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Transitioning to Safer Chemicals in Academic Research Laboratories: Lessons Learned at the University of Washington

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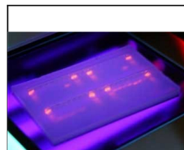
Supporting Information



	Grade	Carcinogenicity	Mutagenicity/ Genotoxicity	Acute Mamammalian Toxicity	Acute Aquatic Toxicity	Persistence	Bioaccumulation
Ethidium bromide	F	M	M	vH	DG	vH	vL
SYBR® Safe	F	*L*	M	DG	*vH*	*vH*	*L*

Hazard Levels: VL=very low;L=low;M=moderate;H=high;VH=very high;DG=data gap; Grade F=Avoid

ABSTRACT: Chemicals are an integral component of laboratory activities in academia but minimizing hazards and environmental impacts of chemicals is challenging. This paper describes how laboratories in University of Washington's Department of Environmental and Occupational Health Sciences (UW DEOHS) partnered with the UW Green Laboratory Program to explore approaches for assisting laboratories to adopt green chemistry principles and select safer chemicals. Chemical inventories, purchasing records, and hazardous waste data were used to quantitate chemical use in DEOHS. Characterizing chemical use based on the data sources provided the project team with a summary of the high volume chemicals used by departmental laboratories. As a way to target chemicals that are highly hazardous but not used in large masses/volumes, laboratory managers were asked about highly hazardous or toxic chemicals they used. Two chemicals were selected for alternatives assessments and developed into case studies that represent different barriers that laboratories face in their efforts to transition to greener and safer chemicals. This project provided a unique opportunity to survey chemicals used by a set of laboratories with diverse research topics and to assess the practicality of transitioning to safer and greener chemicals in laboratory research using case studies.

KEYWORDS: *Hazard, Assessment, Safety, Nucleic stains, Green certification programs*

INTRODUCTION

Chemicals are an integral component of laboratory activities in academia, used for various purposes in research, analytical, and instructional laboratories. While the volume of chemicals used and waste generated by academic laboratories is likely to be small relative to industry, it is not negligible. Environmental health and laboratory safety are still major concerns because of the use of highly toxic chemicals, multitudinous chemicals used across universities, and unknown mixtures in chemical hazardous waste, among other issues. Minimizing hazards and environmental impacts of chemicals at universities is challenging because of the diverse applications of chemicals, continuous evolution of methods used by laboratories, lack of awareness of environmental impacts and safety culture, and varied individual behaviors and experience.[1,2] On most college campuses in the United States, university environmental health and safety programs (EH&S) oversee the management and handling of chemicals, but they are often limited by the number of staff available to conduct audits and evaluate the effectiveness of training materials. EH&S generally uses a waste management approach that follows compliance standards, with little attention given to preventative measures that eliminate hazardous chemicals and promote the selection of safer and environmentally preferable chemicals. Decentralized purchasing systems with limited regulatory oversight of the procurement of hazardous chemicals by laboratories also make it difficult to manage hazardous chemicals on university campuses.

Since the principles of green chemistry were developed over two decades ago to address environmental and human health impacts of chemicals, tools and resources to aid in selecting safer and greener chemicals have become increasingly available.[3] For example, Yale Center for Green Chemistry and Green Engineering uses solvent selection guides,[4] which help to identify greener solvent replacements. The Yale laboratory also uses solvent dispenser which controls solvent use and limits waste generation. Developing and refining solvent selection guides has been a major focus of the pharmaceutical industry because solvents make up over half the mass of the materials used to manufacture active pharmaceutical ingredients.[4,5] Other groups have developed solvent scoring systems for use in the methods development stages of research projects,[6] and alternative solvents derived

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from natural and renewable resources are being synthesized and ranked.[7,8] There are also several green chemistry metrics available to evaluate the impact of chemical processes.[9] For example, "greenness" profiles have been developed for a subset of methods in the National Environmental Methods Index (NEMI) database.[10] In scientific literature, green chemistry methods are utilized across a wide variety of processes, such as nanoparticle synthesis,[11] enzymatic chemistry in drug development,[12] and various analytical processes.[10−13] Industrial hygienists are adopting best practices to drive green chemistry as a means for protecting workers.[14]

Chemical alternatives assessment tools designed to identify chemicals of concern (i.e., hazardous chemicals) and rank alternatives on a variety of hazard, toxicity, and life cycle end points are being used to comparatively assess chemicals in various industries.[15] These tools attempt to provide the highest degree of certainty possible against regrettable substitution (the replacement of one chemical with another that is equally or more hazardous), using a peer-reviewed, independent, and transparent process. These assessment tools assign hazard levels, ranging from very low to very high, to human health, environmental fate, and safety end points (e.g., carcinogenicity, mutagenicity, flammability, acute mammalian and aquatic toxicities) based on a set of authoritative references and available data on chemical properties and structures.[16] Some of the tools assign final grades or benchmarks that range from safer (preferable) to avoid, while others leave hazard levels in disaggregated forms to allow for comparison of specific end points. These tools have been applied to comparatively assess flame retardants[17] and chemicals in the photovoltaic manufacturing process.[18] The GreenScreen for Safer Chemicals[19] is an alternatives assessment tool based on the Environmental Protection Agency's Design for the Environment Alternatives Assessment process,[20] which many companies have used to further their sustainability efforts. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification program incorporates the GreenScreen as part of LEED criteria. A simplified version of the GreenScreen, the Quick Chemical Assessment Tool (QCAT),[21] was developed by the Washington State Department of Ecology as a higher level screening tool for small- and medium-sized businesses that have limited resources.[21]

While there are examples of university teaching laboratories integrating green chemistry principles and chemical selection tools into curricula,[22−24] formal adoption of these principles in academic research settings has been slower. Chemicals used in laboratory protocols and standard operating procedures are often selected without considering factors such as aquatic and mammalian toxicities, persistence in the environment, and biodegradability. Research laboratories may lack the technical staff and resources to use safer alternative tools to assess chemical hazards and toxicity, comparatively evaluate procedures within the time constraints of grant funded research, and screen out the use of undesirable chemicals in their processes.

There are a number of existing and emerging laboratory sustainability programs on campuses that offer resources for initiating green chemistry and safer chemical selection processes in academic research laboratories. Over 50 university green laboratory programs across the United States and Europe encourage research laboratories to adopt sustainable practices, which include the use of greener and safer chemicals.[25] Many of these programs offer green laboratory certifications as a way to inspire laboratories to implement sustainable practices.[26−31] These certifications encourage laboratories to move beyond a risk management and compliance approach for chemicals to a preventative approach that focuses on finding alternatives to toxic chemicals and designing inherently greener and safer procedures and technologies to eliminate hazards and negative environmental impacts. The Massachusetts Institute of Technology (MIT)'s green laboratory program developed two widely used resources to promote safer chemical alternatives. An ethidium bromide alternatives guide was developed in partnership with MIT's EH&S and local utility authorities. The guide was one of the first widely shared efforts in the academic community to compare product functionality, toxicity, disposal regulations, and cost for a common laboratory chemical.[32] Additionally, MIT's green laboratory program introduced laboratories to their "Green" Alternatives Wizard, a step-by-step web-based tool to explore alternative chemicals and processes.[33] While green laboratory programs can point laboratories to resources for learning about transitioning to safer and greener chemicals, such as those developed by MIT, they may be limited in their capacity to provide technical advice (e.g., training on how to conduct chemical hazard assessments or use of complex computerized modeling programs such as the Environmental Protection Agency's Ecological Structure Activity Relationships (ECOSAR) Predictive Model for aquatic toxicity[34]).

In this paper, the authors will describe how laboratories in University of Washington's Department of Environmental and Occupational Health Sciences (UW DEOHS), with expertise in assessing chemical toxicity and hazards, partnered with the UW Green Laboratory Program to explore approaches for assisting laboratories to adopt green chemistry principles and select safer chemicals.

BACKGROUND

UW Green Laboratories Certification Application. The UW Office of Sustainability launched a Green Laboratory Program in the spring of 2013.

Before the program was launched, a committee of campus stakeholders in environmental health and safety, purchasing, facilities, laboratory staff and faculty, and sustainability and recycling was formed and worked together to develop a certification application for the UW Green Laboratory Program. They reviewed 13 existing US higher education green lab certification programs as a starting point for certification criteria, scoring rubrics, and program structure.[35] Additional criteria development was informed by practices from contributing nonprofits, governmental agencies, and laboratory product suppliers. The Supporting Information provides the UW Green Laboratory Certification Application.

As of February 2014, 29 of 4500 UW laboratories applied for certification, and 15 were certified as green laboratories. Participating laboratories adopted various innovations, such as reducing and reusing disposable laboratory supplies and using automation and timers to decrease energy consumption, demonstrating that sustainable practices were being adopted on the UW campus. However, applicants consistently scored low in the "Chemical Usage and Disposal" section, which addressed certain elements of the principles of green chemistry and covered best practices in regards to chemical safety, management, and disposal.

Department of Environmental and Occupational Health Sciences (DEOHS). Researchers in the Department of Environmental and Occupational Health Sciences (DEOHS)

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Table 1. Number of DEOHS Laboratories by Research Focus, and the Average Number and Quantity of Chemicals Listed in Inventories

research focus	number of laboratories	average number of laboratory members[a]	average number of chemicals[b]	average mass of solids (kg)/volume of liquids (L)[bc]
toxicology	9	7	522	125 kg/3637 L
industrial hygiene/exposure science	5	5	28	49 kg/387 L
microbiology	3	6	269	114 kg/199 L
analytical chemistry	2	6	1386	217 kg/4530 L
genetics	1	8	52	21 kg/140 L

[a]Laboratory members include staff and undergraduate and graduate students. [b]Estimates from MyChem, the mandatory UW chemical inventory tracking system, obtained on May 14, 2014. [c]Excludes molecular biology kits and other kits used in laboratories.

at the University of Washington (UW) operate 20 research and analytical service laboratories that study how chemicals in the environment impact human and ecological health. Paradoxically, researchers in DEOHS laboratories often follow protocols that require the use of hazardous and toxic chemicals when analyzing samples and conducting studies. Several members of DEOHS were interested in integrating green chemistry principles in their research and began discussing strategies with the UW Green Laboratory Program in the Fall of 2013. Prior to this point, DEOHS laboratories had not participated in the UW Green Laboratory Certification Program and were not aware of the program.

Forming a Collaboration Between the UW Green Laboratory Program and DEOHS. After DEOHS and the UW Green Laboratory Program representatives met, it became clear that there were limited green chemistry resources for academic research laboratories and information gaps on current chemical use and green chemistry awareness and practices on the UW campus.

In 2014 DEOHS representatives applied for and received funding from the UW Green Seed Fund, which provides funding to UW faculty, staff, and students to advance sustainable research while identifying solutions to pressing environmental issues.[36] The grant was used to fund a collaboration with the UW Green Laboratory Program, DEOHS, and UW EH&S to explore the implementation of safer and greener chemistry approaches in academic research laboratories on the UW campus.

■ METHODS

To begin efforts in DEOHS laboratories, an interdisciplinary team was established to engage department laboratories and learn more about how to integrate green chemistry activities and safe chemical practices. Participating laboratories were first categorized based on their research activities (Table 1). The project team then used the UW Green Laboratory Certification Application (Supporting Information) to engage DEOHS laboratories in the project, introduce laboratory sustainability concepts, and gain a sense for DEOHS laboratories' understanding of green chemistry practices. Laboratories were asked to complete the application without making to their current practices any changes to represent baseline status' of laboratories. The project team reviewed responses with laboratory managers during interviews. As a way to identify chemicals of concern in DEOHS laboratories, managers were also asked to identify highly hazardous or toxic chemicals they used but would like to substitute or eliminate from their laboratories.

Characterization of DEOHS Laboratory Chemicals. In addition to qualitative data from interviews, the project team sought to quantify chemical use in DEOHS, so high volume hazardous chemicals could be identified and prioritized for alternatives assessments. Chemical inventories, purchasing records, and hazardous waste data were all used to quantitate chemical use in DEOHS.

Chemical inventories were obtained for each laboratory during the spring of 2014 from UW EH&S. UW EH&S manages a mandatory chemical tracking system, called MyChem, that laboratories use to maintain a list of chemical names and quantities. MyChem provided a snapshot of laboratory inventories at that particular time. Over 2900 different chemicals were listed in DEOHS inventories, including solvents, reagents, and analytical standards. The average number and quantity of chemicals listed in inventories was calculated for each research focus category (Table 1). Masses were calculated for solids and volumes were calculated for liquids listed in inventories. The analytical chemistry laboratories had the largest number of chemicals, in terms of unique chemicals as well as quantity. The top five chemicals in the inventories were solvents (Table 2). Methanol,

Table 2. Chemicals in Inventories and Hazardous Waste Database, Ranked from Highest to Lowest Mass (kg)

MyChem chemical inventory[a]		chemical hazardous waste[b]	
chemical	mass (kg)	chemical	mass (kg)
methanol	147	methanol	340
ethanol	116	acetonitrile	141
isopropanol	111	ethanol	98
acetonitrile	101	hydrochloric acid	86
acetone	74	nitric acid	65
tris(hydroxymethyl) aminomethane	51	ethyl acetate	58
ethyl acetate	48	acetone	52
hydrochloric acid	47	tris(hydroxymethyl) aminomethane	44
glucose	42	toluene	37
methylene chloride	41	methylene chloride	24

[a]Mass in kilograms of top chemicals found in MyChem chemical inventory. Data was obtained from UW EH&S on May 14, 2014 and represents chemicals reported in inventory on that day. All chemicals reported in volumes were converted to mass using densities of the chemicals. [b]Mass in kilograms of top chemicals in EH&S chemical hazardous waste database from 2009 to 2013.

ethanol, isopropanol, and/or acetone were found in most laboratories. Acetonitrile, methylene chloride, hydrochloric acid, ethyl acetate, and toluene were found mainly in the analytical chemistry laboratories. Glucose and tris(hydroxymethyl)aminomethane (TRIS) were more common in the microbiology and toxicology laboratories.

DEOHS chemical purchases made during 2013 were examined by reviewing UW electronic purchasing system entries. Information on volume or mass was not readily available, so purchases were described by cost. DEOHS spent approximately $700,000 dollars on chemical purchases, which represented 34% of all purchases DEOHS made using the electronic purchasing system in 2013. Most purchases (73% by value) were in the form of assays or kits that have various chemical components. Kits are becoming increasingly popular in molecular biology, and there are hundreds of types of kits available.[37] There are

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small amounts of various chemicals in each kit, and the chemical components were not captured in inventories or purchasing records.

Chemical hazardous waste data from DEOHS over a five year period (2009−2013) were obtained from the UW EH&S chemical hazardous waste database. Over 5400 kg of chemical hazardous waste was collected from DEOHS from 2009 to 2013, with solvents representing about 20% of the chemical hazardous waste. The most abundant hazardous waste chemicals by mass are listed in Table 2. The cost to UW EH&S to dispose of this waste was approximately $14,000. Almost 700 kg (13%) of hazardous waste consisted of mixtures, without any description as to the specific chemicals.

Characterizing chemical use based on the data sources was a useful exercise and provided the project team with a summary of the high volume chemicals used by departmental laboratories. However, each chemical may serve different purposes, even within the same laboratory, so targeting one chemical may mean changing multiple processes. In addition, identification of high volume chemicals did not highlight the most toxic or hazardous chemicals. The top three chemicals in the inventories were ranked as preferable solvents in a widely used pharmaceutical industry resource, the GlaxoSmithKline (GSK) solvent selection guide.[4] Inventories and hazardous waste data did indicate that chemicals flagged in the GSK solvent selection guide as having major issues (i.e., having significant environmental, health, or safety issues), such as methylene chloride, hexane, and chloroform, were used (ranked 10 (24 kg), 12 (18 kg), and 17 (13 kg), respectively, in DEOHS chemical hazardous waste). The project team ultimately selected two chemicals to target for alternatives assessment case studies based on interviews with laboratory managers, not on volume or toxicity/hazard rankings. The chemicals were identified as chemicals of concern by laboratory managers, and the project team thought it important to be responsive to laboratories' concerns as a way to continually engage them in the project. These case studies represent different barriers that laboratories face in their efforts to transition to greener and safer chemicals and initial steps taken to overcome those barriers.

RESULTS

Case Studies. *Case Study 1: Ethidium Bromide.* Ethidium bromide is used in the laboratory to stain DNA and other nucleic acids. DEOHS laboratory staff identified ethidium bromide as a chemical of concern, expressing health and safety concerns because it interacts with DNA and may lead to gene mutations. In this case study, ethidium bromide and an alternative were assessed using two chemical alternative assessment tools, the QCAT and the GreenScreen.

The research team chose QCAT as the first tool because it is a user-friendly screening tool that provides basic information on the hazards of a chemical. The QCAT method was used to evaluate ethidium bromide, and data was identified for five of the nine QCAT health and ecological end points (Supporting Information). A number of alternative nucleic acid stains have emerged as replacements (e.g., SYBR Safe, GelRed, EZVision). Manufacturers claim these alternative stains are safer, though toxicological and environmental fate data are limited. One product, a cyanine dye with the trade name SYBR Safe (Thermo Fisher Scientific Inc.), is an alternative that is marketed as being safer, and several DEOHS laboratories had selected this stain as an alternative to ethidium bromide.

When the research team applied the QCAT method to compile information on the dye molecule of the SYBR Safe product, there was inadequate publicly available data to assign hazard levels to any of the nine end points. However, the structure of the dye molecule was available from a reliable source,[38] which made it possible to assess using the GreenScreen method. The GreenScreen method allows for the inclusion of additional sources and modeling approaches but also requires expertise in interpreting the data. A toxicology consulting firm and Certified GreenScreen Profiler, ToxServices, was employed to conduct an assessment of the SYBR Safe dye molecule. Of the 18 health end points the GreenScreen assesses, levels were assigned to 12, although 11 of these were based on modeled data, analogues, or lower quality data (Supporting Information). The ethidium bromide QCAT and SYBR Safe GreenScreen were compared, and SYBR Safe was not recommended as a safer alternative to ethidium bromide. Both stains were assigned the poorest final grades/benchmarks, indicating they should be avoided. If ethidium bromide was assessed using the GreenScreen method, some of the hazard levels assigned to end points may be different, owing to the additional data sources in the GreenScreen and slight differences in the scoring algorithms. However, the final recommendation to avoid ethidium bromide based on its very high acute mammalian toxicity and persistence would remain the same regardless of the assessment method used. The project team posted the assessments on the Interstate Chemicals Clearinghouse Web site, which is managed by an association of state, local, and tribal governments that disseminate resources to promote the use of safer chemicals and products.[39] While the results of the comparative hazard assessments did not result in a clear recommendation, it summarizes available health and safety information for laboratories so they can consider these metrics in their chemical selection decisions.

This case study illustrates the challenges associated with assessing hazards of proprietary chemicals. There are numerous proprietary chemical products with little hazard information, though they may be marketed as the environmentally preferable and safer alternative. Although they place the burden of determining relative safety on the consumer, chemical hazard assessment tools provide a way to systematically assess and compare chemicals. They enable complete chemical hazard assessments based on high quality data for chemicals that have been studied extensively, as well as useful assessments based on modeling programs and analogous molecules for chemicals with limited hazard data. Assigning hazard levels using modeling programs utilized by the GreenScreen assessment method requires knowledge of the chemical structure. The DEOHS research team was fortunate to have a reliable source that identified the chemical structure of the SYBR Safe dye molecule, which made it possible to use modeling approaches to assign hazard levels for end points with insufficient data. While this approach worked in this particular case, it may not be successful in all situations. In many cases the chemical structure is known only by the manufacturer, and the process of identifying a structure using analytical chemistry takes unnecessary time and resources. Many products are also mixtures of chemicals, and chemical hazard assessment tools are limited because they only compare individual chemicals. In order to make useful assessments of chemicals and products that are promoted as safer and greener alternatives, manufacturers will need to provide complete toxicological and environmental fate data. The strategy of publishing hazard assessments, particularly if done in collaboration with multiple laboratories, may induce manufacturers to provide more information.

Case Study 2: Carbon Disulfide. Carbon disulfide is a solvent used to desorb, or release, volatile organic compounds (VOCs) from activated charcoal air sampling tubes in approved analytical methods published by the National Institute of

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Occupational Safety and Health (e.g., NIOSH analytical method 1005 to analyze air samples for methylene chloride).[40] Carbon disulfide is acutely toxic, highly flammable, and has a strong, unpleasant odor, so staff in the DEOHS Environmental Health Laboratory expressed interest in identifying an alternative. A QCAT hazard assessment of carbon disulfide was completed to systematically identify hazard end points. In this case study, a field sampling method was reviewed and modified so the subsequent laboratory analysis would not require carbon disulfide.

A QCAT hazard assessment identified carbon disulfide as a reproductive and developmental toxicant in addition to being highly acutely toxic and flammable. A literature search was conducted to identify alternative solvents for analyzing charcoal sorbent tubes. Alternative sampling and analysis approaches were also evaluated, and a different sampling method using thermal desorption tubes was identified as the most promising alternative by the Environmental Health Laboratory. In thermal desorption tubes, VOCs are desorbed by heat rather than solvents, eliminating the need for carbon disulfide in the analysis. Because the thermal desorption process does not require solvents for desorption, a comparative chemical hazard assessment was not necessary. Instead, the feasibility of using thermal desorption tubes was evaluated as an alternative sampling method.

Side-by-side samples were taken in a spray paint facility using charcoal sorbent tubes and thermal desorption tubes. The samples were analyzed in the laboratory for seven spray paint analytes, and air levels results from sorbent tubes and thermal desorption tubes were compared. Results indicated that analytes were detected by both methods but in different concentrations (unpublished). This initial study demonstrated that thermal desorption tubes may be a promising alternative to charcoal sorbent tubes. If thermal desorption tubes are used in the future, the laboratory analysis used to process the field samples will not require carbon disulfide.

The carbon disulfide case study is an example of functional substitution, where a process was changed but achieved the same objective of analyzing air samples for VOCs in occupational settings.[41] Developing a new field sampling methodology with thermal desorption tubes will take time and additional funding for comparative testing, both in the field and in the laboratory, before it can be considered as an acceptable alternative sampling method. Although further studies are needed to evaluate the reliability and validity of using thermal desorption tubes in occupational settings, this project prompted DEOHS laboratories to consider a new sampling method and encouraged staff to continue exploring ways to eliminate or substitute carbon disulfide in the laboratory. This case study illustrates several challenges. Laboratories that perform analytical services, such as the DEOHS Environmental Health Laboratory, generally receive accreditation and need to use published analytical methods from federal agencies to maintain their accreditation. Agencies such as the Environmental Protection Agency and NIOSH have published analytical methods that have been adopted by many laboratories conducting environmental and occupational health research; many of these methods to detect compounds harmful to human and ecological health use chemicals that are also quite hazardous themselves. While these "gold standard" methods can be modified or substituted with new methods as long as they are equal or superior in performance (i.e., performance-based analytical methods), demonstrating this generally takes time and resources that are limited.[42] As the use of more sustainable laboratory technologies increases, data will become available to compare the results of approved and new procedures. Green laboratory programs may provide the opportunity to share and promote performance-based analytical methods, including more environmentally sustainable technologies.

■ DISCUSSION

This project provided a unique opportunity to survey chemicals used by a set of laboratories with diverse research topics and utilize expertise within DEOHS to assess the practicality of transitioning to safer and greener chemicals in laboratory research. The main lessons learned were that champions are needed (in our case, the departmental leadership), communication using an iterative process is necessary to address laboratories' concerns and raise awareness, and recommendations need to be backed by evidence.

The data sources used to describe chemical use in DEOHS provided a rough estimate of chemicals used but would not be appropriate for a more accurate characterization or tracking changes in chemical use over time. Inventory data provided a snapshot of chemicals. Each laboratory updates its inventories at different times, and there may be a lag between chemical use or purchase and inventory updates. Additionally, chemicals in inventories may not reflect what is actively being used; for example, legacy chemicals left by staff and students that have accumulated over decades were found in many inventories. There were inconsistencies in the data set (e.g., units of measurement) and challenges associated with characterizing and quantifying mixtures, proprietary products, and kits. While each kit has small quantities of chemicals, their cumulative impact may be substantial. Purchasing records are likely to have the most current and accurate information on chemical and product names, but the database did not have fields for mass or volume of chemical. Chemical hazardous waste data were the most accessible and easiest to use for quantification. One major limitation of chemical hazardous waste data was that chemical mixtures were described generically, and the composition of those mixtures was unknown. It is possible that improvements in hazardous waste reporting by laboratories may occur if UW EH&S provides additional guidance on separating and reporting hazardous waste for pick-up. The amount of chemicals disposed of in municipal waste streams and volatile chemicals lost to evaporation were not captured by any of the data sources. In the future, designing databases from purchasing and EH&S to make it easier to obtain quantities and reconcile chemical names and Chemical Abstract Service (CAS) numbers are the first steps in being able to accurately capture chemical use on a departmental/university level and track changes over time.

Comparing the crude estimates from this project to chemical use by other departments and universities is not possible at this point. Characterizations of chemical use do exist for certain industries, such as the pharmaceutical industry.[4] This is the first paper to quantify or characterize chemicals used by academic laboratories to the authors' knowledge. UW EH&S estimated that UW generates 200 000 kg of chemical hazardous waste each year (though the percent of this waste attributed to laboratories could not be estimated).[43] While the chemical hazardous waste generated by DEOHS is estimated to be less than one percent of the total amount of UW chemical hazardous waste each year, practices that DEOHS adopts can

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be transferred across the UW campus via the UW Green Laboratory Program and result in a cumulative positive effect.

This project served as a starting point for DEOHS to learn more about their current chemical use and explore strategies for transitioning to greener and safer chemicals. The chemicals most prevalent in inventories and chemical hazardous waste were solvents, indicating that the use of solvent selection guides would be an appropriate starting point for DEOHS laboratories.[5] Process modifications such as optimizing reaction conditions, using different catalysts, and reducing organic solvents have also been shown to be effective toxic waste source reduction strategies.[44] Decision-making for future case studies may be supplemented by authoritative lists of chemicals of concern, such as the International Chemical Secretariat's SIN List,[45] or a widely used resource that ranks chemicals, such as the GSK solvent selection guide.[4]

Positive reinforcement through communication by the project team and departmental leadership was essential to the success of the project. The department leadership made it an implicit expectation that all laboratories participate in the project, and they set a positive example by being among the first laboratories to complete certification applications. During the course of the project, keeping in contact with laboratories through informal visits and organized events to communicate progress and share information about existing resources and other academic research laboratories helped to raise awareness and motivated laboratories to discuss change.

The barriers to transitioning to safer and greener chemical use that were described in the case studies are similar to what has been reported previously for other settings.[46,47] Major barriers included lack of time to develop greener and safer methods and financial barriers associated with developing new methods, such as the costs of new laboratory instruments and personnel time. Additionally, there may not be sufficient evidence to satisfy laboratory principal investigators that newer techniques perform as well as their current methods. Overcoming these barriers will require the participation of laboratory staff, departmental faculty and administration, and other university departments such as EH&S and procurement. This project was dependent on collaborations between laboratories in the department, the UW Green Laboratory program (run through the Sustainability Office), UW EH&S, and UW Purchasing. This highlights the need for an interdisciplinary approach to encourage the adoption of green chemistry and improve laboratory safety on university campuses.

Results from this project were shared with the UW Green Laboratory Program, and they are in the process of strategizing ways to address barriers as well as updating their application to better explain green chemistry principles and incorporate laboratory safety. For instance, the UW Green Laboratory Program recommends sharing surplus chemicals with other laboratories on the UW campus (by posting on EH&S) to reduce chemical waste, but DEOHS laboratories were unlikely to participate because they did not have the same degree of trust in opened containers compared to newly purchased products. Different strategies, such as setting up departmental sharing programs to facilitate sharing between laboratories that are familiar with each other, are now being considered.

Given the lack of transparency on chemical structures and paucity of research studies on the toxicological effects of many new chemicals, it is not feasible for complete hazard data to be drawn from publicly available data. Data gaps in chemical hazard information make informed comparisons difficult; and recommendations for proprietary products often come from suppliers, making it difficult to distinguish "greenwashing" (making claims to be green without supportive data) from legitimate sustainability efforts. The biggest impact will occur if universities and laboratory sustainability programs work together and support suppliers that provide independent hazard assessment information on their products. At present, some manufacturers have entered into confidentiality agreements with independent chemical assessment teams, allowing them to share chemical structures and additional data for hazard assessments without disclosing trade secrets.[48] These hazard assessment results could be made available to the public, which would provide much needed support for those making concerted efforts to design and use less toxic products. Leveraging the buying power of research universities and commercial laboratories to demand more transparency, toxicity testing, and independent chemical hazard assessments would further enable laboratories to select potentially safer chemicals. The UW alone spent over 30 million dollars on purchases from laboratory supply companies in 2013.[49]

Even when information from comparative hazard assessments is available, the decision over which chemical to use is not obvious. It is important to consider the overall goal of the process because there may be solutions other than substitution. Focusing on the function of a chemical in a process and identifying alternatives that achieve the same end result may be more successful, as it opens up options and reduces the risk of regrettable substitution.[41] Different instrumentation or sampling methods may achieve the goals of reducing the use of hazardous chemicals in laboratories. In other cases, there may not be a greener or safer solution, and trade-offs and exposure scenarios need to be evaluated. Practical considerations, such as cost and chemical performance, also need to be factored into the decision-making process. Adding life cycle assessment information adds another layer of complexity.[50]The MIT Green Chemistry Purchasing Wizard[33] and NEMI,[10] are examples of tools to simplify the process for researchers, but neither of these databases is updated because of lack of funding. In order for continuous improvement, these tools and resources need to be maintained. One possibility is to design academic courses for students to add recommendations and update existing information in these resources by conducting chemical hazard assessments, literature reviews, and evaluation of other relevant data sources under the guidance of faculty. This will not only keep valuable databases and resources current, it will provide applied experience for students, so they can learn how to incorporate these tools into their various fields.

As professionals in the field of environmental health and occupational safety, DEOHS researchers strive to overcome these barriers and lead by example in conducting laboratory activities in a manner consistent with green chemistry principles. Integrating green chemistry principles and safer chemical selection in laboratories can have a far-reaching effect. Students who receive training in laboratories that conduct alternatives assessments and include health and safety criteria when developing methods will be equipped with skills needed to implement such activities in their careers. Transitioning to greener and safer chemicals in academia, in addition to prioritizing government and industry efforts, is essential to reducing the negative human health and ecological health effects of chemicals in the environment.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acssuschemeng.6b00926.

UW Green Laboratory Certification Application is a short online survey that allows laboratories to see what steps they are taking to be green and includes action-based categories such as energy usage, communication, waste, chemical usage, water usage, and work-related travel (PDF)

Results of a Quick Chemical Assessment Tool (QCAT) to evaluate ethidium bromide (PDF)

Results of a GreenScreen to evaluate SYBR Safe (PDF)

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