, for water remediators, and for isolating metal ions in non-aqueous solution

Abstract: Two molecules, each including tris-2-amino-ethyleneamine (tren), have been produced using a Schiff's base condensation and long-chain, aliphatic aldehydes. The syntheses are straightforward and can be run in air at ambient temperature. The ability of these molecules to complex with metal ions makes them good candidates for water remediation. The ability of these ligands to hold metal ions in 0.03 M non-aqueous solutions was unexpected. Their syntheses and characterization are discussed.

Keywords: coordination chemistry, chelation, multi-dentate ligands, Schiff's Base condensation

5.1 Introduction

5.1.1 The synthesis, chelators

The history of the production of multi-dentate ligands is approximately a century old, with salen having first been reported in 1933 [1]. Multi-dentate ligands can be produced in numerous ways, one of which is the addition of functional aldehydes to multi-amine molecules in what is the now classic Schiff's base condensation. The reaction is well-established, robust, and capable of being performed in virtually all solvents but water. The starting amine tren was used in this study precisely because it is stable, inexpensive, and easy to work with.

There are differences in how the Schiff's base condensation proceeds, according to whether or not the amine is aliphatic or aromatic. For example, aliphatic amines generally do not require elevated temperature for these condensations to occur, and

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Pothoof, J., Ruprecht, M., Sliwinski, B. D., Sosnowski, B. M., Fitzgerald, P. R., Kosmas, S., Benvenuto, M. A. Synthesis of "Three-Legged" Tri-Dentate Podand Ligands Incorporating Long-Chain Aliphatic Moieties, for Water Remediators, and for Isolating Metal Ions in Non-Aqueous Solution. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0076

https://doi.org/10.1515/9783110566499-005

can be run in most organic solvents. Aromatic amines normally do require elevated temperatures because of the stability of the benzene ring and its direct connection to the amine. This project used tren exclusively as the starting amine, an aliphatic amine, which meant that starting materials and reactions to form ligands could be handled easily and without elevated temperature.

Historically, people have almost always lived by water, and have always needed clean, potable water for their survival. This need has driven a number of different human innovations to clean or remediate saline, brackish, or otherwise polluted water – from evaporation, to settling and filtration through sand, to more specific and developed molecules for chelation [2–13]. Today, ethylenediamine tetraacetic acid has proven to be an excellent chelator, but this does not mean that the search for other molecules that can complex with metal ions in water is over [14–21].

Perhaps ironically, the presence of people near the very water that is needed for their survival and for an enhanced quality of life often means that water close to them becomes polluted through human activities. Examples of such activity include farming, mining, and large-scale transportation of commodities. For this reason and others, the search for effective means to clean water, and to do so in an economically favorable manner, is a continuing one.

5.1.2 The pedagogy

This research is the result of a collaboration formed through the American Chemical Society’s (ACS) Science Coaches Program, in which a high school teacher and high school students worked with a college professor and undergraduate college students. One of the authors (Kosmas) is a high school teacher, while another (Benvenuto) is a college professor. The ACS program encourages collaboration between the two levels of educator, but gives few guidelines about activities, other than urging them to be productive for students as well as teachers. This project became one in which four high school students and one undergraduate college student worked together to synthesize the target molecules.

It was felt that the project needed to be relevant to a modern problem – the cleaning of polluted water – and be based on techniques and processes that could be performed by a team that was both at the beginning of their careers as scientists and available to work in the laboratory for only limited amounts of time. Importantly, it was also a first step in expanding what can be called the green chemistry mindset of the researchers involved in it [22].

Importantly, these syntheses of new ligands for water remediation requires no more in terms of mathematical calculations than that which is seen in a general chemistry class, either at the high school or at the college level. A one-to-three stoichiometric ratio of amine to aldehyde can be used to produce the ligands. This is similar to any stoichiometry-based problem in a general chemistry class, simply using what might be described as more exotic chemical reagents than those that high school students normally see.

Another concept used and emphasized in the project is molarity, because it is easiest to use the target ligands as a solution of known concentration than it is to evaporate the solution to dryness, characterize the full sample, then measure small portions of the "dried" ligand for further use. This is because the target ligands, like many molecules which contain long-chain aliphatic moieties, exists as extremely viscous, waxy liquids. Thus, solutions of known concentration become a convenient way to deliver exact amounts of the ligands in reactions that formed metal–ligand complexes.

5.2 Safety

Tren and long-chain aliphatic aldehydes should be handled with care. In all cases in this study, students were supervised by faculty, although the actual reaction chemistry was always run by student researchers.

Likewise, perchlorate salts must be handled with care. In this study, all salts were purchased in small amounts (10 g bottles or smaller) to minimize any hazard should one be mishandled.

5.3 Discussion

5.3.1 Ligands

The ligand synthesis involves the addition of one molar equivalent of tren and three molar equivalents of octanal at room temperature, or three molar equivalents of dodecanal under similar conditions. The reaction was run in one of two solvents, monoglyme or toluene, and stirred mechanically for a minimum of 1 h, but can be stirred for days without degradation of the products. A solution of the starting amine in solvent is clear. Addition of the aldehyde produced pale yellow colors after stirring. Figure 5.1 shows an example of the reaction chemistry for the production of the ligand utilizing octanal, producing Ligand **1**. If dodecanal is used, the three "arms"

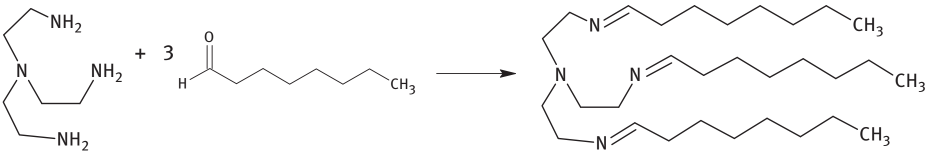


Figure 5.1: Representative ligand formation, Ligand **1**.

are simply four aliphatic carbon atoms longer (one *n*-butyl group longer per arm), resulting in Ligand **2**.

5.3.2 Metal–ligand complex formation

The formation of ligand–metal complexes can occur through two different approaches. A solution of a metal salt can be produced in distilled water and added to a separatory funnel. The solution of the ligand is then transferred into it in the separatory funnel and the two are mixed. Complex formation is immediate, and the complex precipitates into the aqueous phase. Alternatively, a sample of a dry metal salt can be added directly to the ligand in its non-aqueous solution. The complex can then be separated from the solution by rotary evaporation.

In this research project, emphasis was placed on being able to see the formation of a metal–ligand complex, as opposed to quantifying it through instrumental characterization techniques, such as ^{1}H NMR. The reason is that the aim was to produce ligands and ligand–metal complexes in a manner that can be reproduced at the high school level. High schools do not normally have access to characterization techniques beyond UV-Vis spectrometers. Thus, characterization was confined to visible changes in solution colors.

The ability of an organic solution to hold metal ions in such a solution is not unheard of, but is relatively uncommon [23–27]. Since this occurred with seven of eight metals that were used to form complexes, the results of the complex formations through the direct addition of a dry salt to the ligand solution are summarized in Table 5.1. The transition metal ions were all delivered as perchlorate salts, while the lanthanide ions were all delivered as trifluoromethylsulfonate salts. It is noteworthy that the neodymium complex forms a precipitate at this concentration (0.03 M), while the other metal complexes do not do so.

Table 5.1: Metal complex relative solubilities.

Metal ion	Solubility at 0.03 M	Color
Co^{2+}	Soluble, no precipitate	Blue-green
Fe^{3+}	Soluble, no precipitate	Red-brown
Zn^{2+}	Soluble, no precipitate	Goldenrod
Cu^{2+}	Soluble, no precipitate	Green
Nd^{3+}	Precipitate forms	Yellow, with precipitate
Yb^{3+}	Soluble, no precipitate	Light yellow
Pr^{3+}	Soluble, no precipitate	Light yellow
Ho^{3+}	Soluble, no precipitate	Light yellow

5.4 Experimental

Reagents tris-2-aminoethyleneamine (tren) (98 %), octanal (99 %), and dodecanal (> 98 %) were purchased from Aldrich and used without further purification. Reagent purity was verified by running ^{1}H NMR of a sample from each reagent bottle immediately upon opening. Solvents were also purchased and used without further purification.

All ^{1}H NMR, of reagents as well as the target ligands, were run on a Jeol 300 MHz multi-nuclear instrument.

5.4.1 Ligand 1

The starting amine (0.25 g, 1.710 mmol) was added to a 60 mL of monoglyme or toluene and stirred for 5 min. No precipitate was present, and the resulting solution was a very pale yet transparent yellow. Three equivalents of octanal (0.690 g, 5.129 mmol) were then added and the resulting darker yellow solution was stirred for 16 h. The resulting 0.03 M solution was used for metal complexation trials.

5.4.2 Ligand 2

The starting amine (0.561 g, 3.84 mmol) was added to 100 mL of monoglyme (or 100 mL of toluene) and stirred. The resulting solution had a very pale white appearance. Three equivalents of dodecanal were added (2.121 g, 11.52 mmol) and the resulting solution stirred for 16 h. After stirring, the solution was a bright yet transparent yellow. This 0.038 M solution was used for metal complexation trials.

5.4.3 Complex formation

For Ligand **1**, complexes of eight metal salts were formed. The Co^{2+}, Fe^{3+}, Zn^{2+}, and Cu^{2+} were each added directly to Ligand **1** as perchlorate salts in a 1:2 molar ratio of metal to ligand. The Nd^{3+}, Yb^{3+}, Pr^{3+}, and Ho^{3+} were all added directly as trifluoromethylsulfonate salts.

For Ligand **2**, only one complex was formed, using Fe^{3+}, added directly as a perchlorate salt, again in a 1:2 molar ratio of metal salt to ligand.

5.4.4 Control experiments

An aliquot of each unreacted ligand was placed in a sample vial of the same size as those in which the complexes were formed, and they were compared visually. In all cases, the starting ligand solution was not the same color as the complex solution.

In the case of Ligand **1** and the ytterbium trifluoromethylsulfonate, a one-half molar equivalent of the salt was added to a solution of just the starting amine in monoglyme, and the resulting solutions were visually compared. The amine–monoglyme–ytterbium salt solution was colorless, while the Ligand **1**–monoglyme–ytterbium salt solution was a transparent yellow.

5.5 Conclusions and directions for the future

The search for effective, inexpensive molecules that can remediate polluted water is a continuing one. This research thrust has shown that there is a simple set of ligands that can be produced in a straightforward manner, at ambient temperature and pressure, and in a time frame that can be easily adapted to the time allotted to high school chemistry laboratory classes. This should be very easy to apply when teaching students in the upper levels of K-12 education, and should be amenable to performing research using local waters.

Importantly, this series of ligands appear to be a series of molecules that are able to function as water remediators. They readily complex with metal ions in water, and immediately form precipitates from aqueous solutions.

Additionally, the project emphasized a current problem that is direct and obvious, and with which high school and college students can easily identify.

It is believed that while this project gave satisfactory results, it might be expanded to determine if complexes form preferentially for specific Lewis acids, meaning larger versus smaller ions, or those with larger versus smaller charge-to-size ratios.

References

[1] Pfeiffer, P, Breith E, Lübbe E, Tsumaki T. Tricyclische orthokondensierte Nebenvalenzringe. Liebigs Ann Chem. 1933;503:84–130.
[2] Saline Water Conversion Vol. 27. Washington, DC: American Chemical Society, 1960 January 01
[3] In: Gould RF, editor(s). Saline water conversion - II Vol. 38. Washington, DC: American Chemical Society, 1963 January 01
[4] In: Kavanaugh MC, Leckie JO, editor(s). Particulates in water: characterization, fate, effects, and removal, advances in chemistry Vol. 189. Washington, DC: American Chemical Society, 1980 November
[5] Vickers A. The handbook of water use and conservation. Amherst, MA: WaterFlow Press, 20011-931579-07
[6] National Academies Press. Urban stormwater management in the United States. Washington, DC: National Academies Press, 2009
[7] Binnie, C. Basic water treatment. 4th ed. London: Royal Society of Chemistry, 2009. ISBN 9781847558787.
[8] National Academies Press. Letter report assessing the usgs national water quality assessment program’s science framework. Washington, DC: National Academies Press, 2010

[9] National Academies Press. Letter report assessing the usgs national water quality assessment program’s science plan. Washington, DC: National Academies Press, 2011

[10] Ghaffour, N, Missimer TM, Amy GL. Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. Desalination. 2013;309:197–207.

[11] In: Baker A, editor(s). Environmental chemistry of lakes and reservoirs Vol. 237. Washington, DC: American Chemical Society, 19941994. 05 May 1994

[12] Water: Our Thirsty World. National Geographic, A Special Issue. National Geographic, 2010.

[13] Benvenuto, MA. Industrial chemistry. Berlin: DeGruyter, 2014.

[14] Paolieri M. Ferdinand Münz: EDTA and 40 years of inventions. Bull Hist Chem. 2017;42:133–40

[15] Izatt, RM. The synthesis and ion bindings of synthetic multidentate macrocyclic compounds. Chem Rev. 1974;74:351–84.

[16] Bradshaw, JS, Izatt RM. Crown ethers: the search for selective ion ligating agents. Acc Chem Res. 1997;30:338–45.

[17] Gordon, AE, Xu J, Raymond KN, Durbin P. Rational design of sequestering agents for Plutonium and other actinides. Chem Rev. 2003;103:4207–82.

[18] Sessler, JL, Melfi PJ, Dan Pantos G. Uranium complexes of multidentate N-donor ligands. Coord Chem Rev. 2006;250:816–43.

[19] Hayes, CE, Leznoff DB. Actinide coordination and organometallic complexes with multidentate polyamido ligands. Coord Chem Rev. 2014;266–267:155–70.

[20] Jin, Y, Wang Q, Taynton P, Zhang W. Dynamic covalent chemistry approaches toward macrocycles, molecular cages, and polymers. Acc Chem Res. 2014;47:1575–86.

[21] He, Q, Zhang Z, BrewsterJT, Lynch VM, Kim SK, Sessler JL. Hemispherand-strapped calix[4] pyrrole: an ion-pair receptor for the recognition and extraction of Lithium Nitrite. J Am Chem Soc. 2016;138:9779–82.

[22] Kosmas S. Growing your green chemistry mind set. Green Chem Process. 2017;2:137–43.Walter DeGruyter, GmbH.

[23] Sessler, J, Davis JM. Sapphyrins: versatile anion binding agents. Acc Chem Res. 2001;34:989–97.

[24] Liu, Z, Samanta A, Lei J, Sun J, Wanng Y, Stoddart JF. Cation-dependent gold recovery with α-Cyclodextrin facilitated by second-sphere coordination. J Am Chem Soc. 2016;138:11643–53.

[25] Lee, S, Hua Y, Flood AH. β-sheet-like Hydrogen bonds interlock the helical turns of a photoswitchable foldamer to enhance the binding and release of Chloride. J Org Chem. 2014;79:8383–96.

[26] Bonnesen PV, Delmau LH, Moyer BA, Lumetta GJ. Development of effective solvent modifiers for the solvent extraction of Cesium from Alkaline high-level tank waste. Solv Extra Ion Exc. 2003;21:141–70

[27] Lohrman, J, Telikepalli H, Johnson TS, Jackson TA, Day VW, Bowman-James K. Pyrazinetetracarboxamide: a duplex ligand for Palladium(II). Inorg Chem. 2016;55:5098–100.

Dalila G. Kovacs, James Krikke and Kristina Mack

6 An introductory course in green chemistry: Progress and lessons learned

Abstract: This work provides a description of our experience with designing and implementing green chemistry elements in higher education. It addresses the problem of content and methodology in green chemistry education and provides models of innovative approaches in design and teaching practices.

An introductory course, *Pollution Prevention, Green Chemistry and Green Engineering*, supported by a grant from Michigan Department of Environmental Quality, was designed at Grand Valley State University (GVSU), in Michigan, in 2008 and run for the first time in 2009, with 12 students. The positive response from the students who took the class coupled with increasing visibility of green chemistry initiative at the state level (MI Governor's Green Chemistry directive and Green Chemistry Round Table) led the GVSU administration to recognize the need of such a course and, after revision, to its inclusion into the Chemistry Department curriculum, under the designation "*Introduction to green chemistry*", CHM 111. This remains to be a sought-after course for freshmen and upper-level undergraduates interested in the issues of green chemistry who have no chemistry background in their education. Since 2011, the course ran twice a year with a total of 302 students to date (December 2017). From semester to semester, it underwent several modifications, in order to accommodate the most recent, up-to-date developments in green chemistry and green engineering. The repository of teaching materials created is growing continuously. The progress and lessons learned throughout the years in running this course are summarized here.

Keywords: education, green, green chemistry, methodology, teaching materials

6.1 Introduction

Chemistry is a fascinating and diverse field affecting all areas of human life and the environment. It is the largest field of employment from all the sciences. Today's shift from traditional to sustainable chemistry practice, driven by profit and controlled by regulatory and governmental policies, is well recognized in the field of applied chemistry.

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Kovacs, D. G., Krikke, J., Mack, K. An Introductory Course in Green Chemistry: Progress and Lessons Learned. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0077

https://doi.org/10.1515/9783110566499-006

The concept of green chemistry was introduced in the early 1990s. Understanding of chemical reactions has greatly enhanced our life but, to-date, unfortunately has also been associated with pollution and waste. Green chemistry is gaining a strong foothold in the areas of research and development in both industry and academia. Prominent conferences and meetings are held each year with green chemistry/technology as their focus. The *Green Chemistry Institute* was created in 1995 and the Presidential Green Chemistry Challenge Awards were established in the same year. The journal *Green Chemistry* made its debut in 1999.

Despite the massive growing interest in environmental protection and sustainability on one hand and green chemistry serving as "preventative medicine for the environment" (as Dr L. Goldman, US-EPA mentioned in 1996) on the other, education in green chemistry is only slowly making its way into college and university curricula. At the time our work was initiated, the history of green chemistry education was brief. The first PhD program to offer a degree in green chemistry started in 2001 at University of Massachusetts with 15 students. Programs offered at the undergraduate level were like "green islands" throughout the country. MIT had a leading program in undergraduate chemical engineering; University of Oregon had a green organic laboratory course "Introduction to Green Chemistry"; the Universities of Massachusetts at Lowell and at Boston, as well as the Center of Green Chemistry & Engineering at Yale, offered green chemistry courses, while University of Scranton had a series of modules in Green Chemistry.

The Chemistry department at GVSU, accredited by the Committee on Professional Training of American Chemical Society, offers a Bachelor of Science in chemistry and, since 2014, in Biochemistry. Until 2016, only one specialty course in green chemistry and industrial processes (part of the upper-level requirements for the technical emphasis degree option) and one introductory course in green chemistry, targeting freshmen, were included in the curriculum. A significant departamental program change was implemented since 2016; two new courses and an uppper level lab are focused on green chemistry, polymers, and environmetal chemistry. Green chemistry elements are also embedded in other core courses and laboratory sequences. A green chemistry certification with a required hands-on lab experience was instated in 2010.

6.2 The beginning

Pollution Prevention, Green Chemistry and Green Engineering, a course targeting particularly freshmen, was designed by A. Lantz, M. Qi and D. Kovacs, and run for the first time in Winter semester 2009. The work was supported by a grant, won by the chemistry faculty at GVSU, from Michigan Department of Environmental Quality (MI DEQ). The curricular process was successfully completed in 2010 and the class run each semester since 2011 to current date.

The course was run the first time under a special topics designation, CHM 180. The tremendous response from the students supported a strong curricular proposal, materialized in a permanent course, included in the curriculum, under the designation "Introduction to Green Chemistry" CHM 111. This remains to be a sought-after course for freshmen and upper-level undergraduates interested in the issues of green chemistry who have no chemistry background in their education. Since 2009, the course ran twice a year, at full capacity most of the semesters, with a total of 302 students enrolled, including the Fall 2017 semester.

Objective: the class was designed to provide the student with an overview of the fundamentals of pollution prevention, green chemistry and green engineering. The main goal was for the students to gain a greater appreciation of how improvements and modifications are being made in both chemistry research and manufacturing to maintain, and furthermore, to enhance human health and environmental quality. With the assumption that many freshmen, undecided about their undergraduate degree, would enroll in the course, an anticipation existed that this course may also assist students in choosing a professional career.

The initial syllabus concentrated on five major themes, Humans, Water, Air, Energy and Agriculture. The support from the MI-DEQ grant allowed for specific activities that otherwise would be difficult to be incorporated in a freshmen course. A series of field trips were scheduled to bring the real-world experience necessary to attain the proposed objectives. They included a tour of MAREC (Michigan Alternative and Renewable Energy Center) in Muskegon, Wyoming Clean Water Plant, AWRI (Annis Water Resources Institute) in Muskegon and newly (at that time) constructed Zeeland Power Plant which utilizes natural gas as opposed to coal.

Specialists in the field were invited to lecture for the course; Dr Clinton Boyd, formerly from the

Sustainability Research Group and currently at Steelcase, made the introduction to the field of green chemistry. Dr Rick Rediske from GVSU's AWRI (Annis Water Resources Institute) opened the Water unit, while a visit from Dr David Shonnard from Michigan Technological University was the highlight of the Energy unit.

Students were evaluated based on web and literature searches (15 %), participation in group discussions/questions with invited guest speakers (5 %), active participation in field trips (5 %), unit presentations (40 %) and a final presentation (35 %).

Statistical data collected and provided by the GVSU Admission office [1] for the period of 2009–2017 are represented in Figure 6.1 and Figure 6.2 below. It is interesting to notice that degree seeking undergraduates represent only 17 % of total enrollment. An increased interest spiked the enrollment from 2011 to 2014 with a lower but steady distribution of students throughout the following years. The high enrollment experienced lead to changes in the design of the course that affected mainly the field trips. We experimented with several models of course design to accommodate the logistics and time requirements for field trips. When students' opinions on the course

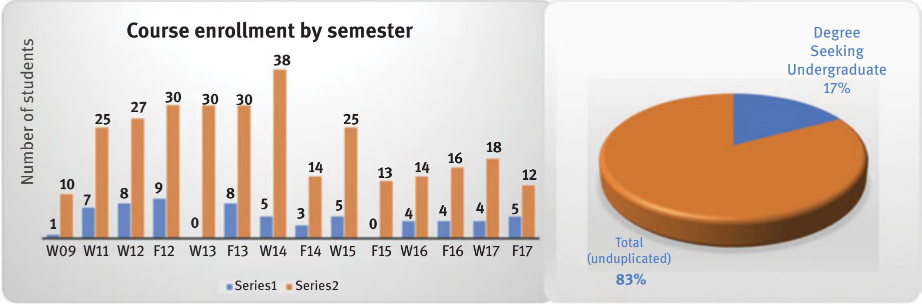


Figure 6.1: Total number of students enrolled in the course 2009–2017. The "degree-seeking" students were plotted separately.

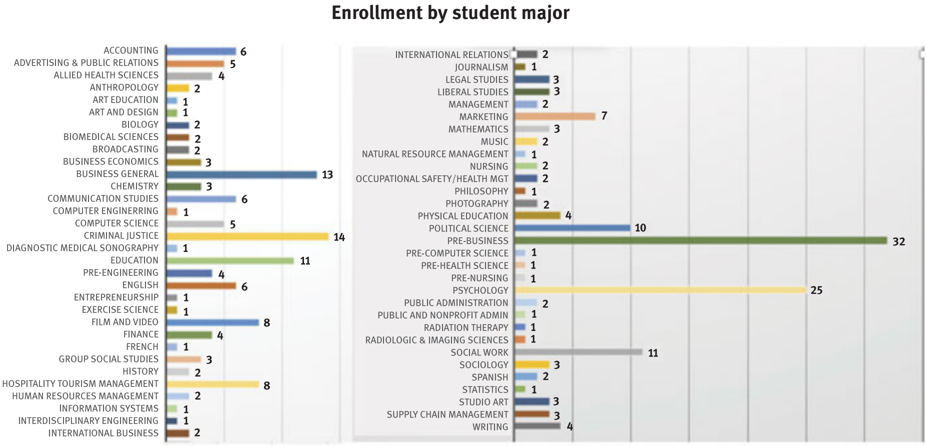


Figure 6.2: Enrollment by students' major. The degree seeking undergraduates were not included.

features were requested, the field trips were ranked repeatedly among the favorites. A once-a-week 3 h timeslot for the course is the best way, in our experience, to secure the time for these activities. However, pedagogically speaking, it is not the most favorable way to secure a steady stream of students' engagement throughout the week; the intellectual fatigue rendered by a three-hour class time is detrimental for both instructor and for students. A typical 3 × 50 min class time, on the other side, while pedagogically sound for the learning process, is not conducive to inclusion of 2–3 h field trips. A compromise that worked was having the class meet twice a week with one or two field trips scheduled well in advance, hence students could work them in their schedule; an alternative assignment was included for students who could not attend the field trip.

In Figure 6.2, a distribution of course enrollment by student major is presented. Students from 65 different majors took this class since its inception. Leading in numbers are the Pre-Business and Psychology majors with 32 and 25 total students, respectively. A steady stream of students from Business, Social Work, Criminal Justice, Political Sciences, Marketing and Education were enrolled every semester. It is interesting to mention that enrollment from students in business-related majors experienced a peak in 2012–2014 and dwindle down since then. It is worth mentioning that no special advertising was used for the course, hence its initiation.

The instruction was secured through the years by different categories of faculty, from tenured to affiliates, and to visitors. Good collaboration, sharing teaching material and collegial discussions, alongside the general education requirements, led to a set of core values regarding the topic distribution and student learning objectives to be maintained throughout the years. A master course was created on Blackboard (the learning management system used at GVSU) to keep not only the overall content and format of the course, but also to provide a solid scaffold for any instructor willing to teach, but new to the course. The master website is also a growing repository of resources and teaching materials, where any new resource or innovative teaching technique is added and shared from semester to semester and from instructor to instructor.

6.3 Syllabi

The course has been included within the university's General Education Program since Fall 2011 under the Physical Sciences Foundation. It is designed around the twelve principles of green chemistry and green engineering, and include elements of pollution prevention from the original course design. As a part of the General Education Program, Physical Science Foundations, the course must:

- explain the methodologies physical scientists use to explore and understand the physical universe
- explain the ways in which physical scientists use observations and theory to explain and predict the structure and processes of the physical universe
- explain the fundamental concepts, principles, and issues of the physical sciences

The main student learning objective, as defined initially and as is in place to date, has been to provide the students with *basic chemistry concepts* while emphasizing aspects that are used currently in the field to *designate a process, a solvent, a reaction, etc., as green or sustainable*. Green chemistry is not and should not be considered a separate area of chemistry. A course such as this brings the opportunity for the students to learn the "responsible" or "right" chemistry from the very beginning. Students who never took a chemistry course are introduced to its basic concepts with emphasis on practical applications significant for modern life, as we know it, along with principles of green chemistry. Thus, the course syllabi are generally constructed such that the students will be provided with enough knowledge to make, as consumers, informed decisions for themselves, along with an appreciation of the principles behind green chemistry, green engineering and sustainability. A bona fide consequence of this main objective is the capability of the course, in its entirety, to assist the students, who are yet undecided, in their major degree choice and with selecting a professional career.

Web searches, papers and oral presentations were and remain the basis of course assessment. Evaluation is generally focused on measuring the *upward progress* of students' ability to:

- participate in discussions with special emphasis on those following guest speakers and field trips
- complete meaningful web searches and evaluate the quality of the resources found
- communicate well, both verbally and in writing

Introduction to Green Chemistry integrates group presentations or personal responses, case-study assignments based on individual readings followed by answering to guided questions, various hands-on activities, one or two hourly exams, a final exam and an end-of-semester written or oral informative project, where students prepare and present an innovation in green chemistry or green engineering. Basic chemistry concepts are included within the course's objectives. The course requires students to follow portions of a textbook or a wiki-book while including selected resources from publications outside of these texts. Some of the innovative approaches tested for this course include (i) the use of Rachel Carson's *Silent Spring* as a reading assignment to introduce students to basic chemistry and toxicology concepts by learning about pesticides and their fate in the environment (2014); (ii) an ice-breaker introduction via reading a poem written by an artist whose family settled near the Carbon River in the Pacific Northwest, followed by personal reflections and open conversation (2016); (iii) the use of "the most-wanted toxic characters" (inspired by a posting on the Advancing Green Chemistry website); this set of six groups of chemicals were followed, like the main characters in a story, throughout the course, and used as model for introduction of basic chemistry concepts typical for an introductory one-semester course, along with green chemistry, and toxicology principles.

A selection of different textbooks included in the syllabi are listed in Table 6.1.

A multitude of other resources were used through the years. Materials were from the American Chemical Society (ACS) division of education and the Green Chemistry Institute (ACS-GCI) website [2], Environmental Protection Agency (EPA) Presidential Green Chemistry Award [3], newer textbooks, such as the 2014 *Green Chemistry and Engineering: A Pathway to Sustainability* [4], as well as materials published on different organizations' websites such as Green Chemistry Excellence Centre at the

Table 6.1: Textbooks included in syllabi from 2011–2017.

1	ACS (2008) Chemistry in Context, 6th edition (later editions followed); McGraw-Hill Higher Education
2	Paul T. Anastas and John C. Warner (1998) Green Chemistry: Theory and Practice; Oxford University Press
3	Rachel Carson (1962) Silent Spring; Houghton Mifflin
4	ACS (2014) Chemistry in Context with Connect 8th edition; McGraw-Hill Higher Education

University of York [5], in the UK, Beyond Benign [6], Institute of Green Sciences at Carnegie Mellon [7], and others. Articles from the ACS news magazine, Chemical and Engineering News [8], C&EN, were often used in the course. The C&EN magazine is conveniently available via the GVSU library; it is one of the first publication students were introduced to and it is used as a vehicle for practicing online library searches. In addition, a collection of articles is maintained on the course master website; they are also available on the GVSU library repository.

The rapid growth in the green chemistry and engineering fields, and the diversity in course instructors since the course's pilot in 2009, have kept *Introduction to Green Chemistry* a progressive non-laboratory physical foundations course option for GVSU students. The topics generally covered in the syllabus are outlined in Table 6.2, in no specific order. Instructor's preference and his/her expertise allow for changes and improvement. Each new instructor is encouraged to use his/her creativity when designing the course and to strive to stay up-to-date with the advancements in the field. It is necessary to emphasize here that the natural lack of expertise in green chemistry is a big hurdle to overcome when staffing such a course. Only the willingness to try new areas of teaching along with curiosity and desire to stay current in the field

Table 6.2: Units included in syllabi from 2011–2017.

1	History leading to the basics of sustainability, green chemistry, green engineering; introduction to chemistry
2	Basics of sustainability, green chemistry, green engineering and introductory chemistry
3	Chemical production, batteries and plastics
4	Fate of chemicals in the environment: including pesticides, heavy metals, pharmaceuticals and personal care products
5	Air pollution
6	Toxicity
7	Biomimicry
8	Metrics in green chemistry
9	Alternative energy and energy storage

make for a good instructor. Thanks to cumulated efforts from our department, a team of vested faculty was formed, willing to assist any new instructor; a growing network of specialists, willing to act as guest speakers, is maintained to the benefit of our students. In addition, the master web-based teaching site (Blackboard) is maintained and enriched with each new teaching cycle, while support with field trips and guest speakers is always offered for new instructors.

A network of campus-wide resources is available. The university's campus grounds, chemistry organic laboratories, the campus library, the GVSU solar garden, the sustainable agricultural project, the technology center, the Annis Water Research Institute, and various forms of the campus' ongoing commitment to sustainability are used as teaching support for introducing or exemplifying various topics. Ongoing research projects within the chemistry department, businesses in the community [9] and neighboring universities [10] are included in class-related activities. A cooperative laboratory opportunity for the students taking this non-laboratory course was designed during and effectively used during winter 2015 and the fall of 2016. The activity was run under the guidance of both this course instructor and the Organic Chemistry laboratory instructor; the CHM 111 students were paired with the upper-level undergraduate students (Organic II laboratory) to complete one lab experiment. The students appreciated learning through a cooperative activity which brought green laboratory techniques to "life" unlike any of the reading assignments, video or lectures could do. A surprising and unexpected benefit was the peer-to-peer interaction; such a cooperative activity was appreciated by most of the upper-level lab students because they were able to "teach" their younger colleagues not only about the experiment that was run but also about materials and equipment typically used in an organic chemistry lab, and about the general requirements of a lab course.

Throughout the years this course underwent several modifications to include the most recent, up-to-date developments in green chemistry and green engineering. The repository of teaching materials created initially is growing continuously. Small group activities were designed for the classroom environment in order to engage the students directly with the principles behind sustainability, green chemistry and engineering. For example, newer additions to the course include a history lesson leading up through the Pollution Prevention Act of 1990, a new unit on biomimicry and a detailed green chemistry metrics unit. The metrics unit takes advantage of new published literature [11] and covers not only atom economy but also reaction efficiency assessment via the E-factor. Students are required to calculate the "success" of a chemical reaction/process via the traditional percent yield and compare and contrast this calculation method with that of Barry Trost's atom economy [12] and Roger Sheldon's E-factor calculations [13]. An innovated form of practice with green chemistry metrics used by K. Mack in 2016 was to integrate with a cooperative learning activity in a real upper-level laboratory [14].

The incorporation of this course into the University's General Education Program was also a significant factor that allowed for growth in the course quality, in encouraging the use of most recent developments within the field. Regardless of curriculum changes over the years, the students continuously exit *Introduction to Green Chemistry* with an appreciation of green chemistry and green engineering that they did not have at the beginning of the course. It successfully encourages students' professional growth and provides a forum in which the students develop the ability to make informed decisions and gain specific communication skills regarding the connection between chemistry and chemical engineering on one side and the environment and health on the other.

6.4 Samples of innovative approached and teaching techniques

A short selection of innovative approaches to assignment design, in-class activities and other course materials are presented here. The reasons behind the usage of a particular material, the way the materials were handled, as well as data from students, when available, are included. Detailed description of a couple of selected materials is available (see Appendix: Sample teaching materials to this chapter).

6.4.1 Persuasive essays on global warming: 2009 and 2014

Two consecutive lectures were given in class, the first depicting global warming as being a real threat and certainly anthropogenic. In addition, students were given statements and campaigns about global warming being touted by politicians and Hollywood celebrities. During the next class period, evidence was given, primarily from a document by Robinson and Soon [15], which debunks global warming. The professor also tried to convince students that politicians and Hollywood celebrities should not get involved in a topic that may be out of their realm of true deep understanding.

The students were assigned to write a *persuasive essay* on the issues surrounding global warming. In this essay, the students were graded based on their ability to convince fellow students and the professor to agree and think the same way that essay's author did about the topic. Students could choose one of two opposing sides of a controversial issue presented during lectures concerning global warming and advised to answer to the following questions as they progress through writing their essays:

- Is global warming real or simply a cycle we are going through?
- Is global warming actually being caused by man's activity on Earth?
- Is global warming a political issue and/or should it be?
- Should Hollywood celebrities express their opinions on issues like global warming?
- Do Hollywood celebrities influence public thinking (relate it to global warming)?

A review of how students felt about these issues changed significantly over the 5-year period observed. The numbers, even though from small class sizes, do reflect student opinions at large. A detailed survey of students' papers revealed a general shift in the students' views on climate change. Selected results were presented in Figure 6.3. From 2009 to 2014, the percent of students, indicating global warming as being a real phenomenon grew from 30 % and 84 %. In 2009, 20 % of the class felt global warming was not happening; not a single student felt this way in 2014. Clearly a generational shift, students in the same age group and educational stage changed their views on global warming over the 5-year period with many more seeing it as a real concern as time progressed.

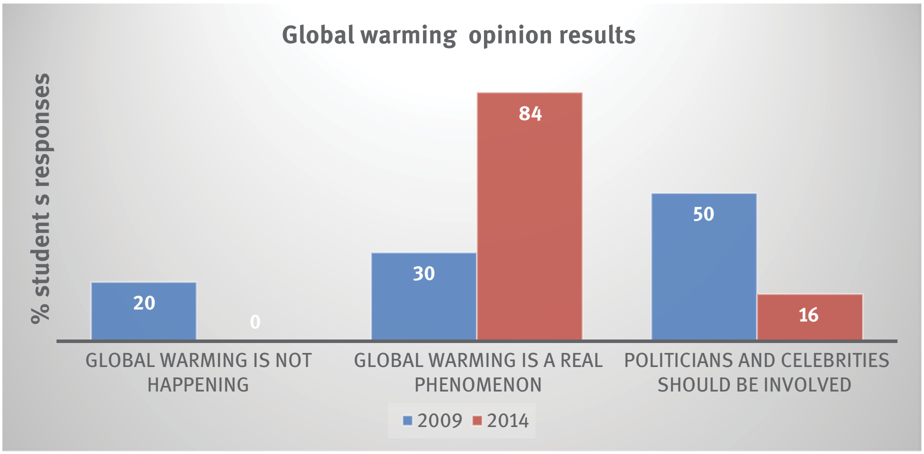


Figure 6.3: Global warming opinion survey.

In 2009, 50 % of the class wrote that politicians and celebrities should be involved in expressing concern about global warming. In contrast, in 2014 only 16 % of the class wrote on this topic but all agreed that politicians and celebrities should not be involved in expressing their ideas, a significant turn-around in the student population opinion. This change may be influenced by the book publication [16] and movie release in 2006 of Al Gore's *An Inconvenient Truth*. In 2009 students may have been more aware of the book and movie. Instructors are encouraged to continue with this persuasive essay assignment and include the second Al Gore's movie [17], in the unit.

Based on his experience with the 2009 class, J. Krikke gave a talk on the design and content of an introductory green chemistry course and its inclusion in the university curriculum, at the National ACS Meeting in San Francisco (ACS, San Francisco, March 2010, Krikke *et al.* [18]); this persuasive essay assignment gathered a lot of attention, evident by the questions asked at the end of the talk and the animated informal discussion that followed. The authors remained in contact with some of the attendees over the years, exchanging views and information related with teaching this type of introductory course.

6.4.2 Visit to a real lab: learning with peers

Since the 1980s, the need for curriculum reform in the sciences has become a concern for educators nationwide. The American Chemical Society (ACS), the National Research Council and the National Science foundation (NSF) found that students were not receiving a curriculum which prepared them for the workforce. As a result, members from various institutions have addressed this concern through the use of different teaching strategies. Gutwill-Wise J. P. and co-workers implemented a modular approach to one section of an introductory general chemistry course at two different institutions (a public and a private one) [19]. The study looked at the student's attitudes toward chemistry. Anders and Berg identified that a positive attitude change toward learning chemistry was strongly linked to motivation [20]. It may be possible that students are motivated when asked to become involved in hands-on activities, discussions amongst peers and when given real-world applications. Allen and Oliver-Hoyo addressed this possibility by implementing the SCALE-UP course format "Student-Centered Activities for Large Enrollment Undergraduate Programs" [21] into two sections of a general chemistry course. The results from their study suggest that positive changes in student's attitudes toward chemistry occur when students are engaged in the subject material. Experience in the classroom, attitude and aptitude are interdependent.

Nespechal [22] suggests that by having students engage each other directly in laboratory concepts before experimentation shapes their feelings toward chemistry and does not adversely affect their ability to demonstrate conceptual skills on laboratory aptitude tests. Cooperative laboratory learning provided positive outcomes and should be incorporated into the traditional lecture mode of teaching chemistry laboratories.

The need for *experiential learning* along with results on *cooperative learning* investigation inspired the use of real-laboratory learning amongst university peers during the coverage of this course's metrics unit [23]. The students were given an activity packet containing a laboratory introduction, detailed procedure with complete waste disposal instructions, data collection tables and post-lab questions. While the activity was designed for students with little to no laboratory experience, it was run alongside students in the upper-level *Organic II for the Life Sciences Lab*. The Lab was scheduled to perform a Diels-Alder reaction, and the students from the Introductory Green Chemistry course were participating alongside the more-experienced organic students. The activity packet is availble in the appendix.

The green chemistry metrics explored in this activity were Barry Trost's atom economy and Roger Sheldon's E-factor. The introductory green chemistry students completed these calculations with the actual laboratory data. The effectiveness of the cooperative learning activity was assessed by determining whether (i) the students found the activity to be intellectually stimulating along with (ii) whether or not this particular activity stretched their thinking. The results were collected via GVSU's course *LIFT* evaluation given at the end of the semester. Some students' comments were selected below:

- "The part that stretched my thinking was the atom economy calculations".
- "Well, I took a Chemistry class last year in high school so I kind of already understood most of the basic things of chemistry. However, when it came to new material, such as atom economy, I appreciated the constant use of examples".

6.4.3 "Most wanted" chemicals: a semester-long assignment

Group work projects are an intrinsic part of the mandatory learning objectives for a general education course. An example of such a project, used throughout the semester to introduce a variety of chemistry topic and green chemistry principles, is the *Most Wanted Toxic Characters*. Groups of 3–4 students, chosen randomly, were assigned to one category of "most wanted" chemicals: atrazines, polybrominated bisphenyl ethers, (PBDEs), short-chained chlorinated paraffins (SCCPs), perfluorinated chemicals (PFCs), phthalates and bisphenol A (BPA). The main task assigned required students to collect information about their specific chemical or class of chemicals and present it to their colleagues, throughout the semester. A final presentation and short paper culminated the experience at the semester's end. Such a project presents multiple opportunities to encourage students to explore a variety of informational sources along with plenty of opportunities to teach chemical concepts, while emphasizing the specific approaches characteristic to green and sustainable chemistry. A selection of such opportunities follows here.

6.4.3.1 Informational sources

Some of the compounds involved in the project were "known characters" from their repeated coverage in the mass media, such as BPA, while others, like SCCPs or PBDEs, seemed strange topics to follow (and rather complicated acronyms to even bother pronouncing). Students used Google and Wikipedia to identify what the compounds are, why are they made, their application in daily life, and why are they "wanted"; they also search what is the reason for being part of the infamous group of chemicals that "are wanted" to be removed and replaced from the market. After the students search and collected information, they introduced their "characters" (assigned topic) to their peers, in the class. Well-structured assignments are key to ensure the effectiveness of any class activity, considering that the majority of the students were freshmen. In this case, the students' first introduction of their assigned topic had to be prepared in the form of answers to the following questions:

- For what purpose are these chemicals made?
- What *Most Wanted* means here?
- Why is this class of compounds on the *Most Wanted* list? List the adverse effects on human and environment that this class of chemicals produces.

In addition to the introductory information, provided to them from the website www.toxiccharacters.org [24], students have to find two or three more websites that talk about this class of compounds in order to formulate their answers.

Students' first introduction of their assigned "characters" led to the development of a class-wide common list of resources pertaining to chemicals, and toxic chemicals, in particular. The list was further divided into primary and secondary sources. The reliability of different sources was discussed. Articles published in peer-reviewed journals were classified as primary literature, followed by information found on NIH, FDA, EPA or OECD, along with science review magazines, company websites, Wikipedia, etc. The communication of scholarly work as published literature was introduced as the standard practice in chemistry and emphasized as common procedure across all other scientific disciplines. Specific literature articles were assigned to students to practice comprehensive and critical reading in order to identify (i) main idea(s), (ii) methods, (iii) significant results, (iv) implications and applications. Besides the practice with chemical journal article reading, this exercise led to an interesting conversation about the societal need of chemical compounds with certain functions and the unexpected outcomes derived from their use.

6.4.3.2 Bond-line structures

A brief introduction to covalent bonding followed by practice with bond-line structures was used to allow students to learn how to communicate the structural features specific to each class of chemicals on the "most wanted character" list. Once they were introduced to it, students from each group had to use the bond-line representation each time they introduce a new feature of their class of compounds, each time they presented an update to their project, throughout the semester. The repetitive nature of this work led to familiarity with features of chemical structure and allowed students to begin to compare the chemical structure features among the six classes of compounds. 3D models were introduced in a practical, in-class exercise, with the intent to build on the direct connection between the actual physical shape of molecule and its representation. Students started with simple structures, such as methane, ethanol or benzene, went back and forth between bond-line 2D representation and 3D models, counting atoms and verifying molecular formulae, and working up to more complex structures. At the end of the class period, students were helped to build 3D models of one representative compound from the "most wanted class" assigned specifically to them.

The extent of student ability to transfer information presented in 2D and 3D structures into physical and chemical properties and their ability to make analogies between structure and chemical activity (a very basic concept of pharmacology and toxicology, SAR) was probed during the final exam. Relevant information about Triclosan, a compound which was not discussed in class or assigned in any of the homeworks, was provided from the FDA website [25], along with its 2D and 3D structural representations; students were required to compare Triclosan's chemical structure with those of the six "most wanted" and decide if Triclosan's structure may support the concerns raised by the FDA article. Eighty-five percent of the students correctly identify the similarities in Triclosan's structure with some of the compounds on the "most wanted" list, a clear indication that, even at such a basic level of understanding, correct assessments could be made.

6.4.3.3 Physical properties vs. toxicity relationship

As an introductory course in chemistry, students were introduced to states of matter, polarity of specific chemical bonds and of molecules, solubility in water *vs*. solubility in nonpolar organic solvents, such as octanol. However, the approach was designed to start with properties characteristic to their assigned "characters". One specific representative of each "most wanted" compound classes was chosen and the following questions were addressed:

- Is the compound assigned to you solid, liquid or gas at room temperature?
- Is the compound assigned to you polar or nonpolar?
- What is octanol/water partition coefficient, K_{ow}, for your assigned compound?
- How is the K_{ow} value connected with the risk/toxicity associated with your assigned compound?

Students were required to make an honest effort to research, analyze and finally, to answer to these questions; they were directed to search the world-wide-web for information about polarity, solubility and partition coefficients, and for specific values for the compounds from the class assigned to them. When the results of each group were shared, an entire class period was dedicated to discussing physical properties and their significance in understanding the relationship between structure of a compound, its physical properties and its toxicity. Starting from the students' own information, key concepts, such as polarity, water solubility and K_{ow} were clarified and correctly defined; the hydrophilicity *vs*. lipophilicity of simple organic compounds, such as ethanol, octane or benzene, were used as practical examples. The class was familiarized with the concept of bioaccumulation by connecting the solubility with the tendency of a compound to accumulate in living organisms. Hydrophobicity and log K_{ow} were defined and their usage in chemical risk assessments were discussed in direct relationship with the "most wanted" chemicals assigned. A common list of specific values for log K_{ow} for one or more representatives from each class of the "most wanted" was produced by students; the power of this important parameter for predicting the distribution of a substance in various environments, such as water, soil, air, biota, was discussed. Students arrived at an understanding of the significance of high log K_{ow} value, (>4.5) as an indicator of the compound being more readily absorbed by organic matter in soils or sediments because of its low solubility (affinity) for water. Considering the overarching conclusion that chemicals with very high log K_{ow} values are of greater concern because they may have the potential to bioaccumulate (bioconcentrate) in living organisms, the class exercise culminated with an overall comparison among representatives of the six classes of “most wanted” compounds.

Homework assignment directed the students to further investigate the differences in log K_{ow} among compounds in the same class, with the intent to reinforce the connections of chemical structure, especially the carbon chain length, with solubility.

For the future, the design of a hands-on experience in collecting solubility data and calculating a partition coefficient for a given compound is being considered as an integrated experiment in the course.

6.4.4 Biomimicry

The experience accumulated through a couple of semesters, backed by students’ expressed interest, indicates that biomimicry is a fascinating topic that allows a fast and fresh view on chemistry as a science. An introductory lesson in biomimicry is always included in the very first couple of weeks of the semester. A combination of (1) games, such as the Biomimicry matching game from Beyond Benign [26], (2) TED-talks, such as Janine’s Benyus’s series [27] and (3) a current literature article, such as B. Yeom *et al.* [28] about a new material that mimics natural enamel structure, were used to introduce and expand the topic.

A variety of mixed methodologies could be used. For example, in our experience, the matching game is very well suited for an in-class activity (it was even used once as an ice-breaker in the first day of class), while for the TED talks, the best experience was reported by students when it was recommended to be watch at-home and follow up with an in-class review and discussion. An in-class activity was also tried when students were handed out a set of pointers and guiding questions before watching the talk.

Guest speakers and representatives from local businesses constitute a tremendous resource, often underutilized for a variety of reasons. Continuous effort is invested to initiate, build and maintain connections with the local community to secure partners willing to visit and interact with our students. In addition to inviting our own colleagues from GVSU, who often introduce topics from their area of expertise, or describe their current research, guest speakers from local companies, such as Steelcase, Amway, SealBond, Herman Miller, Periggo and others, were often invited to the class. The latest example was Fall semester 2017; the class benefited from a guest speaker visit from the Kalamazoo-based Vestaron Corporation [29]. His visit was incorporated in the biomimicry unit and was centered on the company's efforts toward the development and commercialization of biological insecticides to help the world's farmers to produce safer food and ornamental plants in a more environmentally responsible manner.

With no exception, the biomimicry topic is listed as one of the favorites for this course in the students' surveys.

6.4.5 Students final projects

An integral part of the general education program, the evaluation of the improvement of students' oral and written communication abilities, is always done at the end of the semester through a final project assignment. The oral presentation allows for peer evaluation, while the written report is graded following a detailed rubric, provided to students at the same time with the assignment itself. In the first couple of semesters of the course, students were encouraged to work on topics from the Presidential Green Chemistry Award. However, since 2014, these are used mainly as practice for reading comprehension, and communication skills development. Students are encouraged to find a topic of their own interest, research the literature, sort scientifically sound facts from mass media opinion communications and are assisted in preparing the final project in the form of a complete lesson for their peers. The *Informative speech* assignment description, handed out to students at the very beginning of the semester, is available in the Appendix: Sample teaching materials. An assortment of interesting and well executed final projects were created and presented by students throughout the years. The best of these projects are kept on the master course website and utilized, with students' permission, either as models for project preparation or, when the quality permits, even as teaching materials.

6.4.6 Incorporating elements of social and environmental justice

Inspired by a symposium, organized in 2016 at Green Chemistry & Engineering (GC&E) national conference (Portland, 2016) [30], with the aim to start a conversation about steps chemists could take to better understand disparities in how hazardous chemicals impact society, a conscious effort was made toward emphasizing the relationship between green and sustainable chemistry on one side and the social and environmental justice on the other, and to probe students' reaction to it. To accomplish this goal, during the winter 2017 semester we decided to experiment with a student-led approach to the topic, hoping that social and environmental justice will emerge as significant issues when one studies sustainable and green chemistry concepts. The results of this teaching experiments were presented [31] at the national GC&E meeting (Reston, Virginia) in 2017, in a session dedicated to the topic *Green Chemistry = Social and Environmental Justice: Theory and Practice* [32].

A compelling series of presentations, webinars and publication on the topic became available in 2017 [33].

Social and environmental justice was neither included as a separate topic nor explicitly mentioned in students' assignments. Instead, students' work was guided toward research and discovery. The electronics industry was chosen for the first pedagogical experiment, as an efficient example of introducing green chemistry metrics, particularly the life-cycle concept, and to allow the social and environmental justice to emerge as an implicit component of green and sustainable chemistry. As an opening for the topic, students shared what they, their family and their friends are doing with used electronics, especially cell phones, if they donated, recycled or simply threw them away, where and how. Recycling opportunities on GVSU campuses were also discussed. An in-class group exercise followed, including readings of an opinion article published on the website of an industrial coalition claiming that it "promotes green design and responsible recycling in the electronics industry" followed by in-class discussion [34]. After the article was discussed and the industry view was compared with the public understanding, the class watched a CBS documentary regarding the untold story behind electronic waste and, in particular, cell-phone disposal and recycling [35]. This was the point where social and environmental justice emerged naturally, as the result of learning about the disposal and recycling of electronic waste. From here, the students were required to narrow their interest from electronics in general to focus exclusively on cell phones; they were directed to find reliable information on the entire lifecycle of this industry's products. A simplified, cradle-to-cradle life-cycle scheme was provided and different groups of students focused on one of the following stages of the life-cycle: (1) raw materials extraction, (2) chemical processing, (3) component manufacturing, (4) product assembly, (5) distribution, marketing, sales, (6) product use, (7) product end-of-life-disposal or recycling of cell phones. Once the groups started working and sharing aspects of the lifecycle of electronics, an opinion article published in ACS-GCI Nexus [36] was introduced; students were encouraged to consider the social aspects of the entire process. They were asked to specifically look for connections between the "smart choices" green chemistry brings to the table and the *social justice aims in a modern society*; they were encouraged to search for *evidence of such connections* at every step along the lifecycle of the cell phone industry. The chemistry–social justice connection proved to be an unexpected motivational tool, a starting point of many interesting topics of conversation, and a powerful incentive for more in-depth research on some of them. Students were self-motivated to find out about local recycling facilities; they looked very thoroughly into opportunities at our university, in the vicinity and in their own home towns. Special attention was given to the well-advertised and responsible waste recycler e-Steward [37], which has a facility in Grand Rapids, close to GVSU.

This topic was covered in the first unit of the class; hence students were encouraged to continue to consider the possible contribution of applying green chemistry principles to the goals of social and environmental justice. Throughout the entire course, students were directed to (i) look for connections between the “smart choices” green chemistry brings to the table and the social justice aims of a modern society, and (ii) search for evidence of such connections at every step along the lifecycle of chemicals and materials, from resources to design, from manufacturing to end-of-life. They were told that a short (up to 300 words) essay regarding the opportunities green chemistry brings to the social and environmental justice aspects of our society would be part of their final exam. Hence, this theme was front and center throughout the course and led to a thorough integration of the concept within the course. A few student comments follow:

- “ I foresee chemistry and green chemistry becoming a popular contributor in social and environmental justice by affecting education, resources and human and environmental health. When people become educated on the issues they will then proceed to take necessary action”.
- “Before this class I had no idea how much green chemistry encompasses. All of the possibilities I am now aware of are overwhelming. I see environmentally friendly cars, housings and buildings as well as countless biodegradable product, renewable energy sources, and much more. I only hope all these will come to existence in my lifetime”.

6.5 Conclusions

Freshmen have been taking this introductory course in green chemistry at Grand Valley State (GVSU) in Michigan every year, since 2009. For many, this is the only chemistry course they will ever take. Since its inclusion into the curriculum, the course continues to bring a significant and beneficial contribution to the education of GVSU’s students. The authors believe strongly that by being an integral part of the chemistry community and by sharing their experience with the green chemistry education community at large, significant progress will be made in keeping the young generation not only informed, but also motivated toward significant social and environmental goals. GVSU’s experience and growth through the years, supported by the increasing presence of the green chemistry education community nationally and worldwide, is a valid, tested model to be built upon for other institutions interested in integrating green chemistry into their curriculum.

The incorporation of this course into the University’s General Education Program allowed for growth by using recent developments within the fields of Green Chemistry and Green Engineering. Regardless of curricular changes over the years, the students who took this course gained a well-founded appreciation of green chemistry. The course provides a forum in which the students develop the ability to make informed decisions as consumers, and are guided to develop their ability to refer to informational resources while learning to communicate effectively both verbally and in writing.

The advantage of a course like the one described here is in its being part of the general education sequence. The general education program at GVSU encourages innovation while emphasizing the sets of skills to be aimed for, and it demands a rigorous analysis of the students' outcome. The *verbal and written communication skills* were mentioned initially but are currently an integral part of the students' progress evaluation. In this day and age, easy access to information comes at the price of opinions being stated as facts and fake news overshadowing scientific facts. Hence, *newsworthy literacy* became an integral part of the student learning outcomes. The most important and relevant idea to convey in teaching such a course is to keep oneself up-to-date and be ready to utilize current events as vehicle for introducing basic concepts of chemistry and the principles of green chemistry.

Students' interest and overwhelmingly positive response is encouraging but also leads to future directions. Work needs to be done in order to emphasize the basic foundation of chemistry teaching so it can incorporate the newest developments in the field, connect with other sciences and improve the image of chemicals in society and the environment, until naming chemistry "green" will not be necessary anymore, as "greenness" will become an inherited, natural feature of the science that is chemistry.

References

[1] Cronkite J, Admissions Office, Grand Valley State University, October, 2017.

[2] American Chemical Society: Green Chemistry Institute, ACS-GCI. https://www.acs.org/content/acs/en/greenchemistry.html (last accessed December 10, 2017).

[3] EPA Green Chemistry Presidential Award. https://www.epa.gov/greenchemistry/information-about-presidential-green-chemistry-challenge (last accessed December 10, 2017).

[4] Marteel-Parrish AE, Abraham MA. Green chemistry and engineering: a pathway to sustainability. 2014 American Institute of Chemical Engineers, Inc., New York, NY: John Wiley & Sons; 2014.

[5] Green Chemistry Centre of Excellence, University of York, UK https://www.york.ac.uk/chemistry/research/green/ (last accessed June 2, 2017).

[6] Beyond Benign: green chemistry education http://www.beyondbenign.org/ (last accessed December 12, 2017).

[7] Carnegie Mellon Institute for Green Sciences. http://igs.chem.cmu.edu/ (last accessed December 10, 2017); Learning Green, The Institute of Green Sciences, Carnegie Mellon: Introduction to Green Chemistry http://igs.chem.cmu.edu/index.php?option=com_content&view=article&id=69&Itemid=515

[8] Chemical and Engineering News, C&EN, https://cen.acs.org/magazine.html (last access December 15, 2017).

[9] Worth mentioning here is our long-standing collaboration with Steelcase corporation, https://www.steelcase.com/, via Clinton Boyd and Mary Ellen Mika, who delivered invited guest lectures several times. C. Boyd was also the main instructor for course for one entire semester. Accessed 10 January, 2017.

[10] Michigan State, Western Michigan, Kettering Universities.

[11] Dicks A, Hent A. Green chemistry metrics: a guide to determining and evaluating process greenness. In: Sharma SK, Editor. Briefs in green chemistry for sustainability. Cham, Switzerland: Springer, 2015.

[12] Trost B. Atom economy—a challenge for organic synthesis: homogeneous catalysis leads the way. Angew Chem Int Ed Engl. 1995;34:259–81.

[13] Sheldon RA. Organic synthesis; past, present and future. Chem. Ind.,. 1992;903–6.Sheldon, R., A The E factor 25 years on: the rise of green chemistry and sustainability. Green Chem. 2017;19: 18–43.

[14] Mack K. CHM111-Green chemistry principles: a Diels-Alder reaction. See Appendix: Sample teaching materials to this chapter.

[15] Robinson NE, Soon W. Environmental effects of increased atmospheric carbon dioxide. J Am Physicians Surgeons. 2007;12:79–90.

[16] Gore A. An inconvenient truth: the crisis of global warming. 1st ed. New York: Rodale Books, 2006.

[17] Gore A. An inconvenient sequel: truth to power. 2017.

[18] Krikke J. An introductory green chemistry course, ACS National meeting, San Francisco, 2010.

[19] Gutwill-Wise JP. The impact of active and context-based learning in introductory chemistry courses: an early evaluation of the modular approach. J Chem Ed. 2001;78:684–90.

[20] Anders C, Berg R. Factors related to observed attitude change toward learning chemistry among university students. RSC: CERP, 2005;6:1–18.

[21] Oliver-Hoyo MT, Allen D. Attitudinal effects of a student-centered active learning environment. J Chem Ed. 2005;82:944–9.

[22] Nespechal K. Cooperative learning in the laboratory. Western Michigan University, unpublished results 2006.

[23] Class activity package Kristina Mack. See Appendix: Sample teaching materials to this chapter for all materials designed and used for this activity.

[24] Advancing Green Chemistry website http://advancinggreenchemistry.org (last accessed May 25, 2017).

[25] FDA triclosan info https://www.fda.gov/ForConsumers/ConsumerUpdates/ucm205999.htm, (accessed March 17, 2017).

[26] Biomimicry matching game, activity and picture set available from Beyond Benign website http://www.beyondbenign.org/lessons/advanced-biomimicry-matching-game/, (last accessed December 10, 2017).

[27] Links to a selection of Janine Beyhus's talks: https://www.ted.com/talks/janine_benyus_shares_nature_s_designshttps://www.ted.com/talks/janine_benyus_biomimicry_in_actionhttps://www.ted.com/talks/janine_benyus_shares_nature_s_designs/discussion?utm_cahttps://youtu.be/n77BfxnVlyc. Accessed on September 28, 2017.

[28] Yeom B, Sain T, Lacevic N, Bukharina D, Cha SH, Waas AM, et al. Abiotic tooth enamel. Nature. 2017;543:95–8.

[29] Vestaron Corporation: nature by design. http://www.vestaron.com/ (last accessed November 21, 2017).

[30] The 20th GC&E, Portland, OR, symposium Exploring Opportunities for Green Chemistry Educators and Researchers as Change Agents Addressing the Social and Environmental (In) Justices of Chemical Exposure, Brush, E, organizer, 2016.

[31] Kovacs DG. the 21st ACS-National GC&E, an introduction to green chemistry with a twist toward social and environmental justice, Reston, Virginia, June 14, 2017.

[32] 21st GC&E conference, symposium Ed Brush and G.A. Lasker, organizers, 2017.

[33] a) Kirchhoff M. Chemistry in the context of social justice. In Abstract of Papers of the American Chemical Society, vol. 253. 1155 16TH ST, NW, Washington, DC., 2017. b) Brush, E. Green chemistry = social and environmental justice, Beyond Benign webinar series, http://www.beyondbenign.org/bbdocs/webinars/20161018_Brush.pdf (last accessed December, 2016); c) Lasker, G, Mellor, KE, Mullins, ML, Nesmith, SM, Simcox, NJ. Social and environmental justice in the chemistry classroom. J. Chem. Educ. 2017;94:983–7.

[34] Electronics Take-Back Coalition http://www.electronicstakeback.com/toxics-in-electronics/ (last accessed January 24, 2017).

[35] CBS's '60 Minutes' documentary *The Wasteland: E-waste*. https://youtu.be/-jSbYTNAJIQ (last accessed May 30th, 2017).
[36] Brush E, *Green Chemistry = Social & Environmental Justice*, contribution to ACS Green Chemistry Institute® Green Chemistry, The Nexus Blog, Aug15, 2016.
[37] E-Stewards, an initiative that defines and promotes responsible electronics reuse and recycling best practices worldwide. http://e-stewards.org/ (last accessed June 2, 2017)

A Appendix: Sample teaching materials

The authors have chosen to share the teaching materials in this Appendix under the terms of a Creative Commons – Attribution – Noncommercial license, see https://creativecommons.org/licenses/by-nc/3.0/us/. Readers are welcome to copy, share, reuse, and/or adapt the content of this appendix for noncommercial purposes, as long as they provide appropriate credit to the authors.

Keywords: sample teaching materials, green chemstry principles, e-waste

List of sample teaching materials.

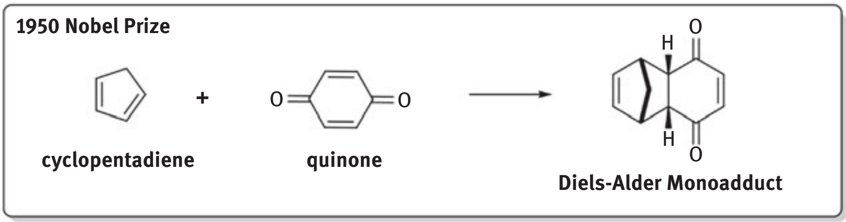
1. Green Chemistry Principles: a Diels–Alder reaction
2. Informative talk assignment
3. Informative talk rubric
4. Green Chemistry vs. Toxic Technology: the problem with e-waste
5. Class ice-breaker – reading Joy's poem

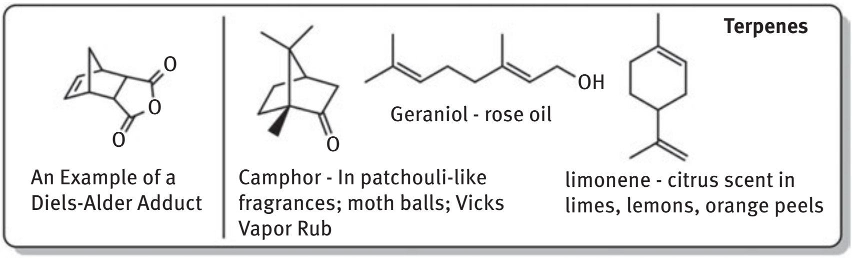
A.1 Green chemistry principles: a Diels–Alder reaction

Kristina Mack, GVSU, 2016

Background:

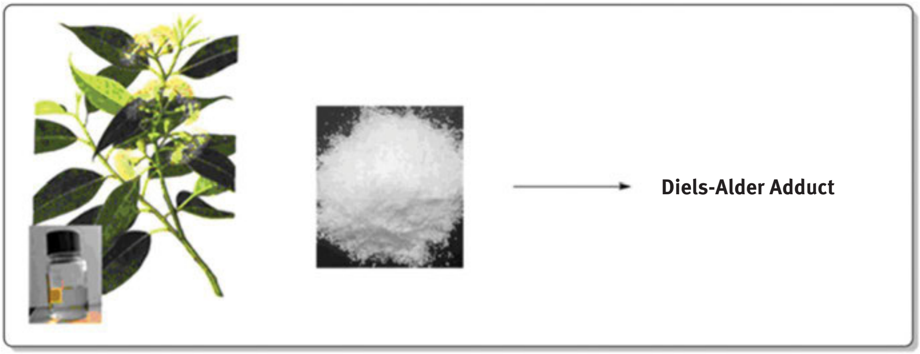
The Diels–Alder reaction was initially discovered in 1928 by Kurt Alder in the laboratory of Otto Diels. This organic reaction, originally called the diene reaction, won Diels and Alder the 1950 Nobel Prize due to its utility in synthetic design. The Diels–Alder adduct, the product, resembled natural products such as the bicyclic ringed-system for the terpene camphor. The reactants involved in this reaction involve a species called a diene and another species called a dienophile. Diels and Alder's original work involved cyclopentadiene and the dienophile quinone. Their discovery allowed for the formation of two carbon to carbon single bonds and a carbon to carbon double bond within a six-membered ring. The Diels–Alder reaction led to the synthesis of many natural products such as terpenes and sesquiterpenes which are noted for their various aromas in the fragrance industry along with the synthesis of morphine by Gates and Tschudi in 1951 and eventually to the total synthesis of cortisone and cholesterol by Woodward et al. in 1952.





The CHM 242 lab today is carrying out a similar reaction today using maleic anhydride as the dienophile and eucalyptus oil as the source of the diene. The oil is a mixture of various terpenes and the CHM 242 students are running the experiment in order to determine the identity of the unknown terpene.

The reaction scheme for the lab today is:

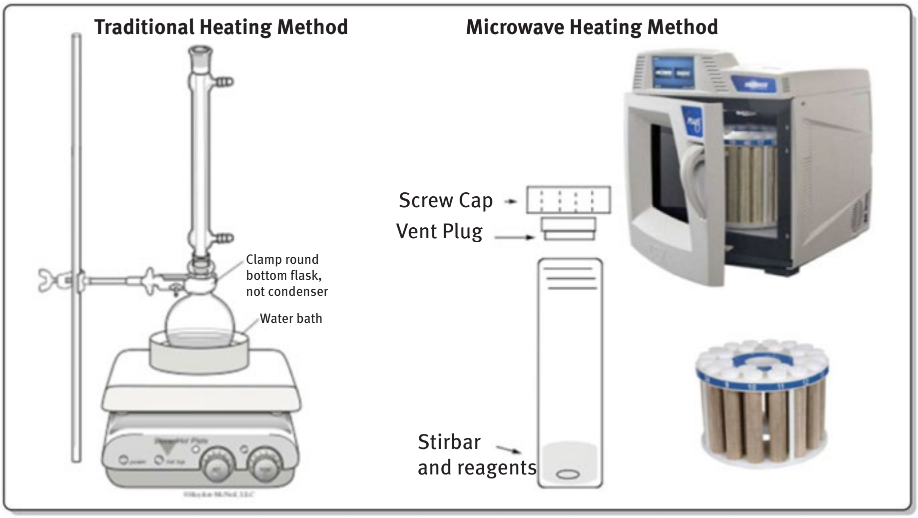


In today's reaction, the eucalyptus oil was determined to be comprised of 57.49% eucalyptol and 30.27% of the diene which reacts with maleic anhydride to yield the final product. Eucalyptol in eucalyptus oil behaves as the solvent medium in which the reaction can take place under pressurized conditions via microwave irradiation. Traditionally, aromatic and chlorinated solvent conditions have been used for the Diels–Alder reaction. The alternate synthetic method for this CHM 242 lab uses the solvent, MTBE which is commonly used as a gasoline additive. In addition, the traditional reaction set-up requires the use of a reflux apparatus which depends upon the boiling point of the solvent being used in the reaction. The apparatus is heated on top of a hotplate for 30 minutes. On average a hotplate draws 1200 W of power.

Microwave-assisted reactions have replaced traditional heating methods in organic synthesis since its introduction in 1986 by the research groups Gedye and Giguere/Majetich. Microwave reactors specific for synthesis using sealed reaction vessels have been in existence since 2000 resulting in over 2500 synthetic publications. While the reactions during the 1980s were carried out in commercial microwaves such as you may have in your home, the microwave reactors of today use fiber-optic probes, infrared sensors, and software to maintain temperature and pressure control by regulating the microwave's power output along with having magnetic stirrers built in to the reactor. The microwave reactor option in the CHM 242 lab today is the CER Mars microwave reactor which draws 1600 W of power to reach a temperature of 80°C over 2 minutes and then is held at that temperature for 10 minutes.

In the sealed vessel for the microwave-assisted reaction the solvent is heated well above its normal boiling point. The solvent today has a separation of charge within the molecule and this charge separation will align itself with the applied electric field. This applied field oscillates and the solvent molecules will continuously realign themselves with the electric field being applied. Energy from this rotational process is lost as heat energy from molecular friction and from the loss of insulation properties of the solvent molecules. The ability of a solvent to convert the electrical energy into heat energy for the reaction to occur is called its loss tangent. A medium to high loss tangent at the operating frequency of the microwave is desired for efficient heating of the reaction mixture.

The diagrams below display the two different heating apparatuses that will be used to carry out today's Diels–Alder reaction:



Procedure:

Using the following URL (*ChemSpider: Search and share chemistry*) and/or your Periodic Tables, complete the following Table of Physical Constants:

http://www.chemspider.com/Search.aspx?gclid=COSmm_mF_sMCFQeGaQodah4AGA (last access 15 May 2020–17).

Table 6.3: Table of physical constants.

Name	Molecular formula	Molecular weight	Boiling point
242 Diene	$C_{10}H_{16}$		
Eucalyptol			
Maleic anhydride			———
Diels–Alder adduct	$C_{14}H_{18}O_3$		———
MTBE	$C_5H_{12}O$		55.2°C

Reaction success can be analyzed in terms of the yield and the purity of the product. In order to reduce waste and limit the amount of undesired byproducts in a green synthetic design, the atom economy for the synthesis must be assessed.

The atom economy can be calculated using the following calculation:

$$\%\textbf{Atom Economy} = \frac{\text{Total Molecular Weight of all of the Reactants}}{\text{Total Molecular Weight of the all of the Products}} \times 100$$

The percent yield for a reaction is based on the ratio of the experimental yield of the product to that of the product's theoretical yield.

$$\%\textbf{Yield} = \frac{\text{Experimental yield of the product in grams}}{\text{Theoretical yield of the product in grams}} \times 100$$

The theoretical yield is based on the amount of diene used in today's reaction.

$$\textbf{Theoretical Yield} = \text{mass of the reactant used in the reaction} \times \text{MW} \times \text{coefficient ratio of reactant :product from the balanced equation X MW of the product}$$

Quantitative observations:

The traditional heating method resulted with an experimental yield of 0.313 g. The microwave-assisted reaction resulted with an experimental yield of 0.470 g.

Qualitative Observations: (Complete this portion *during* your tour of the CHM 242 lab today.)

Calculations:

1. Calculate the theoretical yield for today's reaction.
2. Calculate the % yield for the traditional heating method AND the microwave heating method.
3. Calculate the Atom Economy for today's reaction.

Questions:

1. Is the %yield and the Atom Economy calculated today the same thing? Why or why not? Support your answers using your data in your statement(s).
2. The utility company measure power being supplied to GVSU's labs in kWh (kilowatt-hours). One kilowatt is equal to 1000 W. If nine lab groups are running the traditional heating method for 30 minutes per each group and the hotplate pulls an average of 1,200 W of power, how much power is being consumed during this lab session? How much is being consumed if all the groups are to run the microwave-assisted reaction together for a total of 12 minutes at an average of 1,600 W? Which process most closely identifies with the 12 principles of green chemistry?

A.2 Informative talk (100 points possible)

Presented in class during the week of 5th–9th December in a group of two or may be presented individually15–20 minutes in lengthPrepare an ***Outline*** and a ***Reference Cited*** page to hand in the day of your presentation

Decide upon a green design/product/system/reaction route relevant to one or more of the 12 Principles of Green Chemistry and/or Green Engineering to present on.

Locate references about the topic of your choice

Research background information on your topic to introduce your audience to any relevant issues dealing with human health and/or the environment

Write an outline for your informative speech to turn in on the day of your presentation

Find at least three or more resources (must be from 1996 to current day) and include a References Cited page with your informative speech outline.

The resources you use must be from a variety of formats (for example, a journal and a URL or a magazine article and a newspaper article, and/or a scholarly book)

Visuals/Diagrams/Props/Skits are encouraged – cite any charts, tables, pictures, and/or diagrams on your References Cited page

Introduce the topic to our class assuming your audience does not have a working background/knowledge on green chemistry and/or green engineering

Include any relevant background/history in order to stress the ingenuity, necessity, and/or importance of your topic – this may include set-backs in the development of a process or may include failures (which are the path toward scientific progress) in the development of a novel material or a sequence of reaction routes

You/Your group must ask at least one question following the informative speech of another classmate

A.3 Informative talk grading rubric

Name:____________Overall Score:____/100

Criteria:	**4: Exceptional**	**3: Admirable**	**2: Acceptable**	**1: Poor**	
Nonverbal skills	**4**	**3**	**2**	**1**	**Points**
Eye contact	Holds attention of entire audience with the use of direct eye contact, seldom looking at notes	Consistent use of direct eye contact with audience, but still returns to notes.	Displayed minimal eye contact with audience, while reading mostly from notes.	No eye contact with audience, as entire report is read from notes.	
Poise	Displays relaxed, self--confident nature about self, with no mistakes.	Makes minor mistakes, but quickly recovers from them; displays little or no tension.	Displays mild tension; has trouble recovering from mistakes.	Tension and nervousness is obvious; has trouble recovering from mistakes.	
Verbal skills	**4**	**3**	**2**	**1**	**Points**
Enthusiasm	Demonstrates a strong, positive feeling about topic during entire presentation.	Occasionally shows positive feelings about topic.	Shows some negativity toward topic presented.	Shows absolutely no interest in topic presented.	
Speaking Skills	Uses a clear voice and speaks at a good pace so audience members can hear presentation. Does not read off slides.	Presenter's voice is clear. The pace is a little slow or fast at times. Most audience members can hear presentation.	Presenter's voice is low. The pace is much too rapid/slow. Audience members have difficulty hearing presentation.	Presenter mumbles, talks very fast, and speaks too quietly for a majority of students to hear and understand.	

Timing	**4**	**3**	**2**	**1**	**Points**
Length of presentation	Within 2 minutes of allotted time +/--.	Within 3 minutes of allotted time +/--	Within 4 minutes of allotted time +/--.	Too long or too short; 5 or more minutes above or below allotted time.	

Content	**4**	**3**	**2**	**1**	**Points**
Big picture	Clearly established context, scope, goals, and contributions.	Discussed context, scope, goals, and contributions.	Mentioned context, scope, goals, or contributions.	Did not mention context, scope, goals or contributions.	
Subject knowledge	An abundance of material clearly related to the research is presented. Points are clearly made and evidence is used to support claims.	Sufficient information with many good points made, uneven balance and little consistency.	There is a great deal of information that is not clearly integrated or connected to the research.	Goal of research unclear, information included that does not support research claims in any way.	
Organization	Information is presented in a logical and interesting sequence which audience can follow. Flows well.	Information is presented in logical sequence which audience can follow.	Audience has difficulty following presentation because the presentation jumps around and lacks clear transitions.	Audience cannot understand presentation because there is no sequence of information.	
Visuals	Excellent visuals that are tied into the overall story of the research. Good use of color.	Appropriate visuals are used and explained by the speaker. Adequate use of color.	Visuals are used but not explained or put in context. Some use of color.	Little or no visuals, too much text on slides. No or poor use of color.	
Mechanics	Presentation has no misspellings or grammatical errors.	Presentation has no more than two misspellings and/or grammatical errors.	Presentation has three misspellings and/or grammatical errors.	Presentation has many spelling and/or grammatical errors.	
				Total	

Comments:

A.4 Green chemistry vs. toxic technology

Students were required to access the website of the Electronic Take Back Coalition', an organization that promotes green design and responsible recycling in the electronics industry. They had to read the information, and discuss it. A brief description of green chemistry, followed by facts and figures regarding the toxic materials in electronic products, the toxicity across the lifecycle, and the health risk are provided in a very accessible, interactive fashion.

http://www.electronicstakeback.com/toxics-in-electronics/(accessed 24 January 2017)

To the two links for additional information on the website, students were also provided with the following resources:

- EPEAT: The EPA's Guide Falls Short on Environmental & Worker Protections, http://www.etoxics.org/electronics-purchasing/(accessed 23 January 2017)
- Take it Back, Make it Clean, Recycle Responsibly http://www.etoxics.org/electronics-recycling, (accessed 15 March 2017)
- Mats Linder (2017) Ripe for disruption: reimagining the role of green chemistry in a circular economy, Green Chemistry Letters and Reviews, 10:4, 428–435, DOI: 10.1080/17,518,253.2017.1392618. https://doi.org/10.1080/17518253.2017.1392618

To assess the effectiveness of an exercise of this type, students completed a short quiz, following here along with the answer key. The exercise allowed also to introduce students to search for primary sources and question the validity of information provided via web, such as google search.

E-waste – in class quiz

1. Circle the answer that you consider reflects today's reality on planet Earth
   a. More people than mobile phones
   b. Number of people = number of mobile phones
   c. Number of phones is greater than the number of people on the Earth at current time
2. What is considered e-Waste? Give examples
3. How much e-Waste is produced in US per year (approximately)? ____________
4. What is the difference between recycling and diverting e-waste? How the cost of the two compare?
5. Is e-waste toxic?
6. As of today, could we talk about e-waste as a global or a local environmental problem? Explain.
7. Explain the difference between severity of a toxic effect and potency of a toxic chemical
8. What is in the e-waste?
9. Is there gold in the e-waste? If it is, is the quantity significant, meaning has any value for the market?

Answer key

1. **Number of phones is greater than the number of people** on the Earth at current time (January 2017)
2. Phones, computers, tablets, readers, game consoles
3. As much as in 3.5 million fully loaded semi-tractor trailers = an end-to-end lines of trucks going from San Diego to Boston 18 times.
4. Recycling = Processing (sorted, treated for reused, treated chemically for reuse, burned to produce energy, etc.); ideally Waste = feedstock!

Diverting = send it somewhere else

5 It is the fastest growing component of the municipal waste stream (MWS) and accounts for 70% of our toxic waste

6 Both a global or a local environmental problem.

7 potency of a toxic chemical – Anastas and Warner, Green Chemistry: Theory and Practice page 59, Figure 5.1; for severity of a toxic effect of a chemical – see same textbook, page 60, Figure 5.2.

8 Lead Pb, Cadmium Cd, gold, Au, etc.

9 **1 tone** of smartphones = 10.9 ounces of Gold (Au) = mining more than 1,000.000 pounds of earth (approx. **500 tons** of earth);

1 pound = 16 ounces; ratio approx. 1,468.000:1 – for each ounce of Au, 1.5 million ounces of earth should be mined, redeployed, processed, and disposed of.

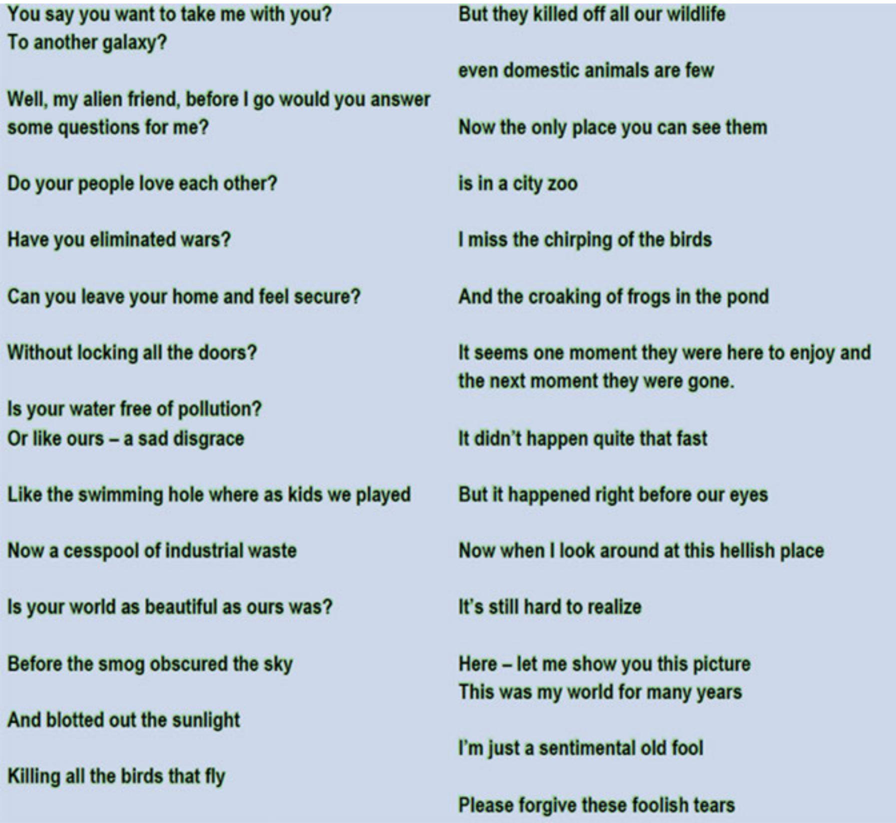
A.5 Class ice-breaker: respond and share via a class discussion

(Used to introduce the concept of shifting baselines)

Write a response to the poem by Joy:

1. Where does this poem take place?
2. When do you think this poem was written?
3. How old do you think the writer is?
4. What do you think the ‘time before’ is that the author is reflecting on?
5. What is the main message/indent of this author?
6. Is there hope? Is hope mentioned?

Joy's poem



You say you want to take me with you?
To another galaxy?

Well, my alien friend, before I go would you answer
some questions for me?

Do your people love each other?

Have you eliminated wars?

Can you leave your home and feel secure?

Without locking all the doors?

Is your water free of pollution?
Or like ours – a sad disgrace

Like the swimming hole where as kids we played

Now a cesspool of industrial waste

Is your world as beautiful as ours was?

Before the smog obscured the sky

And blotted out the sunlight

Killing all the birds that fly

But they killed off all our wildlife

even domestic animals are few

Now the only place you can see them

is in a city zoo

I miss the chirping of the birds

And the croaking of frogs in the pond

It seems one moment they were here to enjoy and
the next moment they were gone.

It didn't happen quite that fast

But it happened right before our eyes

Now when I look around at this hellish place

It's still hard to realize

Here – let me show you this picture
This was my world for many years

I'm just a sentimental old fool

Please forgive these foolish tears

(from an unpublished collection of poems, permission granted directly by the author)

Steven P. Wathen

7 Introduction to cheminformatics for green chemistry education

Abstract: The tools of cheminformatics are used for describing chemical structures for use in computer databases and in analyzing the connections between structure and molecular properties. As several aspects of Green Chemistry are also concerned with structure, properties and the relationships between them, cheminformatics provides tools that can be valuable in the teaching of Green Chemistry. This paper will provide an introduction to cheminformatics with a special emphasis on its value in chemical education and Green Chemistry.

Keywords: cheminformatics, computational chemistry, green chemistry education, chemical databases

7.1 Introduction

Many chemists might not use the labels “Cheminformatics” or “Green Chemistry” to describe what they do, but both fields involve concepts, methods, and tools that are of interest to both chemists and educators. Green Chemistry is a concern in every laboratory experiment even if those doing the work are not familiar with the 12 principles of Green Chemistry. The safety of the people working in the laboratory and managing whatever waste is produced is always important concerns. One aspect of Cheminformatics is concerned with the use of chemical databases. Before starting work in the laboratory the first step is often to look up information about chemicals to be used and necessary safety concerns, which often involves the use of a chemical database. There are some distinct ways in which the needs and concerns of chemical educators and their students intersect with the principles of Green Chemistry and the tools and techniques used in cheminformatics.

In the inaugural issue of the Journal of Cheminformatics, editor David Wild identified what he referred to as four Grand Challenges for cheminformatics [1]. Two of these Grand Challenges are particularly relevant to chemical educators interested in teaching about Green Chemistry. One Grand Challenge directly addresses Green Chemistry and it’s concern with reducing the toxicity of chemicals that are used and produced in the chemical industry. Toxicity is a complex topic and there are many ways in which a substance can be considered to be

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Wathen, S. P. Introduction to Cheminformatics for Green Chemistry Education. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0078

https://doi.org/10.1515/9783110566499-007

toxic such as mutagenicity, carcinogenicity, neurotoxicity, and others. Government agencies require the toxicity of substances to be documented, but determining multiple measures of toxicity experimentally is time consuming and expensive. The methods of cheminformatics can be used to better understand the link between toxicity and the structure of the compound through quantitative structure-activity relationships (QSARs). Using such *in silico* methods to describe toxicity has been explored as a means of meeting some of these regulatory requirements [2]. In the United States, the Environmental Protection Agency (EPA) has been exploring ways to improve, speed up toxicity testing and using computational techniques to augment or even replace animal testing [3].

The second Grand Challenge that relates to education and Green Chemistry is to enable the networking of the world's chemical and biological information to make it more accessible and easier to interpret. The Internet makes a vast amount of information easily available and while there are still sources that require a fee for access, there are many freely available resources of chemical information on the Internet. These range from very general resources like Wikipedia [4] to more specialized databases like PubMed [5] or PubChem [6]. Organizing structural descriptions of chemical compounds in ways that allow their storage, comparison and retrieval in databases is a central feature of cheminformatics.

The third annual ACS Green Chemistry Summer School (GCSS) [7] explored some of the benefits of Green Chemistry in the chemistry curriculum and some ways to implement this. Some topics where Green Chemistry and cheminformatics intersect include toxicology and structure-activity relationships. Chemistry education could be enhanced by including Green Chemistry topics, and cheminformatics provides important tools for doing this. Some critical concerns they highlighted are the connection between structure and activity, enhanced understanding of toxicity, and interdisciplinary awareness.

7.1.1 Bioinformatics

Information stored in databases, and the comparison and analysis of this information by computational tools is a common feature of informatics related work. For instance, the field of bioinformatics is concerned primarily with the structure of proteins and polynucleotides as described by their sequences: the sequence of amino acids in a protein, or the sequence of nucleotides in a strand of DNA or RNA. Storing this information in a computerized database is quite simple: it is a list of letters describing the sequence of interest. Comparing the sequence of interest with all the other sequences in the database is just a matter of matching the letters in each string.

Consider for example two pentapeptides involved in the perception of pain:

Table 7.1: Two Pentapeptides

Met-enkephalin:	TyrGlyGlyPheMet	or	YGGFM
Leu-enkephalin:	TyrGlyGlyPheLeu	or	YGGFL

[1]https://en.wikipedia.org/wiki/Enkephalin

Amino acids are commonly represented using either a three-letter abbreviation for the name of the amino acid or a one-letter code. Both are human readable, the three-letter code being a little more human-accessible. Comparing these sequences "by hand" is simple with the only difference being that the final residue is methionine in Met-enkephalin vs. leucine in Leu-enkephalin.

The hormone glucagon has more amino acid residues than a pentapeptide, but it is still a relatively small protein. The FASTA record from the National Center for Biotechnology Information (NCBI) Protein database [8] is:

```
> AAH05278.1 Glucagon [Homo sapiens]
MKSIYFVAGLFVMLVQGSWQRSLQDTEEKSRSFSASQADPLSDPDQMNEDKRHS-
QGTFTSDYSKYLDSRR
AQDFVQWLMNTKRNRNNIAKRHDEFERHAEGTFTSDVSSYLEGQAAKEFIAWLV-
KGRGRRDFPEEVAIVE
ELGRRHADGSFSDEMNTILDNLAARDFINWLIQTKITDRK
```

The FASTA format was designed for the FASTA software for analyzing sequence databases [9]. In this listing the first line starts with > and can include identifying information about the sequence that is not part of the sequence itself. In this case the identification number, name and species are listed. Starting on the second line the amino acid sequence is listed using the one-letter code. Any white space such as spaces, tabs or carriage returns is ignored. This sequence has 180 amino acid residues. To compare this sequence with another can be done by hand but it would be very tedious and prone to errors. Computers are very good at such highly repetitive tasks.

7.1.2 Cheminformatics

A number of different terms have been used to describe the chemistry version of bioinformatics. The preface to An Introduction to Chemoinformatics [10] by Leach & Gillet provides some interesting perspective on the topic. The term "chemoinformatics" was introduced in the late 1990's, but even the spelling of the term is variable. In addition to "chemoinformatics," Leach & Gillet list three additional terms for the field. A quick Google search (13 December 2017) for the four terms listed by Leach and Gillett as well as the two word phrase "Chemical Informatics" gives the following results:

Table 7.2: Google Hits for Cheminformatics synonyms

cheminformatics	~ 611,000 hits
chemoinformatics	~ 341,000 hits
chemiinformatics	~ 2,480 hits
chemical informatics	~ 186,000 hits

[1] Google search: 13 December 2017.

The consensus seems to be settling on cheminformatics, but the alternate terms are also reported.

Leach & Gillet go on to give the following definition:

> Chemoinformatics is concerned with the application of computational methods to tackle chemical problems, with particular emphasis on the manipulation of chemical structural information.

This would include tasks such as: searching databases, comparing structures and relating structure to activity. It is particularly important that structural information is stored efficiently and that search and analysis be fast because these databases typically have large numbers of structures. As an example, the PubChem Compound database of contains more than 94 million entries as of 16 December 2017.

7.2 Molecular structure and computers

The thing that most concerns a chemist about a chemical substance is the structure of the compound since the structure of a compound determines its properties, both physical and chemical. Finding information about chemical substances and their properties is something that every chemist and chemistry student needs to do, frequently by using a web browser. A Google [11] search is an easy first step, a somewhat more sophisticated source would be Wikipedia. Such searches start by entering text into the search bar using search terms like the compound's name, formula, CAS registry number, or even an image file using Google's Image search function. All of these search options have their limitations and none uses actual structural information that the computer can easily use for any type of analysis.

Organic compounds like ethanol, styrene, or morphine cannot be represented quite as easily as protein or nucleotide sequences which are essentially one-dimensional. Most organic compounds require at least a two-dimensional representation to describe their structures. One aspect of cheminformatics is concerned with how to describe molecular structure in a format that computer algorithms can use and how does the computer compare such structures.

With protein or nucleotide sequences the computer simply compares the letters. This can be quite tedious for a human to do "by hand" when the sequence is dozens or hundreds of residues long, but it is possible. Organic molecules require a different approach to both describe the structure in a way that the computer can use and to compare the structures of two or more molecules.

7.2.1 Encoding molecular structure

In the past one would find data about a given chemical compound by using a reference book that lists compounds alphabetically by name, with additional indexes ordered by formula or CAS registry number. Now one would more often that not use an online database for this purpose. A search for the name of the compound using Google or Wikipedia will often work even if there are multiple names used for the compound. Some other common ways to search might involve using the formula or CAS registry number. If the name of the compound or its CAS registry number is not known, the empirical formula might work as a search term but it is just as likely to not be very helpful if multiple isomers are possible. Even with an appropriate search term, this strategy is really only useful for single compounds. There are times when a collection of related compounds is desired.

The most intuitive way for a chemist to describe the structure of a compound is to draw a picture. While most Google searches take text as the input, Google is able to do a search based on an image file but the results are not likely to be very helpful for finding reliable chemical information. Online chemical databases like PubChem usually give the option of drawing the structure using a web app. Once this is done the computer does not use the picture itself, but usually converts the structure into a text-based format that is then used to query the database. The process then becomes just another search by comparing an alphanumeric search term to the listings in the database.

The structures of biopolymers like polypeptides and polynucleotides can easily be encapsulated relatively easily as a list of the residues. Organic chemical structures are often not reducible to a simple list of residues in a chain. Branching structures and rings are common, and often stereochemical aspects need to be described as well. Some examples: Ethanol (a small, simple structure), styrene (a cyclic compound with branching), morphine (a complex ring structure with multiple stereochemical features).

Many methods have been developed to encode chemical structure to allow a computer program to compare one structure to another. Three of the most common types of encoding used in cheminformatics are International Chemical Identifier (InChI) [12], Simplified Molecular-Input Line-Entry System (SMILES) [13] strings, and connection tables such as the mol format developed by MDL Information Systems [14]. The first two are line notations that use a single string of characters to represent chemical structure. The third encoding, connection tables, is usually found as a text file with an ending such as .mol, .xyz, etc. Connection tables are used when more explicit geometry information is required than the SMILES or InChI can provide. All three methods are commonly used in cheminformatics databases, as well as appearing in the Chemical Infobox [15] on the Wikipedia pages for chemical compounds.

7.2.1.1 International Chemical Identifier

The InChI was developed primarily to replace the use of CAS registry numbers for identifying chemicals. CAS registry numbers are assigned by a proprietary system that relies on an outside organization to assign a number like a serial number. A benefit of using CAS registry numbers as chemical identifiers is that each number is unique, but on the other hand there is no structural information contained in the number. InChI was designed as a nonproprietary method to encode information about the structure of the compound in a format that is unique and compact. While InChI is human-readable it is not really intended to be used that way and is used for database searching. Since the InChI code for a compound can become quite long and cumbersome, the InChI Key system was developed to serve as a hash system that can be used to convert the InChI into a fixed length string of characters that is no longer human interpretable, but still useful for computer algorithms.

InChI examples:

Ethanol	InChI=1S/C2H6O/c1-2-3/h3H,2H2,1H3 Key: LFQSCWFLJHTTHZ-UHFFFAOYSA-N
Styrene	InChI=1/C8H8/c1-2-8-6-4-3-5-7-8/h2-7H,1H2 Key: PPBRXRYQALVLMV-UHFFFAOYAB
Morphine	InChI=1S/C17H19NO3/c1-18-7-6-17-10-3-5-13(20)16(17)21-15-12(19)4-2-9(14(15)17)8-11(10)18/h2-5,10-11,13,16,19-20H,6-8H2,1H3/t10-,11+,13-,16-,17-/m0/s1 Key:BQJCRHHNABKAKU-KBQPJGBKSA-N

https://en.wikipedia.org/

The InChI for a compound always starts with “InChI = ” followed by the version number, which is currently 1. The standard InChI is indicated with the letter “S” following the version number. All three examples shown above are Standard InChI’s. The InChI software can also generate InChI codes that include non-standard features, e. g. relating to specifying uncertainty about stereochemistry, tautomers, and other features [16]. For a non-standard InChI there would be no “S” following the version number.

After the version number there are several sections called layers that are separated by slashes. The first layer is the empirical formula, the second layer describes the connectivity of the non-hydrogen atoms, the third layer describes the locations of the hydrogen atoms. Other layers describe other aspects of structure, while some layers are optional and not always included.

7.2.1.2 Simplified Molecular-Input Line-Entry System

Using the Simplified Molecular-Input Line-Entry System (SMILES) the structure of a compound can be represented as a single string of characters. A SMILES string looks rather like a more conventional condensed organic structure with the hydrogen atoms left out. Branching groups are enclosed in parentheses, double bonds are represented with an equal sign (=) and triple bonds by a pound sign (#). Rings are indicated using numbers to indicate points of connection. Aromatic atoms are indicated with a lower case letter. There is also a system for indicating the stereochemistry.

One drawback of the SMILES system is that there can be more than one way to represent a given molecule. Ethanol can be denoted with four different strings: CCO, OCC, C(C)O or C(O)C. There is no way to condense a long SMILES string the way that the InChI key does for InChI strings.

SMILES string examples:

Ethanol	CCO
Styrene	C = Cc1ccccc1
Morphine	CN1CC[C@]23C4 = C5C = CC(O) = C4O[C@H]2[C@@H](O)C = C[C@H]3[C@H]1C5

https://en.wikipedia.org/

7.2.1.3 Connection tables

Connection Tables are more often used with programs that display the 3D structure, or as the input or output for computational chemistry programs. Many common molecule file formats – xyz, mol, pdb, cml, sdf – all use a version of a connection table. There are two parts to the connection table. The first is a list of the atoms with their xyz coordinates, and maybe additional characteristics. The second part lists which atoms are connected to one another and the bond order of the connection.

An example of a connection table for ethanol is shown below. This connection table was generated by the Online SMILES Translator and Structure File Generator from the National Cancer Institute's Computer-Aided Drug Design (CADD) Group [17].

```
C2H6O
APtclcactv12181707283D 0 0.00000 0.00000
9 8 0 0 0 0 0 0 0 0999 V2000
1.2852–0.2462–0.0000 C 0 0 0 0 0 0 0 0 0 0 0 0
–0.0112  0.5663  0.0000 C 0 0 0 0 0 0 0 0 0 0 0 0
–1.1303–0.3223  0.0000 O 0 0 0 0 0 0 0 0 0 0 0 0
2.1388  0.4316  0.0000 H 0 0 0 0 0 0 0 0 0 0 0 0
1.3202–0.8745  0.8900 H 0 0 0 0 0 0 0 0 0 0 0 0
```

```
1.3202−0.8745−0.8900 H 0 0 0 0 0 0 0 0 0 0 0 0
−0.0462 1.1947 0.8900 H 0 0 0 0 0 0 0 0 0 0 0 0
−0.0462 1.1947−0.8900 H 0 0 0 0 0 0 0 0 0 0 0 0
−1.9249 0.2289−0.0000 H 0 0 0 0 0 0 0 0 0 0 0 0
1 2 1 0 0 0 0
2 3 1 0 0 0 0
1 4 1 0 0 0 0
1 5 1 0 0 0 0
1 6 1 0 0 0 0
2 7 1 0 0 0 0
2 8 1 0 0 0 0
3 9 1 0 0 0 0
M END
$$$$
```

A connection table is often stored as a stand-alone text file. The header section consists of the first three lines which include a title and information from the program that generated the file. The connection table itself starts on the fourth line with information about the number of atoms and bonds in the file and possibly other information. In the present example there are nine atoms and eight bonds. The next nine lines describe the xyz coordinates and identity of each atom. This is followed by eight lines describing the bonds, for example atom 1 is connected to atom 2 with a single bond. Finally, the $$$ signifies the end of the file. The sdf format is similar in organization and can contain multiple molecular structures in a single file.

7.2.2 Searching chemical databases

Once the molecular structure of a compound has been encoded into a computer interpretable format it can be used as a query for accessing a database of molecular structures. There are three basic types of search that are commonly carried out on structure databases: identity search, substructure search, and similarity search. An identity search returns an exact match if present, substructure and similarity searches return many compounds that match their search criteria.

An identity search queries a chemical database to determine if the query molecule is present in the database and retrieves whatever data is stored about it. In this case the objective is generally information about a single molecule, like looking up the entry for morphine in a reference book. If the compound is present in the database, then whatever information is stored for that compound can be retrieved.

It can also be useful to search a database for compounds that share some common structural feature. The result will be a group, perhaps a very large group, of compounds that fit the search criteria. When using structure as input this way there are two common types of search: substructure and similarity.

Substructure searching compares the query to all molecules that contain the same pattern. For example, all benzoic acids or all benzodiazepines. Substructures to match can be simple or quite complex. The SMARTS [18] system is similar to SMILES and is used for designating a pattern to search for. The user does not generally have to be aware of the SMARTS string, although advanced users might use it in favor of drawing the desired substructure to search.

The similar property principal [19] states that if two compounds have a similar structure they can be expected to have similar properties or behavior. This principal has been of particular use in drug design and predictive toxicology. If it is known that a given compound is toxic, any molecules that are similar in structure would reasonably be expected to also be toxic in the same way.

A similarity search [20] produces a ranked list based on similarity to the query. Similarity is measured by a similarity coefficient which ranges from no similarity with a value of zero to complete similarity with a score of one. Similarity scores are most often obtained by comparing molecular fingerprints which consist of a bit string. A molecular fingerprint is usually a list of bits that represent characteristics that might be present in the molecule. Each bit is either a “1” when that characteristic is present, or a “0” when it is not present. The bits represent structural features that may be present in the compound. A similarity search will usually include a limit on compounds to be returned, e. g. similarity > 0.9, and the results of the search will be listed in order of decreasing similarity.

The most common method for comparing fingerprints is described by the Tanimoto coefficient, also known as the Jaccard coefficient. Tanimoto similarity $= c/(a + b - c)$ where “a” is the number of bits set to 1 in compound a, “b” is the number of bits set to 1 in compound b, and “c” is the number of bits set to 1 in both compounds. In addition to the Tanimoto coefficient, a number of other coefficients have been defined that compare the bit strings in ways that emphasize different aspects of what makes them similar to one another. Examples include city-block distance, Euclidean distance and the dice coefficient. For some applications it is important to have a diverse set of compounds, rather that a similar set. In such cases, a dissimilarity measure is used that emphasizes bits that are different rather that bits that are shared by compounds.

7.2.3 Cheminformatics databases

There are many freely available chemical databases on the Internet. On his Depth-First blog, Rich Apodaca lists 64 databases for cheminformatics [21]. Cheminformatics databases are largely concerned with biological matters such as drug behavior, toxicity, and metabolism. Some widely used cheminformatics databases are:

PubChem is hosted by the NCBI. In addition to listing individual chemicals also has database of chemical substances which may be mixtures and a database of assay data.

ChEMBL [22] is a manually curated chemical database of bioactive molecules that is maintained by the European Bioinformatics Institute (EBI) of the European Molecular Biology Laboratory (EMBL).

ChemSpider [23] is a free chemical structure database that provides access to over 26 million structures from hundreds of data sources.

The journal Nucleic Acids Research [24] has an annual Database issue that often lists cheminformatics databases.

7.2.4 Structure encoding and database applications for education

Being able to find data about chemicals is a fundamental skill for people working in chemistry, whether physical data such as molecular weight, density, melting point, boiling point or more specialized data like safety, toxicity, or regulatory information. It is worthwhile to have some understanding of how computer searches work rather than simply treat the database as a black box. While Google and Wikipedia can be very useful places to start, familiarity with specialized chemical databases provides better tools to work with. SMILES in particular can be a useful shortcut to preparing figures for reports since structure drawing programs can generate a 2D or 3D structure from a smiles string, either SMILES composed “by hand” or copied from another source such as Wikipedia. CAS registry numbers have often been used to identify chemicals unambiguously. InChI may take the place of CAS registry numbers in this function and understanding what InChI is and how it is generated could be valuable for the informed chemical worker.

To give my students experience with finding and using chemical data, this author has given assignments to introduce SMILES and InChI. ChemSketch is available as freeware for educational use from www.acdlabs.com and can convert SMILES to structural drawings, it can also generate SMILES and InChI from the structure. Students can use ChemSketch to prepare figures for laboratory reports, including data such as formula, molecular weight, etc. Avogadro [25] is a free molecular modeling program for computational assignments, can generate 3D structures from SMILES input, which can be easier than using the 3D structure-drawing interface.

7.3 Relating structure to behavior

In addition to encoding, storing and retrieving chemical structure information, cheminformatics is also concerned with the link between structure and behavior, particularly behavior that is complex and difficult to predict such as solubility, biological activity or toxicity. Once a quantitative relationship is established, that structural information can be used to understand and predict the behavior of chemical substances. These approaches could be used to find new, “greener” materials or for predicting the toxicity of such substances.

In Green Chemistry, toxicity is an important issue relating to the structure and behavior of chemical compounds. The concern here is to make the whole process safer: reduce hazards due to chemical reactivity (corrosiveness, oxidizing power, flammability, etc) and hazards due to interactions with biological systems (toxicity). This applies to the hazards of the reactants and intermediates used in the process, the hazards of finished product, as well as any waste materials that are produced.

Chemists have had a lot of experience with recognizing compounds that are hazardous to work with because they are highly reactive, but recognizing the potential toxicity of a compound based on its structure and biological activity is more complex and draws some important parallels with the development and understanding of drugs: can the compound be absorbed into the body, can it move through the bloodstream, is it metabolized to a new compound, does metabolism make the compound more toxic or less toxic, does it interfere with important biological processes, will it be readily excreted?

The mechanisms of toxicity and drug behavior involve many of the same types of interactions. Developing new drugs is expensive and time consuming, and cheminformatics techniques can be used to streamline that process. Pharmaceutical chemists can use cheminformatics techniques to look for links between the structure of drug compounds and their behavior as drugs in the way the drug binds to target molecule such as a specific protein or nucleotide, but other factors as well: absorption into the body, transport from one part of the body to another, metabolic breakdown to form more toxic or less toxic compounds, or possible side effects.

Governmental regulatory agencies now require the reporting of toxicity data and there is interest in using cheminformatics techniques to complement or possibly replace costly and time consuming testing. As with the behavior of drugs, toxicity is a complex process and structure will influence many of the processes involved, but not in any way that is easy to predict.

7.3.1 Molecular descriptors

It is axiomatic that structure determines properties and chemists have often used simple rules of thumb to make chemical predictions based on molecular structure. Effects such as electron withdrawing groups and electron donating groups, resonance stabilization, the presence of hydrogen-bonding groups can help to understand chemical behavior. Quantum mechanical calculations can shed some light on predicting behavior but the interpretation is not always straight forward. A QSAR [26] is a statistical model that provides a way to make a quantitative link between structure and behavior. A quantitative structure activity relationship takes a group of compounds with known properties and provides a strategy for looking for correlations between structural features and behavior of interest.

Some early examples of quantitatively relating structure to behavior include Hammett's sigma (σ) constant as a measure of the electron donating and withdrawing power of a substituent group [27], the Weiner index describes on the effect of alkane branching on the boiling points of a series of alkanes [28]. Hansch developed this as a general approach while initially looking at the relationship between the log of the octanol-water solubility partition coefficient (log P) of a series of phenoxyacetic acids and their biological activity [29].

These factors, Hammett's σ describing electronic effects, Wiener's index describing topological effects, and the log P which is a physical property represent numerical measures that have been shown to be related to chemical behavior. In a QSAR study they would be referred to as descriptors. A great many chemical descriptors [30] have been defined that can be used in structure-activity studies.

Molecular descriptors are typically numbers that describe some aspect of molecular structure and are straight forward to calculate for a computer. Some examples are: molecular weight, topological polar surface area (TPSA), molar refractivity (MR), Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO) energies, simple counts such as the number of carbons, carbonyl groups, hydrogen-bond donors, etc. Computational packages can calculate hundreds, even thousands of different descriptors for each compound.

7.3.2 Quantitative structure-activity relationship

In a typical QSAR study the objective is to develop a model that will predict a specific activity such as skin absorption, enzyme inhibition, antibiotic action, etc. This process starts with a data set of compounds whose activity is already known. The data set will often be divided into two groups, a training set and a validation set. A large number of descriptors are then generated for each compound in the data set. A model will be developed by looking for a mathematical relationship between the activity and the descriptors of the compounds in the training set. Many descriptors will not be relevant, so there is a process of reducing the number of descriptors to a minimum number. Once this is done, the model is tested by having it predict the activities of the validation set. This allows you to see how well the model does with compounds that were not part of the model-building process.

The pharmaceutical industry has made much use of cheminformatics techniques, including QSAR in the drug development process. Many drugs in development are discarded fairly late in the process due to toxicity that appears during animal screening or through adverse effects on humans. Many of these effects are related to absorption, distribution, metabolism and excretion (ADME) and Toxicity which could be predicted via QSAR methods. Screening out such problematic compounds early could save a lot of time and money. Likewise QSAR can be used in a Green Chemistry sense to recognize potentially toxic compounds during development, rather than discovering it afterwards.

7.3.3 Education applications

Many organic chemistry textbooks will include figures that plot the number of carbons in a compound versus some physical property such as melting point or boiling point. Pointing out the way that structure affects physical properties and chemical behavior is a common approach. Structure-activity relationships are common in education, although they are often presented qualitatively. QSAR is a technique that makes such relationships more quantitative, and allows for the influence of more than one aspect of structure to influence the activity in question.

I have used QSAR as a learning activity in my sophomore Organic Chemistry classes to highlight this connection. In addition, the QSAR exercise exposes students to Data Science. “Big Data” has become a familiar phrase in recent years, and this exercise gives students a taste of one way that this is used in a chemical field. I also teach an upper level special topics course also does a QSAR exercise which is a more elaborate project in which the students generate descriptors starting with a list of SMILES strings, and then have to reduce a fairly large number of descriptors to a practical subset.

7.4 Conclusion

Anyone who has done a computer search for information about chemical substances has in some sense used cheminformatics techniques. With the widespread use of computers and Internet-based databases, the techniques of cheminformatics are used by chemists and their students every day. A deeper knowledge of some of the ways to encode molecular structure for use in databases, how chemical databases use that data allow the users to make better use of these resources. These are valuable skills for any student of chemistry.

References

[1] Wild D Grand challenges for cheminformatics. J Cheminf. 2009;1:1.
[2] Benfenati E, Diaza R, Cassano A, Pardoe S, Gini G, Mays C, et al. The acceptance of in silico models for REACH: requirements, barriers, and perspectives. Chem Cent J. 2011;5:58.
[3] Erickson B. U.S. embraces new era in risk assessment. Chem Eng News. 2017 Dec;4:18–9.
[4] Wikipedia. Available at:https://www.wikipedia.org/. Accessed December 13, 2017.
[5] PubMed. Available at:https://www.ncbi.nlm.nih.gov/pubmed/. Accessed December 13, 2017.

[6] The PubChem Project. Available at:https://pubchem.ncbi.nlm.nih.gov/. Accessed December 13, 2017.

[7] Kitchens C, Charney R, Naistat D, Farrugia J, Clarens A, O'Neil A et al. Completing our education. J Chem Ed. 2006;83:1126–9.

[8] NCBI Protein. Available at:https://www.ncbi.nlm.nih.gov/protein. Accessed December 16, 2017.

[9] Lipman D, Pearson W Rapid and sensitive protein similarity searches. Science. 1985;227:1435–41.

[10] Leach A, Gillet V An introduction to chemoinformatics. Dordrecht, The Netherlands: Springer, 2007.

[11] Google. Available at:https://www.google.com/. Accessed December 13, 2017.

[12] Stein S, Heller S, Tchekhovskoi D An open standard for chemical structure representation: The IUPAC Chemical Identifier. Proceedings of the 2003 International Chemical Information Conference. Nimes, France, October 19–22, Infornortics: Tetbury, UK, 131–43.

[13] Weininger D. SMILES, a chemical language and information system. 1. Introduction to methodology and encoding rules. J Chem Inf Comput Sci. 1988;28:31–6.

[14] Dalby A, Nourse J, Hounshell W, Gushurst A, Grier David D, Leland B, et al. Description of several chemical structure file formats used by computer programs developed at molecular design limited. J Chem Inf Comput Sci. 1992;32:244–55.

[15] Wikipedia Chemical Infobox. Available at:https://en.wikipedia.org/wiki/Wikipedia:Chemical_infobox. Accessed December16, 2017.

[16] Technical FAQ InChI Trust. Available at:http://www.inchi-trust.org/technical-faq/. Accessed Dec 16, 2017.

[17] Online SMILES Translator and Structure File Generator, Available at:https://cactus.nci.nih.gov/translate/. Accessed December16, 2017.

[18] Daylight Theory Manual. Available at:http://www.daylight.com/dayhtml/doc/theory/. Accessed December 16, 2017.

[19] Johnson M, Maggiora G Concepts and applications of molecular similarity, New York: Wiley, 1990

[20] Willett P, Barnard J, Downs G Chemical similarity searching. J Chem Inf Comput Sci. 1998;38:983–96.

[21] Sixty-Four Free Chemistry Databases. Available at:http://depth-first.com/articles/2011/10/12/sixty-four-free-chemistry-databases/. Accessed December 16, 2017.

[22] ChEMBL. Available at:https://www.ebi.ac.uk/chembl/. Accessed December 16, 2017.

[23] ChemSpider. Available at:http://www.chemspider.com/. Accessed December 16, 2017.

[24] Nucleic Acids Research. Available at:https://academic.oup.com/nar. Accessed May1, 2018.

[25] Avogadro - Free cross-platform molecular editor. Available at https://avogadro.cc/. Accessed online May 1, 2018).

[26] Hansch C, Leo A, Heller S Exploring QSAR: volume 1: fundamentals and applications in chemistry and biology. Am Chem Soc. 1995.

[27] Hammett L. The effect of structure upon the reactions of organic compounds. Benzene derivatives. J Am Chem Soc. 1937;59:96–103.

[28] Wiener H Structural determination of paraffin boiling points. J Am Chem Soc. 1947;69:17–20.

[29] Hansch C A quantitative approach to biochemical structure-activity relationships. Acc Chem Res. 1969;2:232–9.

[30] Todeschini R, Consonni V, Mannhold R, Kubinyi H, Timmerman H. Handbook of molecular descriptors. Wiley-VCH, 2002.

Larry Kolopajlo

8 Green chemistry outreach

Abstract: This paper discusses several approaches used to infuse green chemistry and its core values into the outreach curriculum spanning 2013–2017 at Eastern Michigan University. Pertinent pedagogy, best practices, suggestions on how to organize an outreach activity, and common pitfalls to be avoided will be discussed. A unique feature of the outreach camps described is that diversity is addressed.

Keywords: CSI, outreach, green chemistry, high school, pedagogy, NGSS, diversity

8.1 Introduction

While giving a talk on green chemistry to a packed audience of K-8 teachers at a Michigan Science Teachers Association Meeting in 2016, the author realized how powerful the name green chemistry was in attracting the interest of educators. Thus, given the interest expressed by teachers on green chemistry, it is surprising that more K-12 educators have not been involved in the green chemistry movement.

The purpose of this paper is to describe green chemistry outreach programs that have been developed and employed across the K-12 spectrum at Eastern Michigan University (EMU) from 2013 to 2017. EMU is a comprehensive, co-educational public university located in Ypsilanti, Michigan. It has been recognized for its diversity, and moreover, has a large population of nontraditional students. In fact, many of its students are the first in their family to attend college. In this introductory section, the important components of this paper will be outlined.

While service work in the form of outreach by tenured faculty are often a discouraged, overlooked, and underappreciated professional activity, at EMU service is a valued component of the teaching–research–service triad and can impact promotion. One reason for valuing service work done by tenured faculty at EMU is that the main focus is on teaching and service, rather than research. In this narrative, it will be explained why service as outreach should be valued, not only for its benefits to the community, but as a tool to promote science literacy. Moreover, this paper will also point out the huge time investments and difficulties associated with implementing outreach.

In this paper, green chemistry outreach is also framed in terms of promoting the science literacy of K-12 students. Although the model and pedagogy of green chemistry outreach was pioneered by Beyond Benign [1], the program described in this

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Kolopajlo, L. Green Chemistry Outreach. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0083

https://doi.org/10.1515/9783110566499-008

paper has some novel features. For example, one hallmark of EMU's green chemistry outreach program was that it emphasized diversity and inclusivity across a spectrum of culture, gender, and race. Another program feature was that it spanned grades K-12. Third, the program was designed to not only make chemistry relevant and stimulating, but to bridge the gap between theory and practice by engaging students as citizen scientists through hands-on activities.

Information on how the outreach program was designed to make it fun and engaging for students will also be provided. One question probed during the program was whether chemical outreach could reduce chemophobia and motivate students toward a career in science, but admittedly, questions like these remain unanswered. What's more, beyond including some staples such as safety, the outreach program provided teachers with professional development in the form of training and activities that could be taken away and used.

Program logistics, an overlooked aspect of outreach, will be delineated in order to provide novices with an understanding of how important preparation is. Moreover, issues and common pitfalls to be avoided will also be discussed. Last of all, financial support for the outreach programs addressed in this paper will also be acknowledged.

8.2 Science literacy and green chemistry

8.2.1 PISA

Sustainability and science literacy shape the conversation on why green chemistry is important. On the one hand, chemists have a social responsibility to move their discipline to an environmentally friendlier state, but to accomplish this, a population of scientifically literate citizens is required.

The issue is clear: the United States must promote science in its K-12 educational systems. However, there is evidence that the United States is not improving in science education. One way to gauge the preparedness and competitiveness of US students in science and mathematics is to look at PISA scores. PISA, the Programme for International Student Assessment [2], assesses the scientific and mathematical literacy and achievement of 15-year-old students across the globe. Rather than focusing on content learned, PISA tests the ability of students to apply scientific knowledge to new situations. Such higher-order thinking skills are important in spurring economic growth and competitiveness. Administered by the Organization for Economic Co-operation and Development or OECD, the PISA science assessment is given to both its 35 members and more than 60 nonmember countries.

According to published PISA results [3] listed in Table 8.1, the United States has not performed as well as its counterparts in both OECD and non-OECD countries. In Table 8.1, the third column is most meaningful because it accounts for the fact that not all scores higher than the US score in column 2 are statistically different.

Table 8.1: US PISA results.

Year	Absolute ranking	Corrected ranking
2015	25th	19th
2012	28th	28th
2009	17th	13th
2006	29th	23rd
2003	29th	Not available
2000	14th	8th
Average	24th	18th

8.2.2 The condition of STEM in the United States

As of 2014 [4], about 40% of all B.S. degrees earned by males were obtained in Science, Technology, Engineering and Mathematics (STEM) fields. The analogous statistic for women is that about 30% of all B.S. degrees were earned in STEM fields. However, according to NSF, the number of undergraduate chemistry degrees continues to decline, even though chemistry has been made more accessible through alternate degree programs, not just the American Chemical Society (ACS)-approved degree [5]. Demographics of the Science and Engineering workforce [6] also show that Hispanics, African Americans, and American Indians or Alaska Native Hispanics are woefully underrepresented in STEM professions, while Caucasian women continue to make great strides. For example, women now dominate the Life Sciences professions [7]. The current status of STEM literacy can be summed up in the following statement, which echoes what has been said by many in industry and government: The United States must succeed in promoting scientific achievement among its K-12 students; otherwise it may lose its global STEM leadership position.

In 2016, ACT [8] published a report titled “The Condition of STEM 2016” in which it surveyed STEM interest amongst its high school Advanced Placement (AP) test-takers. Some of the key findings, as shown below, indicate a largely stagant STEM landscape:

a. About 50% of AP test-takers in the class of 2016 have an interest in STEM.
b. Average AP Mathematics test scores changed little between 2012 and 2016.
c. Average AP Science test scores increased from 27.9 to 28.6 over 2012–2016.

8.2.3 NGSS

To improve science literacy, Next-Generation Science Standards (NGSS) have been unveiled, and they offer a paradigm shift in science education. Although the words “chemistry” and “green chemistry” do not appear in the NGSS framework, green chemistry could easily be incorporated into the engineering design of its three-dimensional structure. There is therefore a method in place to meet the need of incorporating green chemistry activities into NGSS.

Although training teachers to think within the three dimensions of NGSS is a challenging task, the analogous pedagogic approach in green chemistry instruction seems natural and much simpler. Imagine lecturing about disciplinary core ideas, crosscutting concepts, and scientific practices when planning and doing outreach? The green chemical pedagogic approach is inherently streamlined, because the very name green chemistry invokes a higher calling than just doing science for the sake of increasing standardized test scores. Published papers [9, 10] support the idea that green chemistry pulls in people and increases scientific interest. Once green chemistry is successfully communicated to students as a humanitarian practice, in other words, as service in the name of sustainability, it can then be used as a tool to promote science literacy. The obvious extension is to integrate green chemistry into the science outreach curriculum. Although cognitive knowledge is not generally assessed in outreach because outreach is usually designed to stimulate science interest, using green chemistry may allow an avenue to address science content knowledge. Green chemistry outreach activities, as will be delineated below, can offer several components of STEM science practices in a single activity. In Table 8.2 below are condensed NGSS performance expectations that can be addressed in green chemistry outreach.

Table 8.2: Some next-generation standards applicable to outreach activities.

Standard	Performance expectation
2-PS1-1	Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties.
2-PS1-2	Analyze data obtained from testing different materials to determine which materials have the properties that are best suited for an intended purpose.
5-PS1-1	Develop a model to describe that matter is made of particles too small to be seen.
5-PS1-3	Make observations and measurements to identify materials based on their properties.
MS-PS1-1	Develop models to describe the atomic composition of simple molecules and extended structures.
MS-PS1-2	Analyze and interpret data on the properties of substances before and after the substances interact to determine if a chemical reaction has occurred.
MS-PS1-3	Gather and make sense of information to describe that synthetic materials come from natural resources and impact society.
HS-ETS1-3	Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.
HS-PS2-6	Communicate scientific and technical information about why the molecular level structure is important in the functioning of designed materials.

[1] Next Generation Science Standards. https://www.nextgenscience.org/

8.2.4 Green chemistry pedagogy

The green chemistry outreach pedagogy described in this paper was unconventional, disregarding the standardized formats of a structured classroom, and excluding instructional tools such as cookbook laboratories, and worksheets, which by some exaggerated accounts, students see by the millions in their daily classrooms. Although worksheets were avoided, many outreach activities were described to participants through handouts. In short, the main pedagogic goal for the outreach described in this paper was to make the green chemistry classroom as unlike their daily school schedules as possible. To accomplish this, active learning strategies were employed. Such best practices included spanning the domains of learning by making science outreach fun (affective), involving students in stimulating hands-on learning (psychomotor skills), and addressing some interesting science content (cognitive). Claim-Event-Reasoning (CER) and Predict-Observe-Explain (POE) learning cycles which actively involved students in constructing models of natural phenomena replaced cookbook and algorithmic activities. Another best practice involved having instructors view effective outreach from a participant viewpoint in order to understand how to create an environment that made students feel like citizen scientists. Moreover, in order to create a good experience for the participants, instructors focused on building relationships with them. Therefore, when the lead instructor was male, having females leading some of the activities was a factor of key importance.

It is also essential that deployed pedagogy match the grade level of the student audience. Doing outreach with children in elementary school is particularly satisfying because they are open-minded, are questioning, and view a field trip to a college laboratory as a highly stimulating experience. However, the author has found that third-grade students may not have the attention span and finger dexterity to complete tasks that fourth graders can do.

8.3 Green chemistry and K-12 education

Green chemistry, initiated by academics, has spread rapidly in higher education and industry, but its growth has lagged behind in K-12 education. In this section, the recognition of green chemistry by organizations involved in K-12 education, namely NSTA, AACT, Beyond Benign, and NGSS, will be reviewed.

There can be no doubt that the largest organization promoting green chemistry is the powerful ACS [11]. But what about other groups? A brainchild of ACS, the American Association of Chemistry Teachers (AACT) was organized in 2013; it is an organization administered by high-school chemistry teachers who promote chemistry education across the K-12 spectrum. It is open to anyone having an interest in K-12 chemistry education. In the area of green chemistry, the AACT website offers several webinars [12].

The National Science Teachers Association (NSTA), by far the largest science education organization, has published a very limited amount on green chemistry, and its journal articles have been reviewed [13]. It has posted four green chemistry podcasts on its website [14]. Moreover, under the green chemistry theme, "is *there a place for green chemistry in the high school curriculum*," NSTA surveyed these few topics:

1. Energy required to heat water
2. Modeling atom economy
3. A clock reaction with safer substances
4. Sample laboratories, demos, and activities

Another way to integrate green chemistry into K-12 education is through active learning in the format of case studies. However, as of May 2017, there are no case studies addressing green chemistry as listed in on National Center for Case Study Teaching in Science website [15] which contains 676 peer-reviewed cases.

Although professional educational societies have the major responsibility of teaching science content and laboratory skills, to bridge the green chemistry –K-12 gap, Beyond Benign has pioneered the development of green chemistry curricula and teacher instruction. Bodner [16] has recently reviewed Beyond Benign.

8.4 Review of published articles on outreach

Many published papers appear in the literature on outreach. However, only a few published outreach papers deal exclusively with green chemistry. In this section, several outreach papers that have appeared in the *Journal of Chemical Education* will be surveyed. The review will show that a lot of creative work takes place in the field of outreach, and that outreach is advancing on several fronts. Best practices and lessons learned will be addressed. While some papers discussed below are very sophisticated, are supported financially, and include many leaders and workers, in contrast the reader will see that some of the science camps described by the author in this report are comparatively streamlined, and while some were supported by external grants, most operated on a shoestring budget.

8.4.1 Green chemistry outreach

In 2009, Cannon and Warner [17] reported a pedagogical model for outreach in green chemical education and demonstrated its relationship to science literacy. Their paper was one of the first to present a coherent structure for the role of green chemistry outreach in a K-12 science curriculum. In the article, the role of Beyond Benign in providing green chemistry outreach is described in detail. One key idea of these authors is to engage children early in green chemistry outreach using a green chemistry curriculum and continue the outreach through high school. The article, titled *K-12 Outreach and Science Literacy through Green Chemistry*, adopts the viewpoint that green chemistry not only provides a path to a sustainable future through joint environmental and economic products, but also serves as an effective way to motivate student interest in science. The authors establish some best practices in green chemistry outreach as summarized below:

1. engage students in green chemistry at an early age
2. engage students in the invention process of green chemistry
3. use hands-on experiments
4. train teachers in green chemistry
5. reach all students
6. use college students as volunteers in a service learning model

In another paper, Guedens and Reynders [18] described a Belgium high-school outreach program that mainly addressed green activities in nutritional chemistry, water, and nanochemistry. One feature of the university-based program was that it trained high-school science teachers to lead outreach sessions with children from their own classes. Teachers were trained in two sessions per year, each session lasting 3 hours. In a second phase of the same program, local pre-college high-school students were invited to perform laboratory experiments at the university in 2.5 h-long activities. The program served as a bridge between science in high school and college.

8.4.2 Outreach courses

LaRiviere et al. [19] published a paper describing a service learning course on chemistry outreach whose goal was to produce highly qualified chemistry teachers. Of the ten students in the course, five were enrolled in an education minor program. The program major of the remaining students taking the course was not provided. College students developed and deployed about 30 different outreach activities that were used with fifth-grade children. One goal of the program was to have students apply their chemical content knowledge to new outreach situations. Many of the activities focused on chemical and physical changes. Students enrolled in the course devised, tested, and peer reviewed each others' work. To evaluate the program, students, child participants, and their teachers were surveyed. Pre- and postsurveys showed that positive gains were made, especially for girls. In response to the question, "Do you want to be a scientist?". Girls increased their scores from 38% to 46% in pre- versus postsurveys. In addition, teachers thought of the program as professional development because they learned new science activities.

In another outreach focused paper by Ophardt [20], students enrolled in a chemical demonstration course, titled: "Chemistry in the Natural World." Demonstrations were selected to match topics discussed in lecture. One objective was to move education students from cookbook laboratories to inquiry laboratories. The course was initially deployed in the month of January in order to meet a state requirement for science methods instruction. However, the course revision targeted nonscience majors, although education majors also enrolled in it. Demonstrations covered the following: density, gases, polymers, and chemical changes. Demonstrations included the nylon rope trick, elephant toothpaste, liquid nitrogen, polyurethane foam, and hydrogen balloons. College students were expected to fulfil three learning objectives: (a) to understand and explain chemical principles, (b) to develop oral and written communication skills, and (c) to develop and modify demonstrations to practice aspects of the scientific process. Once students successfully learned how to perform chemical demonstrations, they performed a demonstrations show at a local elementary school to children from grades 3 to 5.

8.4.3 Young women

Levine et al. [21] published results on a week-long chemistry camp conducted for 36 middle-school girls. Among the goals realized included addressing the gender gap by using female role models to make science relevant and promoting STEM interest. Outreach activities addressed numerous experiments, field trips, and interactions with female scientists. Experiments covered polymers, crime scene investigation (CSI), lipstick chromatography, cabbage juice as an acid–base indicator, oil spill clean-up, and demos such as square bubbles, lava lamps, slime, Mentos, and diet Coke. Surveys (pre and post) evaluated the camp, but only 28 girls from the 36-member group consented to be evaluated. However, there was a significant gain for each of the 17 questions in the survey, demonstrating that the camp succeeded.

8.4.4 Elementary outreach

In 2014, Houck et al. [22] published an article describing how chemistry graduate students from the Universities of Virginia (UVA) and Vermont (UVM) were employed to successfully run a one-day summer chemistry camp devoted to food chemistry (pH, emulsions, and chromatography) for elementary school students. From 2012 to 2013, the program served about 225 K-5 students. Unique features of the program were that: (a) it was managed by graduate students, (b) trained graduate students in planning and conducting outreach activities, (c) fostered graduate student interest in outreach and service, (d) generated funds to be used for travel grants, and (e) generated funds for a student-outreach club that taught hands-on science lessons at local elementary schools. Student hours also counted as service time. Parent reviews of the program were very positive, and parents greatly appreciated that children exhibited and documented their work in laboratory notebooks (UVM) and folders (UVA). The camp was run on a Saturday for 5 h. The course fee (technically a donation by UVM) was $50 per student. No demographic data were provided on the gender or race of students involved, or of the volunteers. Because of the excessive cost associated with background checks, international students could not serve as volunteers. Using procedures established by the American Camp Association, students were divided into groups of 16 with two graduate student teachers per group (male and female if possible). Students conducted five 1-h experiments, each in different rooms. Students used a special laboratory notebook and worksheets to assess their learning and demonstrate their achievements to their parents. One negative thing cited by Houck's graduate students was that students sometimes finished experiments too quickly. Feedback through surveys was solicited from parents and graduate student teachers. As a result of feedback, three goals for improvement were formulated: (a) better training of graduate students would be offered in a precamp, (b) diversity would increase, and (c) more sophisticated experiments would be devised to match NGSS.

In 1995, Tracy and colleagues [23] published a summary of their chemistry outreach program titled "Chemistry Abounds," which used a dozen undergraduate chemistry students as volunteers and reached over two thousand fourth-grade children. The program targeted science literacy by having children perform experiments on phase changes, physical and chemical changes, gases, dry ice, the hydrogen balloon explosion, and writing a message with phenolphthalein indicator and sodium hydroxide solution. It was organized and supported both by the University of Maine and by the ACS. The program addressed basic chemistry through demonstrations in nine modules. Student-led demonstrations followed a POE (predict–observe–explain) cycle. The major strength of the program was viewed as making science fun.

8.4.5 Middle-school outreach

Van Doren et al. [24] reported on the importance of engaging middle-school students in outreach, and her group accomplished this through a fictional CSI (crime scene investigation) mystery outreach involving a stolen painting. Goals of the program included sparking interest in science and building student self-confidence. CSI activities began with a dramatic enactment to frame the activity, which mainly involved identifying white powders. After students collected evidence and performed chemical analyses, they convened in a meeting room to organize and evaluate the evidence. Although the chemical aspects of the outreach are identified very clearly, there seems to be no data showing to what extent students were actually engaged.

8.4.6 High-school outreach

Exstrom [25] described a novel high-school chemistry camp at the University of Nebraska, which promoted chemistry as a potential college major to promising high-school students. The 1-week program can be used as an outreach model for regional colleges and universities. The program utilized four faculty mentors, each supervising four high-school students. Faculty contact time was 40 h/week. The program also employed two camp coordinators and two undergraduate assistants. Exit surveys showed that students were very positive about their experience. For example, on a scale from 1 to 5, most responses were close to 5. High ratings addressed the following: fun, content knowledge, research, and preparation for college. In summative evaluations, students gave ratings of 4.9 to the questions on recommending the camp to others, and to having the camp meeting their expectations. The lowest rating was for the food at 2.95. Two scores obtained were around 4.1, and they rated field trips and dorms. Students paid a $275 registration fee for the program, not a high price for having experts mentor research in a university environment.

In 2011, Bodsgard et al. [26] described an annual National Chemistry Week (NCW) high-school outreach event. In the event, labelled “Chemistry Night,” over a 4.5 h period, college students performed many demos, including fake blood, slime, ferrofluids, invisible ink, fire/explosions, lasers, shape memory alloy, and others. High-school teachers and their students experienced many demonstrations that would be difficult for them to experience at their schools.

8.4.7 Miscellaneous outreach

Pratt [27] investigated outreach demonstrations through a survey instrument of faculty, staff, and student volunteers. Questions and responses mainly covered the affective realm. One frequent comment found in the survey was that the audience should learn science content knowledge. Another result found was that faculty emphasized that college students should run outreach events, although faculty had actually ran them with the help of students. In reviewing his work, Pratt questioned whether students helping with the outreach had sufficient content knowledge to be effective instructors.

Gaquere-Parker et al. [28] developed a STEAM (Science-Technology-Engineering-Art- Mathematics) experiment to make a malachite paint. However, the experiment utilized turpentine, and so was not green.

8.5 Planning outreach

In this section, best practices associated with planning green chemical outreach will be described. Preparing for an outreach activity can be an overwhelming experience, and not all outreach experiences are successful. There are so many details to be taken into account that forgetting minor things like pencils can cause a major roadblock.

Planning begins by understanding who the audience of participants will be. Obviously, activities selected must match the cognitive, affective, and psychomotor attributes of participants. The author found that finding engaging activities to span the grade range 3–12 of participants was a challenge, but by trial and error, lessons learned from mistakes (described in subsequent sections of this paper) made subsequent iterations more successful. For example, third-grade students often lacked the finely tuned manual dexterity needed to perform many tasks, and they required help. Third-grade students also required nurturing, but they were a rewarding group to work with. Other factors taken into account included grade-level, special education, school system, socio-economic level, and diversity (ethnic group or race, religion, and gender).

Since students will generally be working in groups, knowing the number of visitors beforehand is important so that the correct number of student stations can be set up, but this is not always possible. It is even a good idea to have some extra activities on hand in case something does not work out. Moreover, it is good to have the planned laboratory exercises formulated in written form.

The first and foremost issue in hosting any outreach activity is the safety of all participants. Safety begins upon entrance to laboratory, when students are supplied with goggles, gloves and aprons. A discussion of safety must be provided along with each activity. All students should be wearing goggles, even if they are just observing demos. Generally speaking, most outreach groups are accompanied by their teachers who help enforce safety standards. Toward that end, the author advises that all dangerous demos involving fire be performed in a fume hood with the sash down.

Unless one has a laboratory room devoted to outreach, then a site must be selected and approved, which in some cases involves asking colleagues and the department chair. If a laboratory must be found, one should always check in advance to see that all equipment, like projectors, are in working order. All equipment and chemicals must be carted to the laboratory and set up, and when the outreach activity is finished, everything must be promptly removed and stored. The laboratory must be left spotless to keep on good terms with those instructors who normally use the laboratory. It is best practice to not use any drawer equipment normally used by regularly scheduled classes, so that nothing is lost or contaminated. Another good approach is that when activites end, to engage student participants in clean-up, before asking volunteers.

Outreach experiments require a lot of preparation time, in the form of choosing activities, ordering equipment and chemicals, and in the mundane tasks of preparing solutions, and putting chemicals in vials with labels. At EMU, because a limited amount of stockroom help is available, the outreach instructor must begin preparing weeks in advance. With so many factors to be taken into account, in addition to the foregoing advice, one of the most essential elements in preparing for an outreach activity is to go through a trial run to be sure that no surprises are encountered when an actual student group arrives.

8.6 Student volunteers

Because it is not advisable to perform a large outreach project alone, recruiting and training student volunteers is strongly advised, but this takes much time and effort. A secondary component of doing outreach in an academic setting is training volunteer students in the art of teaching. At EMU, recruiting volunteers is not always an easy task because many students are nontraditional and may have jobs, families, or both. Hence, they have trouble arranging for any activity outside their busy schedules. With that said, volunteers may also be recruited from industry, professional organizations, colleagues, teachers, classes, science clubs, and undergraduate STEM majors. In several EMU outreach events, DTE (Detroit Edison) Energy employees served admirably. One special group of outreach volunteers that deserve special consideration are preservice teachers, who are required to perform service work as part of their program.

A successful outreach activity depends on its lead teachers as their interpersonal and teaching skills will either impress volunteers or turn them off. One goal should be to build and inspire volunteer confidence because each volunteer comes in with unique gifts that can be used to advantage. However, lead instructors should be mindful that not all volunteers are ready to take an active role in outreach, due to their backgrounds, limited experience, limited content knowledge, confidence, or undeveloped social skills. Moreover, elementary and secondary students should be expected to have different skill sets. For example, one can assume that secondary science preservice teachers are generally more confident, more eager, better motivated, and better able to do outreach than elementary preservice teachers who may suffer from a lack of content knowledge, and may even have anxiety about working with a group of students. Although elementary preservice teachers present more of a challenge, they can be trained to be successful as long as the instructor shows sensitivity and patience. Moreover, leaders should recognize that student volunteers who express being overwhelmed by outreach can be given other duties such as performing errands, organizing and cleaning, observing, or they can be put to use by labelling bottles, or greeting students, and watching for safety concerns. Student volunteers generally need training in every phase of outreach including content knowledge, experimental skills, safety, and even in ways of being helpful. Another overlooked but important component of outreach is training in diversity. An instructor should not assume that outreach volunteers will give equal time and attention to all kinds of students, and an instructor may need to intervene to ensure that students of different diversities receive the same amount of attention, prizes, and praise. To be successful in this regard, the instructor must be both flexible and patient.

The ideal situation would be to run a volunteer training session a week before outreach is to take place. However, one constraint is that for this to happen, a physical laboratory must be available. When a laboratory is not set aside for outreach activities, then finding space can be a problem. Fortunately, at EMU, colleagues are helpful in this regard, but then the problem of logistics arises. Since day- or week-long outreach activities utilize large amounts of equipment and supplies, the logistics of transporting stored equipment, and setting it up, is both a time-consuming and very tiring activity, especially when one person carries the burden. Since outreach activities usually start in the morning, equipment setup must take place the morning before outreach students arrive. This means arriving to work at pre-dawn hours.

Once student volunteers are recruited, they must be trained, but in order to train students, the outreach activity must be planned and set up. Then, students must be polled as to their availability to receive training. Next a training schedule must be offered. In many cases, students cannot participate in training but show up for outreach “cold”; they simply show up unannounced and receive “on-the-job-training.” One way to overcome this problem is to have students receive training by watching videos, for example, on *You Tube*. Other students sometimes cancel out or are “no-shows.” Volunteers also need to be trained in being observant, and to work with children one-on-one as needed.

8.7 Schools and programs

In this section, the outreach programs undertaken at EMU will be described in detail. They are summarized in Table 8.3. Except for the YMCA-EMU camp, all were free of cost to children. Such programs served not only a wide grade range, but also diverse populations. For example, one outreach activity was performed at a Detroit public school that had a large population of students of Middle Eastern descent. On the other hand, the Digital Divas outreach program, to be described below, catered to young women of all races and religions. Another summer outreach program mainly addressed students from a low-income urban area, mostly serving Hispanic and African American students, while a winter camp mainly served suburban children. It should be noted that students with special abilities were also welcomed into EMU outreach.

As an example of the wide range of schools that have been involved in outreach, consider two middle-school participants, one suburban and one urban that were involved in the programs described in this paper. Both middle schools had student populations very close to 550 children, and teacher to student ratios were also almost the same, at around 18. However, out of 865 Michigan middle schools, the suburban school ranked 45th whereas the urban school was in 271st place. Moreover, the percentage of 8th grade students meeting state science criteria was 65% for the suburban school and 23% for the urban school. Comparing diversity, the urban school had a population that was about 44% African American and Hispanic, whereas the suburban school was only around 3%. One would expect to see differences in student motivation and performance in these respective outreach populations, especially among boys.

Table 8.3: Outreach presentations.

Program school	Year	Grade level	Student diversity	Activity
Flint, MI (1 day)	2015–2017	12	Girls, Students of Color	CSI, cosmetics, pollution, water in a h, gas chromatography, demos
Detroit (1 day)	2016	11	Middle Eastern Americans	Natural acid/base indicators
MSTA Talk	2016	K-12 Teachers	Women	Green chemistry
Digital Divas (1 day)	2015–2017	6 – 12	Girls	Acid/base indicators Erin Brokavich & Cr(VI) polymers, CSI, demos
Winter Camp (1 week)	2017	6th	All	Green energy CSI, polymers, demos
NDEP-TARDAC Camp (2 weeks)	2013–2015	7th – 8th	African American Hispanic	CSI, electrolysis, polymers, color, chromatography
YMCA-EMU Science Camp (3 weeks)	2017		All	Polymers, CSI, green energy, rockets, demos, secret messages

[1] Chemistry Department, Eastern Michigan University

Each outreach session either focused on green chemistry, or at least touched on it. In this section, each type of green chemistry outreach activity will be elaborated in order to explain its green aspects. In the elaborations, specific names of schools will not be used. The total number of students reached in outreach was about 1,000, across grades 3 to 12. Performing approved outreach in a university setting meant that major liability issues were being addressed by administrative rules set in place. The university usually advertised the camps which were given “catchy-names” to attract student interest.

The Digital Divas Program [29] was founded by former EMU Professor Gerald “Skip” Lawver of The College of Technology at EMU. Its mission has been to introduce middle-school and high-school girls to career information on computers and STEM. In doing so, it has served diverse young women in the grade 3–12 spectrum. One goal of Digital Divas was to break down gender stereotypes regarding tech careers. Beginning with under 100 attendees, the Digital Divas conference, by 2017, has grown to over 500 student participants on each offering. Although the program was originally meant to introduce girls to the world of computer science, a profession where they are underrepresented, it has been extended to other fields such as science, including chemistry. It is now designed to provide fun STEM experiences for young females with the hope that they will be spurred to undertake careers in the fast-growing fields of computer science and STEM. Since the program is run at a university, participating students are afforded an opportunity to meet and network with professors and students. The program is run twice a year (fall and spring) in one-day sessions, between 9 a.m. and 2 p.m. In a one-day program, two formats for breakout sessions have been used: (a) three 1-h-long sessions or (b) two 1.5-hour long sessions. After a morning gathering for everyone, including a keynote speech, students select breakout sessions to learn about whatever interests them, and they generally have as many as a dozen programs to choose from. All laboratory experiences are designed and organized with safety in mind. One drawback was that no advance notice on the number of students showing up for sessions would be known in advance. Chemistry breakout sessions have been so well attended that they have exceeded laboratory capacity. Consequently, as many as 50 students might show up for a laboratory designed to hold 24 students. Another problem that occurred infrequently was that middle-school kids would show up for a session designed for high-school students.

A second major outreach event was a winter science camp for sixth graders from a suburban middle school that was run from February 20 to February 24 in 2017. The camp ran from 9 a.m. till 2 p.m. each day. An EMU laboratory served as a classroom. The camp did not focus entirely on green chemistry, and related STEM topics were investigated including balloon cars, rockets, pendulum painting, and CSI. However, some of these activities could be related to green energy. On the last day of camp, a Friday, kids eagerly presented their work before an audience of several hundred parents. The camp was run with one lead instructor (the author) and one student assistant. However, the sixth-grade classroom teacher observed the entire event, and her help was invaluable in establishing a nurturing environment. Moreover, school district superintendent science experts evaluated the classroom and laboratory work, taking copious notes. At times, they viewed activities through a large glass window, while at other times they entered the classroom and watched. There were very few discipline problems in this camp.

Another camp took place during summer 2017 – a series of 1-week camps were run, mainly for children in grades 3–8. EMU partnered with the YMCA to offer it.

Another outreach event, labelled “Detroit” in Table 8.2, involved outreach to a public school whose students were of Middle Eastern descent. The outreach involved green acid–base indicators extracted from flowers. The chemistry teacher at the school learned how to run the event. In the school, classes were segregated by gender, and girls achieved more than boys who were said to be mainly intersted in sports. Addressing the needs of boys remains an overlooked and underinvestigated area of K-12 science education.

An overlooked area of outreach is service to teachers. In 2016, the author presented a talk on green chemistry at a Michigan Science Teachers Association Conference [30]. After introducing the subject of green chemistry, several experiments were described. The 12 principles of Green Chemistry were presented in several novel experiments accompanied with worksheets involving physical/chemical changes, calorimetry, and stoichiometry. Designed for the grades 8–12, the talk was supplemented by handouts.

8.8 Green outreach activities

8.8.1 General comments

In this section, specific green chemistry outreach activities that have been undertaken with elementary, middle-school, and high-school students will be described. They included the following broad areas: secret messages, CSI, cosmetics, acid–base indicators, environmental chemistry, polymers, and combustion. Moreover, several activities connected to the STEAM movement (science, technology, engineering, mathematics, and art) were attempted; these involved pendulum painting and making crayons using green pigments.

The structure of outreach sessions varied but they always began with a warm welcome. Having picked up goggles on entering laboratory, students received a short talk on safety. Then, students viewed a "demo" which was presented using a POE cycle, during which the instructor explained what was happening in detail. Students could film the demo if they wished. Demos were usually shown both at the beginning and at the end of a session. Demos included gummy bear combustion, the dichromate volcano, elephant toothpaste, hydrogen balloon explosions, calcium carbide, ferrofluids, and an oscillating reaction. After the introductory demo, students were given a short lecture on green chemistry, presenting the 12 principles of green chemistry from a nontechnical approach, as for example, provided by the nontechnical green chemistry pocket guide [31] obtained on the American Chemical Society Green Chemistry website. The 12 principles (supplemented with handouts) were then discussed in an understandable manner. Then, the main activity took place with additional handouts on the principles of green chemistry.

8.8.2 Secret messages

One activity involved having students investigate secret messages in four green activities. In each activity, students wrote a secret message which they then gave to their partner who translated it. In the first activity, students used a commercially sold ultraviolet (uv) pen. The class then brainstormed how to make their own uv-sensitive ink and invented their own uv pens using quinine water or fluorescent markers. Another secret message activity utilized the green polymer methyl cellulose cast in a paper that dissolves in cold water. After writing and passing their secret message, the receiver destroyed it in water. Students then examined some of the properties of methyl cellulose (hydrophobic, viscosity, and recoverability) and related them to normal cellulose paper. A third activity involved having students use a candle to write a secret message on goldenrod paper, an acid–base indicator. The partner then decoded the message by painting over it using a Q-tip soaked in a dilute aqueous solution of sodium carbonate.

8.8.3 Crime Scene Investigation (CSI)

One popular activity involved the classic mystery note in which students used paper chromatography to determine which ink pen was used to write it. Students then extended the activity to butterfly chromatography.

Another activity involved confronting students with a mystery involving ballistics. Part of this CSI activity involved a green replacement laboratory, in which students identified gun powder residue by the presence of lead. However, gun powder was simulated by mixing sodium chloride with sodium carbonate, and replacing dithizone solution (which forms a blue lead complex) with the safer universal indicator or phenolphthalein.

Another CSI activity bridged the gap between the environment and pollution by introducing Erin Brokavich as a citizen scientist. The activity began by explaining the problem of chromium pollution in Hinkley, CA, which derived from the improper disposal of chromium being used as a corrosion inhibitor. Pictures of waste ponds were shown, and the issue of using unlined pools allowing Cr(VI) to seep into the groundwater was discussed. Moreover, safety data sheets were discussed, and authentic samples of dissolved chromium in water were shown. Next, videos showing Erin Brokavich were viewed, in order to connect students to her work. Google maps rendered various images of the affected area, showing buildings and important sites. Next, students were given a Google map of Hinkley upon which was superimposed a numbered sampling grid. After taking a visible spectrum of chromium (VI) to find its peak wavelength (using a Vernier spectometer) , students analyzed water samples corresponding to the sampling grid, and created a contour map of the chromium (VI) plume. However, this activity was another green replacement laboratory in which chromium (VI) was replaced with yellow food coloring. Last of all, methods of converting chromium (VI) to its less toxic form chromium (III) were demonstrated with an authentic sample of Cr(VI).

8.8.4 Green cosmetics

Since many participants were girls, specific activities were chosen with gender in mind. In one cosmetics experiment for secondary students, a cold cream was prepared from green ingredients, namely beeswax, lanolin, glycerin, water, and borax. This experiment gave students an opportunity to learn about specific physical properties like melting point, solubility, miscibility, and states of matter. Furthermore, students learned to relate physical properties to chemical structure, intermolecular forces, and emulsification. After preparing the cold cream, students worked together to determine how to set up a commercial cold cream business enterprise.

Another green cosmetics experiment involved mood lipstick. Students learned how an acid–base indicator caused the color change that supposedly simulated mood changes. Students then experimented with different liquids to find what colors could be produced.

8.8.5 General chemistry

Having studied mood lipsticks, students then tested acid–base indicators extracted from flowers including petunias, roses, and daylilies. They also examined visible spectra of the extracted anthocyanins in alcohol solution. The outreach instructor lectured on why acid–base indicators derived from flowers were “greener” than chemical indicators such as universal indicator, and to bring the point home, safety data sheets were presented.

To tie green chemistry to the auto industry, using demonstrations, students were shown the combustion of hexane to simulate octane in gasoline, and the combustion of methane to show how furnaces operate. Students were then shown that carbon particles are formed during combustion. Next, the greener combustion of ethanol, which burns with a blue flame, was demonstrated. Finally, a working model of a fuel cell car was demonstrated. Students then discussed the pros and cons of vehicles powered by octane, ethanol, and fuel-cells.

8.8.6 Polymers

In the polymer slime activities, students synthesized several types, and then studied the physical properties of their products, including elasticity (quick versus slow stretching), transparency, flow, bounce (tested after rolling it into a ball), viscosity, and siphoning ability. By far, the most popular slime prepared was PVA (polyvinyl alcohol)–borax slime. By varying the relative amount of reactants, namely borax and PVA, children learned that they could change the physical properties of slime. Students also studied some of the chemical properties of slime by exposing small amounts to acid, base, water, and isopropyl alcohol. Students also prepared Oobleck, and slime from Elmer’s glue. At the end of the activity, there was discussion of what a polymer is, and of how borax causes the PVA to form long chains through crosslinking. Finally, based on generated evidence, there was a discussion of whether slime should be classified as a solid or liquid, and of it being a non-Newtonian fluid.

Another polymer experiment involved having students investigate sodium alginate, a natural and green gelling agent that is harvested from the cell walls of brown algae. When students added a sodium alginate solution to a calcium chloride solution, a hydrophobic hydrogel formed in small droplets or cylinders (which mimic worms).

8.8.7 Problems

In some cases, students tended to rush through activities, but this only happened when the lead instructor was out of the room. It was found that students were not completing all of the assigned activities. To correct the issue, volunteers were retrained to keep students on task, by sometimes working one-on-one with the children.

8.8.8 Student-led presentations

At the conclusion to many outreach sessions, students were given prizes, handouts such as the current NCW magazine, and sometimes refreshments. Although children did not fill out worksheets, it was found that they had an amazing ability to recall details about the activities they participated in. For week-long outreach activities, the last day was reserved for student presentations. Therefore, to close the loop on content learning, children presented their findings in the form of posters, videos, art, and oral presentations. These presentations were well received by their audiences, which sometimes numbered in the hundreds.

8.9 Financial support

The cost of any outreach can be expensive, and the lead teacher may be left with bills to pay. Costs to consider include refreshments such as food and drinks. In some cases, because students in some areas may not have been provided a breakfast at home, refreshments are important. Other costs include chemicals, equipment, travel, and even pencils and calculators. Funding sources for the outreach described in this paper are provided in the “Acknowledgements” section.

8.10 Summary and Conclusions

In the foregoing narrative, green science outreach camps were described, by focusing on best practices that engaged diverse students through active learning across the dimensions of the cognitive, affective, and psychomotor learning domains. The student audience studied the practice of green chemistry, and were introduced to its 12 principles. Except for the YMCA-EMU summer camps, all camps were cost free to participants. Student volunteers, difficult though they occasionally were, enriched their communication skills while learning the value of green chemistry and community service outreach. The programs described could be used as a model for others. Student feedback from participating children was generally positive. One could tell how well activities were going by how on task students were, and by their comments given on survey questionaires given at the conclusion of session activities. Another benefit was that classroom teachers left with green make and take activities to use in their own classrooms.

Acknowledgements: Financial and service support is gratefully acknowledged. Certain summer camps were supported by grants through the Michigan NDEP-TARDAC EMU STEM program. At EMU, financial support was generously provided from the Department of Chemistry, the College of Technology, and the College of Arts and Sciences. The Huron Valley Local Section of the ACS also provided financial support. Moreover, these instructors helped with the outreach: Sharon Vance and Timothy Brewer. All student volunteers are also thanked.

References

[1] Beyond B, May 2017 Available at: http://www.beyondbenign.org/. Accessed 17 May 2017.
[2] May OECD 2017 Available at: http://www.oecd.org/unitedstates/. Accessed 17 May 2017.
[3] National Center for Education Statistics. May 2017. Available at: https://nces.ed.gov/surveys/pisa/pisa2006highlights.asp. Accessed 22 May 2017.
[4] Bidwell Allie. More Students Earning STEM Degrees, Report Shows. Available at: https://www.usnews.com/news/articles/2015/01/27/more-students-. Accessed 23 May 2017
[5] Annual Reports of Earned Degrees in Chemistry. May 2017 Available at: https://www.acs.org/content/acs/en/about/governance/committees/training/reports/degreesreport.html. Accessed 23 May 2017.
[6] Demographics of the S&E Workforce. May 2017. Available at: https://www.nsf.gov/statistics/seind14/index.cfm/chapter-3/c3h.htm. Accessed 14 December 2017.
[7] National Science Board. Science and engineering indicators 2016. June 2017. Available at: https://www.nsf.gov/statistics/2016/nsb20161/#/digest/u-s-s-e-workforce-trends-and-composition. Accessed 5 June 2017.
[8] The Condition of Stem 2016. ACT. June 2017. Available at: htteps://www.act.org/content/act/en/research/condition-of-stem-2016.html. Accessed 5 June 2017.
[9] Cann MC, Dickneider TA. Infusing the chemistry curriculum with green chemistry using real world examples, web modules, and atom economy in organic chemistry courses. J Chem Educ. 2004;81:977–80.
[10] Braun B, Charney R, Clarens A, Farrugia J, Kitchens C, Lisowski C, et al. Completing our education: green chemistry in the curriculum. J Chem Educ. 2006;83:1126–9.
[11] ACS. Chemistry for Life. July 2017. Available at: https://www.acs.org/content/acs/en.html. Accessed 11 July 2017.
[12] American Association of Chemistry Teachers. November 2017. Available at: https://teachchemistry.org/professional-development/webinars. Accessed 21 November 2017.
[13] National Science Teachers Association. November 2017. Available at: www.nsta.org/. Accessed 21 November 2017.
[14] Green Chemistry. November 2017. http://common.nsta.org/search/default.aspx?action=browse&text= green%20chemistry&price=&type=&subject=&topic=0&gradelevel= &sort=1&page=0&dep=&coll=&author=. Accessed 24 November 2017.
[15] National Center for Case Study Teaching in Science. May 2017. Available at: http://sciencecases.lib.buffalo.edu/cs/index.asp. Accessed 14 May 2017.
[16] Bodner G The quadruple bottom line: the advantages of incorporating green chemistry into the undergraduate chemistry major. In Benvenuto, MA, editor. Green chemical processes Volume 1. De Gruyter, 2017:7–28.

[17] Cannon AS, Warner JC. Outreach and science literacy through green chemistry education. Green chemistry education, In Anastas PT, Levy IJ, Parent KE, editors. ACS symposium series 1011. Washington, DC: American Chemical Society, 2009:167 –86.

[18] Guedens WJ, Reynders M. Science outreach programs as a powerful tool for science promotion: an example from flanders. J Chem Educ. 2012;89:602–04.

[19] LaRiviere FJ, Miller LM, Millard JT. Showing the true face of chemistry in a service learning outreach course. J Chem Educ. 2007;84:1636–39. OphardtCE.

[20] Ophardt CE, Applebee MS, Losey EN. Chemical demonstrations as the laboratory component in nonscience majors courses: an outreach-targeted approach. J. Chem Educ. 2005;82:1174–7.

[21] Levine M, Serio N, Radaram B, Chaudhuri S, Talbert W. Addressing the STEM gender gap by designing and implementing an educational outreach chemistry camp for middle school girls. J Chem Educ. 2015;92:1639–44.

[22] Houck JD, Machamer NK, Erickson KA. Graduate student outreach: model of a one-day “chemistry camp” for elementary school students. J Chem Educ. 2014;91:1606–10.

[23] Tracy HJ, Collins C, Langevin P. An educational outreach program designed For elementary school audiences. J Chem Educ. 1999;72:1111–2.

[24] Van Doren JM, Nestor LP. Engaging students in the action of chemistry. J Chem Educ. 1997;74:1178–79.

[25] Exstrom CL, Mosher MD. A novel high school chemistry camp as an outreach model for regional colleges and universities. J Chem Educ. 2000;77(10):1295–7.

[26] Bodsgard BR, Johnson TA, Kugel RW, Lien NR, Mueller JA, Martin DJ. Organizing a high school chemistry outreach event: celebrating national chemistry week and the international year of chemistry. J Chem Educ. 2011;88:1347–50.

[27] Pratt JM, Yezierski EJ. Characterizing the landscape: collegiate organizations’ chemistry outreach practices. J Chem Educ. 2018;95:7–16.

[28] Gaquere-Parker AC, Doles NA, Parker CD. Chemistry and art in a bag: an easy-to-implement outreach activity making and painting with a copper- based pigment. J Chem Educ. 2016;93:152–3.

[29] Digital Divas Conference. May 2017. Available at: https://www.emich.edu/digitaldivas/, Accessed 7 May2017.

[30] Kolopajlo L Green Chemistry Experiments for Grades 8-12. Michigan Science Teachers Association, 63rd Annual Conference. March 4, 2016.

[31] Green chemistry pocket guide. May 2017. Available at: https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/principles/green-chemistry-pocket-guides.html. Accessed 7 May 2017.

Craig Kohn

9 The development of a bioenergy-based green chemistry curriculum for high schools

Abstract: The Next-Generation Science Standards represent a major shift from learning science content to preparing students to become scientifically literate through inquiry and investigation. This article summarizes the unique opportunities available to develop a biotechnology laboratory course on biofuels that heavily emphasizes scientific practices in a high-school agriscience department in Wisconsin. Through collaborations with universities, federal research facilities, and the surrounding community, students were able to engage in rigorous learning experiences in a sociocultural setting in a manner that maximized their preparation for college and sustainable careers. This example also highlights how effective science teacher professional development and collaboration can allow for improved instructional opportunities in science education while also enabling positive contributions to ongoing scientific research.

Keywords: inquiry, sustainability, biotechnology, bioenergy, agriscience, NGSS, professional development

9.1 Introduction

With the release of the National Research Council's *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* [1] in 2012, science education has been increasingly portrayed as crucial to meeting many of our society's most pressing challenges. The Next-Generation Science Standards (NGSS) [2], which were based on the NRC's *Framework*, incorporate this same view of science education as a means for preparing students to take on the socioscientific challenges that await them throughout the rest of their lives. NGSS reflects a shift from recalling scientific facts to using scientific ideas and practices as tools for reasoning and making sense of the world. From the viewpoint of NGSS, science literacy and sense-making represent the primary goals of science education [3]. These goals require forms of science instruction that enable students to engage with the world around them, develop models to explain natural phenomena, test and refine their conceptual understanding through inquiry, and foster their sense of wonder in a manner that engenders a lifelong commitment to using valid evidence as the primary means of making decisions [4].

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Kohn, C. The Development of a Bioenergy-Based Green Chemistry Curriculum for High Schools. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0080

https://doi.org/10.1515/9783110566499-009

The practice of teaching secondary science has been continuously shaped by the ongoing and sometimes tumultuous debates about the roles and purposes of science education in American high schools. The theories, publications, and debates that helped to cultivate the creation of NGSS also guided and shaped the efforts of individual teachers as they reformed their own practice to keep up with a rapidly evolving profession. This chapter will provide a summary of experiences in developing a sociocultural science curriculum designed to engage students in science and engineering practices through a bioenergy-based green chemistry curriculum. Through partnerships with federal research centers, university campuses, teacher professional associations, and local businesses and community members, high-school students were provided with a unique classroom experience that combined inquiry-based laboratory learning with career shadowing experiences in a manner that encouraged the adoption of sustainable knowledge and practices in students' personal lives and future professions.

9.2 Overview of high-school agricultural education

The anecdotes that frame this chapter are unique in that they pertain to experiences that occurred in an agricultural sciences program (or agriscience program). Agricultural education has been officially recognized as a distinct secondary school subject in American education since 1917. While its original purpose was primarily to prepare future farmers to adopt scientific practices and new technologies, agricultural education has since evolved to reflect a much broader emphasis across all branches of the sciences. This subject now provides rigorous college and career preparation for more than 300 science-based professional pathways ranging from veterinary medicine to genetic engineering to environmental research. Today, there are roughly 12,000 agricultural education programs in the United States enrolling approximately one million students [5].

Instruction in agricultural education is comprised of three interconnecting components – inquiry-based classroom and laboratory instruction; experiential learning through community-based service and career experiences; and leadership education as delivered through involvement in student career-based organizations [6]. This approach, generally known as the "Three Circle Model of Agricultural Education," is highly reflective of sociocultural theories in education such as Lave and Wenger's situated learning and legitimate peripheral participation. These theories stipulate that learning is a process of gaining peripheral experiences in a particular community of practice that eventually build, expand, and develop into expertise in that specific content area [7].

9.2.1 National Agriculture, Food, and Natural Resources academic standards

The National Agriculture, Food, and Natural Resources (AFNR) Academic Standards reflect college-level content that is aligned to the NGSS. These standards utilize an organizational structure that encourages application and mastery of science content by students in agricultural courses. Instruction in agricultural science courses is typically offered by elective course options in US high schools with a certified agricultural instructor. These courses are often aligned to science standards and can result in science equivalency credit for students. While the specific content and titles of agricultural courses can vary, the contents of these courses are generally designed to align to the 8 “career pathways” found in the national AFNR academic standards. Examples of these pathways include animal systems, plant science, and natural resources [10].

Biotechnology represents one of the eight career pathways in the AFNR standards. This is a broad career pathway that encompasses a wide range of science- and research-based topics, including genetic engineering, microbiology, fermentation, enzymology, CRISPR, and more. The course on which this paper is focused was aligned to the biotechnology pathway. It served as a unique opportunity to create an entirely new interdisciplinary course focused on the interrelationships among physics, chemistry, biology, and ecology in a manner the reflected the changing ideals and expectations of secondary science instruction.

9.3 Bioenergy and biotechnology – upper level high-school agriscience

The course that serves as the focus of this chapter was developed for the Agricultural Sciences Department at Waterford Union High School in Waterford, Wisconsin. This is a small, semi-rural village of 5,000 residents about 30 miles southwest of Milwaukee. The high school enrolls about 1,000 students in grades 9–12. The Agricultural Sciences Department consists of 13 different courses focused primarily on the application of science to agricultural and natural resources systems. As one of these course options, the Bioenergy & Biotechnology (AGR 310) course has been offered annually at Waterford Union High School since 2010. The Biotechnology and Bioenergy course enrolled a maximum of 24 students. This course (which was usually abbreviated as just “Biotech” by students and staff) was offered during the spring semester over an 18-week period followed by a 120-min final exam session. Each week consisted of five 47-minute class periods. The Biotech course was open to students ranging from sophomores to seniors who had completed the prerequisite of the introductory Agriscience course (or who had a sufficiently strong background in chemistry and in conducting scientific laboratory work). Students who enrolled in the course typically had a strong background in science or mechanics, and had an interest in laboratory research, engineering, and/or environmental sustainability.

The Agricultural Sciences Department at Waterford Union High School had relatively large and modern facilities due to a school expansion that resulted from a surge in the local population several years prior. The main classroom had a capacity for 24 students and was supplemented with an adjacent laboratory room with six student stations as well as a greenhouse and office. Each laboratory station was managed by a paid student intern (supported with donations from local businesses) who also prepared the materials in advance for each week's laboratory.

9.3.1 Course outline

The course utilized five major units: The Basics of Fuel (including combustion chemistry, sustainability, and life-cycle assessment), Biodiesel (via transesterification), Fermentation and Ethanol, Bioprospecting and Enzymes, and Biogas. Each unit consisted of 3–6 weeks of instruction. A weekly breakdown of the units is shown below:

1. Introduction, Laboratory Safety, Intro to the Supervised Career Experience portfolio.
2. Basics of Fuel
   a. Chemistry of Fuel (thermodynamics, combustion chemistry, bond energies, entropy, enthalpy).
   b. Life-Cycle Assessment (assessing the economic, ecological, and social sustainability of fuel options).
3. Biodiesel
   a. Biodiesel (combustion engines, transesterification reactions).
   b. Biodiesel from Waste Vegetable Oil Laboratory
   c. Biodiesel Challenge Laboratory (group competition to create the highest quality biodiesel from the poorest quality used vegetable oil).
4. Fermentation and Ethanol
   a. Introduction to Ethanol (history of fuel use in the United States, fermentation, octane ratings, energy balances, emissions testing).
   b. Cellulosic Ethanol (carbon cycling, plant cellular biology, basics of fermentation).
   c. Fermentation (cell biology, respiration vs. fermentation, glycolysis, electron transport, biochemical pathways of fermentation, chemical properties of alcohol).
   d. Ethanol Challenge (group competition to develop and test fermentation protocols)
   e. Completion of Ethanol Challenge and Midterm Exam
   f. Cellulosic Ethanol Challenge (group competition to develop and test fermentation protocols for cellulosic sources of ethanol)
5. Bioprospecting and Enzymes
   a. Bioprospecting (enzymatic chemical reactions, enzyme structure and function, active site, polymers vs. monomers, cellulase biochemical pathway).
   b. Bioprospecting Challenge (series of group challenges to find and measure sources of enzymes for fuel and food production).
   c. Genetic Modification (genetic engineering, PCR, CRISPR)
   d. GMO Challenge (identification of genetically modified ingredients in foods via PCR).

6. Biogas (production of natural gas fuel via methanogenic bacterial anaerobic degradation).
7. Final Exams
   a. Presentation of Career Portfolios and Open-Note Essay Exam
   b. Final Exam (closed book, multiple choice)

9.3.2 Overall course format

No textbook was utilized for this course for multiple reasons. First, the pedagogical effectiveness of standard textbooks is questionable, especially in a high-school course with mixed abilities where the use of textbooks can result in achievement gaps. Second, the content of the course was based on the most advanced breaking research in the field. As some content in the course reflected research that had only just been published, a textbook would not lend itself well for this instructional approach to teaching science, nor would it reflect the new expectations of both the NGSS and the new AFNR academic standards. Due to the fact that the course instructor had personal experience in biofuels research at the university and federal level and had served as a content expert for the national academic standards for this subject, it was feasible for the curriculum to be written by the course instructor in collaboration with researchers and staff in nearby federal research facilities on the University of Wisconsin campus in Madison, WI. The curriculum as it was taught can be viewed at wuhsag.weebly.com (use the “Classes” tab to find the course under “Spring 2016”).

The focus of the Biotech course was primarily on providing students with a means to think about the nature of energy and to assess options for fuel in regard to their benefits and opportunity costs for societies and natural ecosystems. Students were introduced to the notion of energy by investigating how and why some substances burn but others do not. This was followed by a discussion about the concept of sustainability and its three primary considerations: social, economic, and ecological impacts. Students were guided to consider not just underlying chemical causes for the energy content of a fuel, but also the net gain or loss of energy as the fuel is acquired, refined, and utilized. Students were also guided in considering additional ramifications and externalities of each fuel choice, including the ecological and health impacts of pollution, whether a fuel increases or reduces social disparities, and whether an option for fuel would require dramatic shifts in infrastructure and societal norms. Overall, students used three primary considerations to assess the value of a fuel option: (1) Is it sufficient?, (2) Is it efficient?, and (3) Is it sustainable? Students used this framework to assess fossil fuels, biodiesel, ethanol, biogas, electrical transportation, and hydrogen fuel cells.

During this introductory general overview, the concepts of energy conservation, entropy, and enthalpy were heavily emphasized as a means to help students understand how and why a substance combusts. High-school students have a wide range of beliefs and interpretations of what actually happens to the matter and energy of a substance when it is combusted. The focus of this introductory portion was to help students to appreciate the relationship between bond energies and the potential value of a fuel. By explaining enthalpy as a kind of "leftover energy" as the atoms of the reactant molecules are rearranged into the product molecules, students not only had a heuristic for determining why some fuels result in the release of more energy than others but also had a means for tracing matter and energy as they are conserved across reactions (dispelling the notion that matter and energy are "used up" during combustion). This is a crucial consideration as students move into a discussion on sustainability because it helps them to better engage in the life-cycle assessment of a fuel. It also helps them to appreciate how and why carbon dioxide is produced during combustion. When students comprehend that any combustion of a carbon-based molecule results in the production of a heat-retaining gas, they can better appreciate the link between climate change and human activity.

After this general overview of the major options for fuel, students spent the remainder of the semester investigating three of the primary biofuel options: biodiesel, ethanol, and biogas. Each fuel type provided a means for discussing various topics in chemistry. In the biodiesel unit, the reactions that occur during the transesterification transformation of highly branched oil molecules into straight hydrocarbon chains become the emphasis. This is then tied to the combustion reaction and the rearrangement of hydrocarbon chains and oxygen molecules into carbon dioxide and water. Students are introduced to the concept of complete vs. incomplete combustion and observe how incompletely combusted products relate to smoke and pollutants commonly found in diesel exhaust. Students also consider how catalysts used in the transesterification process as well as the necessary step of heating relate to the final reaction rate as they are producing biodiesel. While students are in the laboratory, they also learn valuable laboratory practices, including the proper use of equipment, the process of titration, and keeping records in a laboratory notebook.

In the ethanol unit, students are introduced to the chemical processes inherent in fermentation. They consider how the properties of corn ethanol compare to gasoline, and use matter and energy tracing to assess the benefits and limitations of this renewable fuel option before exploring the fermentation reaction in more detail. They consider the potential benefits of cellulosic ethanol (particularly in regard to CO_2 and carbon cycling) and why this type of ethanol is exceptionally challenging to produce. This inevitably leads into a discussion on the nature of enzymatic reactions and how they relate to biology. Students are guided to see enzymes as crucial for living organisms due to their reduction of the activation energy of biochemical reactions. Using a yogurt production laboratory to showcase the lactase enzyme's action on the breakdown of the lactose molecule, students are guided as they apply this model reaction to more complex reactions, particularly the breakdown of cellulosic polymers into simple glucose monomers that can be fermented into fuel ethanol. This opportunity is also used to provide students with explicit instruction on how the human body is affected by alcohol (particularly the different structures of the brain) and how the body enzymatic pathways for processing alcohol result in many of the visible signs of inebriation and recovery. By removing the mystique of alcohol consumption and portraying inebriation as merely the outcome of the body's method for responding to and removing toxins from the body, the intent is to reduce its allure among teenagers.

After a unit on genetic modification as it pertains to enzyme production, the course concludes with a brief discussion about the methanogenesis reactions used to produce biogas in a methane waste digester. Students are once again introduced to the concept of greenhouse gases and are guided in comparing the much greater greenhouse effect of methane gas in comparison to CO_2.

9.3.3 Weekly course format

In the first weeks of instruction in each unit, the course adopted a consistent weekly schedule. Weekly topics would be introduced on Mondays using group- and whole-class discussions. This enabled students to practice sound scientific argumentation from evidence as a means to develop deeper scientific literacy. Students were provided independent work time on Tuesdays to work individually or in small groups to learn the core content for that week. Students were provided with printouts of detailed notes specific to the content of the week. They were also given guided worksheets that helped them to grasp content and understand that content in a deep, comprehensive fashion through the use of specifically tailored questions that helped to reveal connections and themes across the content. The instructor used this time to move from group to group as they worked to provide individual assistance or instruction as needed.

On Wednesdays, students were asked to demonstrate their knowledge in inquiry-based laboratories. Each laboratory was scaffolded in a manner reflective of the Vygotskian Zone of Proximal Development, which stipulates that instruction should be structured in a manner that allows students to engage and utilize knowledge and practices that are still in the process of maturing [9]. The laboratory packets prompted small student groups to independently form hypotheses, justify the hypothesis with a rationale, run the experimental protocol, collect data, and use the data to accept or reject their hypothesis. Follow-up questions were provided to allow the students to form direct connections with the content and classroom discussion at the end of the laboratory. On Thursdays, students were provided a time for group quiz preparation. This was followed by an opportunity for class Q&A, after which students individually took a 20- to 30-question multiple-choice quiz which was immediately graded in class. This immediate feedback proved to be crucial for student improvement and became a standard formative assessment in the course, allowing the effectiveness of each week's instruction to be assessed and to allow for any follow-up instruction where needed.

Fridays were reserved for career preparation or for classroom management. Students would begin each semester by choosing a career related in some way to the course content. Guided by a scaffolded packet and using statistics from the US Bureau of Labor and other sources, students would profile their potential future career. They would develop a path from their current point in high school through college to a successful start in that career. They would identify a postsecondary option for obtaining a necessary degree, choose a major, and even calculate their potential debt based on the average pay of the career in comparison to the tuition of the school. When needed, Fridays could also be utilized to re-teach concepts in the event that a large portion of the class did poorly on the quiz, to provide additional work time if needed for a laboratory or for notes, or to meet with students individually to discuss any concerns related to their performance.

Once students had mastered the content for a given unit, the Monday through Friday schedule was temporarily put aside in order to allow students to spend at least a week on a project-based summative assessment. At this point, the work of the instructor was almost entirely supervisory, with students being responsible for planning their laboratory protocols, collecting and analyzing their data, reaching their conclusions, and formally presenting their findings.

9.3.4 Modes of assessment

Students in the Biotech class were assessed based on their completion of their notes (20 %), weekly quizzes (30 %), unit exams (20 %), labs (10 %), final exam (10 %), and their career portfolio (10 %). The heavy grading emphasis on notes and weekly quizzes helped to ensure that students were encouraged to complete the day-to-day considerations. This foundational knowledge was heavily emphasized because it was vital to the more meaningful learning and comprehension that occurred in later units and in summative projects. Because grades were more determined by the foundational learning, there was more freedom to engage students in authentic assessments that were more like what would occur in a real-world laboratory or career-based situation without students fearing about a poor grade if their investigations did not go as expected. This also allowed the instructor to work more closely with students who had demonstrated that they were not prepared for these more advanced (and "more fun") tasks as their classmates were engaged in independent inquiry. This approach to instruction was essentially an effective compromise between the idealistic goals of inquiry-based science instruction that results in scientific literacy and the realities of teaching in a public grade school where grades are an unavoidable obligation for every instructor.

Notes were graded primarily on a completion basis. Students could receive a "plus" (100 %), a "check" (80 %), or a "minus," which resulted in a grade of 0 % until their notes were resubmitted for re-grading and a reduced late score. This was meant to prepare students for the expectations of real-world professionalism (i. e. do not submit something that is incomplete or poorly developed; no one pays for 50 % of a heart surgery).

While multiple types of weekly formative assessments were utilized (quizzes, self-reflections, discussions, group challenges, bell-ringers, etc.), the most in-depth assessments of student knowledge occurred during the group long-term laboratories at the end of each unit. These laboratories were designed to prompt students to connect their real-world laboratory experiences to specific concepts that they learned in the classroom. During group presentations on the final day, students were asked pointed questions to check for comprehension and assess their ability to relate their findings to broader connections across the course content.

While the district expectations left few options other than a multiple-choice format for the final exam, students were given an “extra” final exam during the last week of instruction. In this essay/short answer exam, students were provided with 4 days to work in teams to respond to questions that reflected the “big ideas” of the course. Questions ranged from why it is so difficult to produce cellulosic ethanol, to what actually happens to molecules and energy in a log when it is burned, to outlining a plan for US energy independence over the next five decades based on critiques of existing fuel options. Students were asked to address the questions in a presentation format that they would deliver in small groups on the final day of class, and these presentations were graded using a rubric based on accuracy, thoroughness, professionalism, full group involvement, and effort.

9.3.5 Supervised Career Experience portfolios

A key aspect of the mission of the Agricultural Sciences Department is to maximize readiness for college and for careers. As such, each student was required to complete a standardized Supervised Career Experience portfolio and present this portfolio in an exit interview during the final week of the semester. In these presentations, students had to outline their future college and career intentions; show how they obtained 15 hours of relevant career experiences with professionals in relevant careers from the surrounding community; provide evidence of their experiences in the form of pictures, reviews from the professionals they shadowed, and personal journaling; and relate these experiences to their eventual college and career path. These career portfolios proved to be incredibly impactful for students. In addition to providing students with the means to chart a clear educational and career trajectory for their future, the mandatory career experiences also helped them to see the relevance of the course material to their own personal lives and allowed them to determine whether or not a given career interest was appropriate given their preferences and abilities. This is reflective of learning as described by Lave & Wenger [7] in that it is more than just comprehending content – it is “becoming a full participant, a member, a kind of person.”

9.3.6 Student reviews

While not required by the district, anonymous student reviews were utilized to assess the effectiveness of the instruction, identify areas for improvement to the course, and provide evidence for the effectiveness of the instruction to the district administrators. Of those who responded over 2 years ($n = 27$), 67 % ranked the class as “Better than most” or “Better than all” when compared to other courses in the school. Only one student ranked the course as below average overall. Almost three-fourths of students ranked the materials and instruction as more effective than average, with more than half (56 %) ranking it as “More Effective than Most” or “More Effective than All.”

9.3.7 Facilities and funding

While the department had relatively new facilities that included a greenhouse and laboratory in addition to a classroom, the funding for high-school agriculture courses is generally limited due to the elective nature of the courses. The Biotechnology and Bioenergy course required extensive expansions to the collection of laboratory equipment, glassware, and facilities. While the content of this course was equivalent to what was offered at nearby colleges and universities, the department budget alone was quite insufficient to provide for these objectives.

Collaborations with researchers and staff at nearby universities proved to be crucial for enabling the course to occur, and a combination of ingenuity and inventiveness resulted in solutions that drastically lowered the costs of operations for this course. In lieu of the standard $800 fermenter devices for students in this subject area, the instructor collaborated with federal researchers to design an equally effective model that could be built for as little as $15 (the current design of this tabletop fermenter can be built for $40 and uses materials that are longer lasting and higher in quality). In lieu of expensive pre-packaged student kits from science supply companies, laboratory chemicals were purchased in bulk and prepared in advance by the instructor outside of standard instructional time. Later, this became the responsibility of a paid student laboratory manager. Ingenuity and a willingness to forgo convenience reduced the final cost of the class by thousands of dollars.

Donations also proved to be key for the implementation of this course. Waterford Union High School, being located in southern Wisconsin, was surrounded by a myriad of dairies, cheese factories, and food-processing companies. Each possessed an ample supply of laboratory equipment, and their donations of used equipment and glassware helped provide much-needed supplies. Educational grants also helped to cover gaps in the budget, allowing for the purchase of equipment that could not be obtained through donations. University resale stores proved to also be a convenient source of affordable but functional glassware that could feasibly be purchased out of pocket by the instructor.

After multiple years of successfully executing this Biotech course, the school's administrators were persuaded to reallocate thousands of dollars budgeted for textbooks for the purchase and installation of new laboratory benches and safety equipment. A one-time sizable earmark in the annual department budget provided for the installation of six modern laboratory stations, overhead electrical, secure chemical storage in the laboratory itself, and a new exhaust system. The laboratory stations were installed by the instructor in exchange for hourly pay to avoid higher costs that would have occurred had the installation been performed by company from which they were purchased.

Finally, local businesses provided annual donations to support a student internship program in the department as part of its mission to maximize student readiness for college and for careers. A minimum of seven student internship positions were supported through a combination of these donations and various fundraisers. These internship positions ranged from management of the department greenhouse to running the department's student office to serving as the laboratory manager who prepared the materials for each laboratory in each class on a weekly basis. Students who successfully completed the internships were provided a scholarship at a percentage rate determined by their quarterly performance evaluations.

9.4 Great Lakes Bioenergy Research Center and the creation of the biotechnology and bioenergy course

While a myriad of factors led to the creation of the Biotechnology and Bioenergy course at Waterford Union High School, the most impactful influence was from the Great Lakes Bioenergy Research Center (GLBRC) on the University of Wisconsin – Madison and the Michigan State University campuses. GLBRC is one of three Bioenergy Research Centers in the United State Department of Energy and is the only one that is based at an academic institution. In addition to its research, the GLBRC has an Education and Outreach group whose focus is to “enhance the broad understanding of contemporary issues in bioenergy” in order to “create a scientifically literate citizenry”[10].

Much of the emphasis of GLBRC Education and Outreach is focused on enabling K-12 instructors to both improve their ability to deliver science instruction while also providing bioenergy-related materials and curricular options free of charge to instructors. The instructor for the Biotech course began his involvement with GLBRC in 2010 when he attended the first-ever Bioenergy Institute for Educators. This 2-week national professional development opportunity was held on the University of Wisconsin campus and provided a crash course on bioenergy, sustainability, agronomy, and engineering while providing attendees with direct experiences with the scientists conducting the research in these areas. Participating educators were also provided with an opportunity to develop curriculum and instruction with the Education and Outreach staff, with the feedback from this partnership guiding their understanding of how to most effectively develop scientific literacy among their students.

9.4.1 Research Experiences for Teachers (RET)

In addition to the Bioenergy Institute, the GLBRC also provides Research Experiences for Teachers (RETs). Through the RET opportunities, teachers work side by side with federal researchers over an extended period of time to learn more about a particular research area while developing curriculum specific to that field. In 2011, Waterford's Biotech course instructor was provided with a RET opportunity in the bioprospecting laboratories of Dr. Cameron Currie at GLBRC. Through the RET opportunity, the course instructor was provided with a stipend to work in the Currie laboratory on the University of Wisconsin campus for 6 weeks. Dr. Currie and his staff research enzyme production of various microbes and identify how the interactions of microbes and other organisms can be symbiotically sustained.

Prior to this joint experience, the bioprospecting assay used by the Currie laboratory for microbial enzyme activity involved expensive media and a series of complex laboratory procedures that left little room for error (which presents significant obstacles for reproducing this work in a high-school chemistry laboratory setting). After completing a chemical analysis of their media, an equally effective microbial media was developed using only Miracle Grow fertilizer and tap water. By adding a sample of microbes to the Miracle Grow media solution in a test tube along with a strip of standard filter paper, the production of cellulose enzymes could be measured simply by recording if and when the strip of submerged filter paper had degraded. This ensured that high-school students could not only recreate the scientific practices of laboratories like Dr Currie's, but also contribute to their research through citizen-science and internet data sharing through Google Forms. Upon successfully developing and testing this simplified laboratory protocol, an accompanying curriculum was developed and professional development opportunities were made available for the purpose of training other teachers to use the protocol and curriculum.

9.4.2 TED-Ed & bioenergy

During this same time period, Waterford's agriscience instructor was offered the opportunity to work with TED (Technology, Engineering, and Design, as generally known from their "TED Talks") to create an online curriculum about bioenergy and bioprospecting based on his experiences in the Currie laboratory. TED was in the process of finding teachers who had utilized unique perspectives to teach in novel ways. The goal of this initiative was to pair these teachers with cartoonists and producers who would animate the lesson and create a 3-min online video. Students would have the opportunity to take an online multiple-choice assessment, engage in discussion boards, and share ideas and suggestions as part of an online community based around each lesson. This lesson has been viewed almost 50,000 times and has resulted in almost 4,000 questions and answers. The lesson can be viewed at https://ed.ted.com/lessons/biofuels-and-bioprospecting-for-beginners-craig-a-kohn [11].

9.5 Conclusion

Science teachers are increasingly being called on to teach in a manner that emphasizes the development of scientific literacy and enable students to use evidence and scientific practices to solve real-world problems. This is particularly true in recent years due to the expectations implicit in the NGSS. However, enabling teachers to adopt these new standards and expectations in their own classroom instructional practices can be challenging, as many teachers have not experienced this type of instruction firsthand and are rarely prepared to fully meet the expectations of new standards without considerable support.

Opportunities for professional development in the natural sciences from federal agencies, universities, and other scientific entities can provide a valuable means to shape and improve the instruction that students receive in secondary science. When these professional development opportunities are tied to outreach efforts, a participating teacher's impact can spread far beyond their own classroom.

In light of the social and political challenges faced by developed nations like the United States, it is increasingly imperative that we provide coherent, applicable, and well-designed professional development opportunities to science teachers in addition to new standards and curriculum. Improving the effectiveness of secondary science instruction through these methods will enable students to become scientifically literate citizens with a greater understanding of the need and means for a more sustainable society.

References

[1] National Research Council (NRC). A Framework for K-12 Science Education. Washington, DC: The National Academies Press 2012. DOI: 10.17226/13165.

[2] National Research Council (U.S.), and National Research Council (U.S.), editors. Guide to implementing the next generation science standards. Washington, D.C: National Academies Press, 2015.

[3] Covitt E, Dauer J, Anderson A. Chapter 4: the role of practices in scientific literacy. chapter in helping students make sense of the world using next generation science and engineering practices. In: Passmore SC, Reiser B, editors. Helping students make sense of the world using next generation science and engineering practices. Arlington, VA: NSTA Press, 2016.

[4] Schwarz C, Passmore C, Reiser BJ, editors. Helping students make sense of the world using next generation science and engineering practices. Arlington, Virginia: NSTA Press, National Science Teachers Association, 2016.

[5] Jackman W, Schescke K.. Discover the possibilities of agricultural education. National Association of Agricultural Educators. February 2014. Accessed on July 8, 2018.

[6] National Association of Agricultural Educators. “What is agricultural education?” National Association of Agricultural Educators. Accessed November 3, 2017. https://www.naae.org/whatisaged/index.cfm.

[7] Lave J, Wenger E. Situated learning: legitimate peripheral participation. learning in doing. Cambridge [England]; New York: Cambridge University Press, 1991.

[8] National Council for Agricultural Education. National AFNR Content Standards, Revised 2015. https://www.ffa.org/thecouncil/afnr. Accessed on July 8, 2018.

[9] Vygotskij LS, Cole M. Mind in society: the development of higher psychological processes. Nachdr. Cambridge, Mass.: Harvard Univ. Press, 1981.

[10] Slater S, Keegstra K, Donohue TJ. The US department of energy Great Lakes Bioenergy Research Center: midwestern biomass as a resource for renewable fuels. BioEnergy Res. March 1, 2010;3:3–5.

[11] Kohn C, Mai Q “What are stem cells? - Craig A. Kohn.” TED-Ed. Accessed November 3, 2017. https://ed.ted.com/lessons/what-are-stem-cells-craig-a-kohn.

Robert Ause

10 Green chemistry in secondary school

Abstract: Green chemistry education requires learning about the scientific facts of chemistry of the environment and also applying the implications of this knowledge to human lifestyles. All students need to learn how chemistry works as a physical science in its part of the ecological system of our planet. Green chemistry also must be modeled as a lifestyle so that this knowledge can be properly applied. In this chapter, the author describes how various green chemistry topics have been incorporated into the science curriculum at Greenhills School. Furthermore, the author also relates how this knowledge is applied in the school setting so that global sustaining principles can be caught by the next generation of our planet's stewards.

Keywords: green chemistry, sustainability, ecology, planet stewardship, green school

10.1 Introduction

10.1.1 Personal Introduction

I write this chapter from the perspective of a secondary school science teacher (grades 6–12) with 25 years of classroom teaching experience. During this period, the "green" movement in society has grown in international awareness. Secondary school science teachers certainly want to pass on the motivation and knowledge behind this movement to our students. Currently, I teach at Greenhills School in Ann Arbor, Michigan. Greenhills is a private, independent day school, which also I attended as a student in the 1970s. I returned as one of its faculty in 2010. In 2018, Greenhills School celebrates its 50th year. From nearly its founding in 1968, Greenhills science teachers have ensured that the school educated its students to have a love of nature, a passion to understand the way nature works and a desire to live in a sustainable way that "... meets the needs of the present without compromising the ability of future generations to meet their own needs."[1] So it is my privilege to continue in this school's tradition by teaching green chemistry to middle and high school students.

---

[1] United Nations General Assembly (20th March 1987). "*Report of the World Commission on Environment and Development: Our Common Future*; Transmitted to the General Assembly as an Annex to document A/42/427 – Development and International Co-operation: Environment; Our Common Future, Chapter 2: Towards Sustainable Development; Paragraph 1." United Nations

---

This article has previously been published in the journal *Physical Sciences Reviews*. Please cite as: Ause, R. Green Chemistry in Secondary School. *Physical Sciences Reviews* [Online] **2018**, *3*. DOI: 10.1515/psr-2018-0081

https://doi.org/10.1515/9783110566499-010

10.1.2 What is “green chemistry education?”

Education in green chemistry lays an important foundation for our young people in understanding how our natural world works. The term “green” in an ecological context has a variety of meanings. In this chapter, what I mean by “green” chemistry education is teaching about the chemistry of our natural world that allows us to live in a sustainable way. Our young people need to understand how the natural world works so that they can choose to live in harmony with the natural life-sustaining systems of our universe. Our children are the next generation of stewards of this earth. So as a teacher of high school chemistry, it is my duty to educate my students in green chemistry. I do this through the content in courses and also through the example that the science faculty set with our own lifestyles. In this chapter, I will refer to various assignments, projects and activities in the science courses at Greenhills as examples of how we do this. I will also illustrate how we, as teachers at Greenhills, attempt to model sustainable living. As a part of the national and international community of science teachers, we are ready and able to share details of what we do to any who are interested.

10.2 Teaching the “facts” of green chemistry

10.2.1 Introduction

The content of what we teach our adolescents about green chemistry can find its way into the curriculum in a number of places in traditional middle school and high school science courses. In this section, I will give several examples of where my colleagues and I seek to do this.

10.2.2 Principles of green chemistry

Firstly, let us look at the principles of green chemistry as summarized by the ACS Green Chemistry Institute in 2014.[2] Several of these principles can be incorporated into the content of science courses and then applied in laboratory work, starting with the design, preparation, conducting and clean-up of the experiments. The first

---

General Assembly. Retrieved 15 January 2018 from Wikisource: https://en.wikisource.org/wiki/Brundtland_Report/Chapter_2._Towards_Sustainable_Development

[2] The 12 Principles of Green Chemistry, found at https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/principles/green-chemistry-pocket-guides.html, retrieved 7 January 2018. The ACS website credits the following as the source of this material: Anastas, P. T.; Warner, J. C. Green Chemistry: Theory and Practice, Oxford University Press: New York, 1998, p.30. By permission of Oxford University Press.

principle is “prevent waste.” This can be done by planning the laboratories well, using small scale as much as possible and asking students to prepare for their experiments so that they do not have to repeat trials because of careless mistakes. Good teacher planning can do the same. The second principle, “atom economy,” is obviously taught from the start, since nature obeys the law of conservation of matter. While several of the ACS Green Chemistry Institute principles are more applicable to industry and manufacturing, (“Less Hazardous Synthesis,” “Design Benign Chemicals,” “Design for Energy Efficiency,” “Use of Renewable Feedstocks,” “Reduce Derivatives,” “Catalysis (vs. Stoichiometric),” “Design for Degradation” and “Real-Time Analysis for Pollution Prevention”), teachers can communicate these as goals and values to our future synthetic chemists and chemical engineers. Two other principles, “Benign Solvents & Auxiliaries” and “Inherently Benign Chemistry for Accident Prevention,” are important for the chemistry teacher who is choosing which chemicals to use in demonstrations and laboratories.

10.2.3 Teaching about climate change

During the study of gases in high school Chemistry class, the students ponder and discuss the question of whether our actions as humans are changing the climate of the planet. Over the course of several days, students learn about what makes a gas a greenhouse gas, the greenhouse effect and various causes of climate change. The students are presented with the various factors that go into the current scientific models that are used to predict changes in climate. These factors come from scientific investigation into the geological record of past climates of the earth. The History Channel’s: “A Global Warning?” offers an excellent survey of these past climates. The current scientific models indicate that human production of greenhouse gases, especially carbon dioxide, leads us to consider our own CO_2 production as individuals, community, nation and human population. So students estimate their ecological or carbon footprint using one of many online tools to do this.[3] However, these sites can change yearly. So in general, I suggest that students search for an “Ecological Footprint calculator” or “Carbon Footprint calculator.” The criteria for a good site include the ability to adjust certain variables to see what changes they will make in the size of their ecological footprint. Students then commit to a 10-day lifestyle change that will reduce their footprint. During this 10-day period, students keep a journal of their personal experiences which include their energy or carbon dioxide “savings.” The project culminates in a reflection paper in which students summarize their overall experience. In almost all cases, students see that because

---

[3] Students are given some suggested websites which they can use to calculate their carbon footprint or ecological footprint (https://www.footprintnetwork.org/resources/footprint-calculator/;https://carbonfund.org/calculate-your-footprint/).

they live in the United States, they consume much more energy and use more resources than the average person anywhere else in the world. They also see that if everyone in the world lived with the same lifestyle that they have, we would need multiple "earths." In other words, most US residents do not live a sustainable lifestyle in terms of our planet sustaining the entire population. This is a shocking revelation, but it drives home the importance of doing something to reduce our overall consumption of energy, water and natural resources.

10.2.4 Energy generation and consumption

Teaching about energy generation and consumption is fundamental to most science classes. This is one of the cross-cutting concepts of the Next Generation Science Standards (NGSS).[4] Therefore, this topic is addressed in many science courses. In middle school science classes, students look at their home water and energy bills. They measure how much energy their various lifestyle activities require. They learn about the law of conservation of energy, that energy is neither created nor destroyed but only changes form and that some of the forms are more usable for us than others. In high school, students can learn in more detail about energy from the perspective of biology, physics and chemistry. Specifically, in chemistry, the sources of energy which drive our society are important topics.

10.2.4.1 Eighth grade alternative energy project

Our eighth grade science curriculum focuses on energy. The course culminates with a project, which requires students to design and build a machine/building that is powered by a nonfossil fuel, renewable energy source or to build a renewable energy system that will accomplish a task. To help the students measure their progress, they design an experiment that will demonstrate that their design works, and how their machine/building operates.

10.2.4.2 Advanced chemistry energy project

One project with which second-year chemistry students finish the school year after the AP Chemistry exam is related to energy. This project requires that a team of 3–4 students develop a plan to take the school off the power grid. They do this by devising a power generation system that will supply the school's electricity and heating needs for the full year. This project requires a detailed analysis of the school's energy and heating needs which is accomplished by compiling energy and thermal profiles of our school. These profiles not only indicate the total energy needs for the school, but also

---

[4] The specific NGSS cross cutting concept is called, "Energy and Matter: Flows, Cycles and Conservation" from *The NSTA Quick-Reference Guide to the NGSS*, ed. Ted Willard, NSTApress, Arlington, VA; 2015, p. 3.

the power demands at any given moment. Each group has a certain power generation method assigned to them. One group investigates wind power, another solar power, a third, nuclear and a fourth natural gas. The groups determine what size wind turbine, solar array, nuclear reactor or natural gas power plant would be necessary to meet the school’s needs for a year. The monetary and environmental costs are assessed for each of these. A unique set of energy generation assets on our school rooftop provides the students with onsite solar power generation data and wind power generation data and the rooftop weather station provides us with temperature, wind speed and solar radiance data for a year. (See the next section for more details of the rooftop energy generation assets, the Gleason Renewable Energy Dashboard.) This project not only allows students to investigate energy use and power generation by renewable and nonrenewable sources, but they also come to terms with our consumption of energy as a school.

10.2.5 The Gleason Renewable Energy Dashboard

The image above is a photo of the Gleason Renewable Energy Dashboard and circuit display case (on the right of the photo), which are located in a wing of the school. Photo taken by author

Unique to our school is the Gleason Renewable Energy Dashboard (GRED). This “dashboard” performs 24/7/365 collection, display and archiving of performance data from the school’s rooftop renewable energy assets which include a 50 W-peak wind turbine, a 5 W solar array and a green roof. Three temperature probes monitor the temperature under the green roof, the normal “white” roof and the air temperature. GRED also gathers, displays and archives data from the rooftop weather station.

The “dashboard” was developed by Jim Gleason, a retired electrical engineer and husband of Chris Gleason, one of Greenhills School’s teachers, now retired. Vernier probes measure the rooftop temperatures and data from the power generating devices. These probes were chosen because our students use the same probes in classroom experiments.[5] This dashboard provides real data which is used in many math and science lessons. The data are available in real time or from archived files for instruction and analysis. A student-developed website allows teachers at other schools access to the data and the classroom lessons based on this data. Teachers in math and science classes use the data in connection to these educational topics: energy, weather, data analysis and STEM. The real-world (i. e. not simulated) data provide a unique opportunity to compare and contrast the performance of a wind turbine and solar array subject to the identical environmental conditions and to observe the impact of changing environmental conditions (as captured by the weather station) over periods of minutes, days and months. Specifically, the data provide a complete characterization of the voltage and current outputs of the two energy sources and relate those to the power provided in parallel to the GRED’s 12 V battery and the two 5 W LEDs which periodically discharge the battery under software control. Rooftop temperature measurements show the value of the green roof to reduce a building’s heating/cooling demands in the face of daily and seasonal variations in air temperature and solar radiance.

10.2.6 Environmental cycles

Teaching about the carbon cycle, water cycle and other natural systems which provide for the earth’s homeostasis offers numerous tie-ins to chemistry curriculum topics. These concepts are introduced in middle school science classes and then explored in more depth in high school science classes. For example, the seventh grade science class studies a local stream near the school campus, investigating the water quality of the stream. I will write in more detail on this project later, but for this section, students learn all about environmental and human activities that affect the water quality of the stream. They also learn about the water cycle and how through this cycle nature purifies water, making it potable for animals and healthy for organisms to live in. In eighth grade, students learn about energy and matter cycles. They learn about the carbon cycle as it moves through living things and how organisms acquire the necessary energy for living. Understanding of these important natural processes is further developed in the high school through biology, chemistry and physics curricula as each discipline provides a more detailed and focused perspective on each topic.

---

[5] GRED was featured in a Vernier publication, The Caliper, on 28 March 2017: https://www.vernier.com/innovate/the-greenhills-renewable-energy-dashboard/

10.2.7 Chemistry of the environment

Chemistry of the environment is a topic explored in second-year chemistry after the AP exam. In the final 4 weeks of the school year, students investigate a local environmental problem related to chemistry. The students are divided into teams of three or four students. The teams investigate relevant, regional, environmental pollution problems. The two problems which have been investigated in the past several years are the Gelman/Pall 1,4-dioxane plume in Ann Arbor, Michigan’s aquifers and the lead (Pb) contamination of drinking water in Flint, Michigan. Teams of students investigate the chemistry, engineering, environmental science and even the public relations issues that make up the complexity of these problems. Students research how the problems came about, what the health and environmental effects are, what the current cleanup remediation plan is and they explore other options. Through these activities, students get to have a peek into the “green chemistry” decisions of industrial chemists and manufacturing companies. They see what happens when the full cycle of chemical production from design, synthesis, use to degradation and disposal is not carefully planned for. In these projects, the students try to find specific answers to the questions: How does chemistry help us as stewards of our planet? How does chemistry hurt our stewardship? Student teams generate written reports which detail their findings on the issue. They also present their findings in open presentations, at which members of the class and the greater community attempt to answer the big questions.

10.2.8 “Green” courses

In addition to incorporating various green chemistry topics into science classes, entire courses can be designed to convey sustainability themes and nature’s homeostatic systems. At our school, one semester of our seventh grade science course is focused on a local stream water quality study. In the high school, we offer a year-long course focused on green education, called Ecology and Global Sustainability.

10.2.8.1 The seventh grade science course

Our seventh grade curriculum is an integrated science curriculum which is focused on water and chemistry. Our students spend the first semester studying the water quality of a small stream on our campus. This stream is fed purely by runoff from nearby roads, parking areas and lawns on our school property and in the surrounding condominium complex. This stream feeds into the Huron River watershed in southeast Michigan, which is part of the larger Great Lakes watershed. Throughout this semester, students assess the health of the stream based on five water quality tests which they learn about and then conduct on the stream. Here is how this study is described:

> "How healthy is the stream for freshwater water organisms? How do our actions outside on land impact the stream?" This semester-long project focuses on earth science, biology, chemistry, and environmental science concepts. Using sensors attached to portable technology tools students collect pH, temperature, conductivity, dissolved oxygen, and turbidity data at the stream on Greenhills' property. They also collect a variety of qualitative data. Students then systematically analyze these data to look for patterns and trends to determine the quality of the stream for supporting life. They also look at how their actions out-of-doors in the mini-watershed can adversely affect the quality of the stream. Students use this real-time data as evidence to create a scientific explanation that they write and revise throughout the semester as more data is collected. Students finish the study by creating models of the water quality of the stream. The project culminates with an interdisciplinary public speaking unit where students connect their science learning with the local community as they share their knowledge through formal presentations.

This course provides a water theme for the entire grade. Each year in the spring, the seventh grade class conducts a service project connected to water. In the wake of their scientific study of water quality, the students come to appreciate what a benefit it is to have clean, fresh, drinking water. They learn about other communities in the world where children their age may walk for miles each day to obtain the clean water they need to live. So in recognition of that fact, the seventh graders make an annual walk of about 3 miles, carrying six liters of our stream water to a location on the Huron River. In this way, they share the experience of other children around the world and they raise money for a freshwater well for one of these communities.

10.2.8.2 The ecology and global sustainability course

As has been presented above, I have described how students in middle school science courses studied water quality and renewable energy generation. In the traditional high school biology, chemistry and physics courses, students complete projects addressing a number of topics essential to understanding how our planet exists in a sustainable way. So in order to bring students' experiences in these various courses into a cohesive and overarching ecological context, the science department designed a year-long course entitled, Ecology and Global Sustainability. This course is intended to be a culminating study for students in science. The course is described in this way:

> How can Homo sapiens lead a fulfilling life and be in harmony with the ecosystems in which we exist? By recognizing that we play an integral role in each ecosystem. In Ecology and Global Sustainability, we investigate our roles in the various ecosystems in which our human lives exist. Our investigation integrates multiple academic disciplines within the science department and from other departments. In this way we seek to grasp the interrelationships of the natural world, to identify and analyze environmental problems, (both natural and human-made) to evaluate the relative risks associated with these problems, and to examine alternative solutions for resolving or preventing them. In this course, we develop the conceptual tools for dealing with complexity using a systems approach to problem solving. We explore historical and current events to determine system boundaries, and study ecosystems in which humans serve a variety

> of roles. The course uses outdoor classwork to give students hands-on experience in environmental data collection and analysis. Students are encouraged to critically and creatively think about how humans can live in a low-impact manner.

While this is not a required course, enrollment usually is around 20 students, which represents about 15 % of the school's juniors and seniors.

10.3 Living out green chemistry education

Many people have used the expression that some desired moral quality or value is "better caught than taught" to indicate the importance of a person gaining a deep personal conviction about this quality or value. Living in a green, sustainable, ecologically harmonious way is one of these qualities. So, let us rephrase the means of achieving our goal in this way, "green chemistry is better caught than taught." While it is very important that students learn intellectually about how our natural world works, sustains itself and maintains its homeostasis, they must "catch" the implications and application of this knowledge if we want them to change their lifestyle. Therefore, an essential element of green chemistry education is for teachers and the school community to live out a sustainable, green stewardship lifestyle before the students.

10.3.1 Individual teacher's example

Such an example can start with the chemistry teacher who makes choices in his classroom and laboratory. He does not need to get a whole school community to adopt a green approach to living and working, before he can take individual action. The choices he makes in his classroom and laboratory space, as well as in his personal life, can show how to live out the implications of the knowledge about green chemistry. Some of these choices include reusing and re-purposing various simple materials such as containers for reaction vessels, choosing common commercial products for chemical reactions and ensuring proper care and disposal of those specific chemicals that have to be used for laboratories. By way of example, one of my colleagues repurposes the empty, plastic tennis ball cans from the tennis team. Throughout the whole year, these serve as containers for solutions, for distilled water distribution at each laboratory bench in her classroom. Personally, I have a set of styrofoam cups that I repeatedly use for thermochemical reactions, "coffee-cup calorimetry." Soda bottles are also very useful as "bottle rockets" and as reaction vessels for conservation of mass experiments, which involve the generation of gas, as the soda bottles are made to withstand higher than normal pressures.

The chemistry teacher can choose simpler, more environmentally friendly reagents for experiments. For example, baking soda and vinegar can be used instead of barium hydroxide and ammonium chloride for endothermic demonstrations. I use hydrochloric acid and store-bought baking soda when conducting a thermochemistry lab quantitatively. Thermite reaction demonstrations can be initiated with a magnesium ribbon “fuse” as opposed to potassium permanganate and glycerol ignition. An added benefit of using more commercial and environmentally safer reagents in reactions is that they are cheaper to purchase and usually can be locally acquired. Another way to save money and minimize quantities of chemicals used is to conduct laboratories on a microscale if possible. Many textbooks offer microscale laboratory manuals to go along with the traditional macroscale experiments. In these ways, a teacher can exhibit some of the Principles of Green Chemistry, namely, “prevent waste,” use “benign solvents and auxiliaries” and “reduce derivatives.”

In the event that the chemistry teacher does need to use a particular, nonbenign chemical for a demonstration or laboratory, she should be sure that it is disposed of properly according to the MSDS and EPA protocols. As the teacher instructs the students how to clean up from a laboratory, she can indicate that the chemical waste needs to be put into a particular beaker or container and that she will properly disposed of it afterward. Communicating the teacher’s proper handling of the class-generated chemical waste lets the students know that the teacher is making a conscious choice to care for the total “life-cycle” of the particular chemicals that she uses in her class. She is modeling green chemistry.

10.3.2 School community’s example

Of course, the message of green chemistry becomes more broadly and deeply heard by students when more than just one teacher live it out. The more people who are working to have a sustainable, environmentally friendly, green school, the better that students will get the message. Student clubs are great ways to help students and the school practice ecological sustainability. Environmental clubs, green clubs, gardening club and sustainability club are all types of clubs that I have seen come and go at schools, and while the student motivation and participation in these clubs waxes and wanes, to have a consistent teacher sponsor/supervisor is key to these clubs’ perpetuation.

10.3.3 State and national organizations

Participation in the Green Schools National Network offers the whole school an opportunity to consider various green habits or actions that different individuals, clubs and groups can practice. The numbers of teachers and students involved can grow from a few to entire school communities. Such participation will support a teachers’ efforts and encourage them in their goals. Many states sponsor a Green Schools association. In Michigan, the Green Schools movement takes place at the county level. A school can apply for Green School status by submitting an application once a year. The application asks about what environmentally sustainable, “green” activities the school conducts. Classroom and extracurricular actions and activities give a participating school “points” toward their Green School status. Some of the activities are no waste lunches, a school-wide recycling program, making double-sided copies the default for printing, submitting assignments electronically rather than on paper, composting and many others. Our school’s green club a few years ago had “No idling, lungs at work” signs made and placed at the drop-off and pick up areas at the school. Each and all of these can catch various students’ imagination and attention. These actions can provide a way that the students can see what they are learning in class, applied to “real life.”

10.4 Summary

Green chemistry is a way of life that is more readily caught than taught. Learning about nature’s systems for homeostasis, the essential conditions for life, the cycles of energy and matter are all important concepts for understanding science and chemistry. However, if students learn the concepts without the implications of these topics as they relate to our very existence, then this knowledge will not change behaviors and attitudes. So green chemistry education requires both the information as to how our natural world works as well as the example of how people and school communities apply and live out these green habits, choices and systems. Our children are the next generation of stewards of this earth. They need to learn the facts from the sciences and discover the life commitment to living in a sustainable way from the example of their school communities.

Acknowledgements: While I am the main “author” of this chapter, I must recognize and acknowledge the contribution of my colleagues at Greenhills School in Ann Arbor, Michigan. Much of what I have written is about how the school community, collectively, teaches and models green chemistry education. This has been the underlying theme of the science department at Greenhills School since its start in 1968. My examples come from courses taught throughout the science curriculum at the school. Just as it takes a village to raise a child, it takes a school community to educate them to be good stewards of our planet.

Index

https://doi.org/10.1515/9783110566499-011

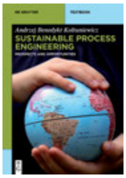
Also of interest

Volume 1
Sustainable Green Chemistry.
Benvenuto (Ed.), 2017
ISBN 978-3-11-044189-5, e-ISBN 978-3-11-043585-6
ISSN 2366-2115

Volume 2
Green Chemical Processes.
Developments in Research and Education
Benvenuto (Ed.), 2017
ISBN 978-3-11-044487-2, e-ISBN 978-3-11-044592-3
ISSN 2366-2115

Volume 3
Green Chemistry in Industry.
Benvenuto (Ed.), 2018
ISBN 978-3-11-056113-5, e-ISBN 978-3-11-056278-1
ISSN 2366-2115

Biorefineries.
An Introduction
Aresta, Dibenedetto, Dumeignil (Eds.), 2015
ISBN 978-3-11-033153-0, e-ISBN 978-3-11-033158-5



Sustainable Process Engineering.
Prospects and Opportunities
Koltuniewicz, 2014
ISBN 978-3-11-030875-4, e-ISBN 978-3-11-030876-1