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Green Chemistry in Higher Education: From Theory to Practice and Beyond

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ABSTRACT

In the current era, there is a growing awareness of global sustainability issues, prompting university students to seek knowledge about the impact of human actions on the health of our planet. This paper addresses the need for educational reforms to equip future chemists with the necessary skills to protect the Earth for future generations. It explores the concept of green chemistry, highlighting its importance and providing insights into teaching approaches. The discussion includes raising awareness, available teaching materials, the utilization of green chemistry metrics, and specific teaching methods for organic and analytical chemistry.

Keywords: Green Chemistry, Higher Education, Teaching Methods, Green Metrics, Educational Tools, Future Trends

Introduction

Green chemistry aims to minimize the use and production of hazardous substances and waste through the design of sustainable products and processes. While the term 'green chemistry' emerged in the past three decades, concerns about chemical pollution and resource depletion existed long before. The increased awareness of hazardous chemicals in everyday products has led to a demand for safer alternatives. This has placed pressure on manufacturers and higher education institutions to address the impact of hazardous chemicals on human health and the environment.

Green chemistry has transitioned from academic research to a widely adopted practice, supported by academia, industry, and governments worldwide. Its application has gained importance globally, particularly in developing countries, as an alternative to traditional industrial practices. Education in green chemistry plays a vital role in addressing environmental challenges and training future scientists for a sustainable society (Zuin and Mammino, 2015). Many institutions are incorporating green chemistry concepts into their curricula, offering numerous benefits across all education levels. By connecting the program of studies with students' everyday environment, beyond issues like pollution and climate change, green chemistry fosters a deeper understanding of chemical concepts and their relevance to various disciplines (Braun et. al., 2006). Students gain the ability to relate chemical ideas to real-world situations and make informed decisions regarding their career paths. The integration of green chemistry principles ensures a more comprehensive and practical education for students across diverse fields of study.

Green chemistry is a valuable addition to chemistry education, but integrating it into existing courses can be challenging. Rather than replacing current material, the focus should be on incorporating key green chemistry concepts into the curriculum (Braun et al., 2006, Zin and Mammino, 2015). Despite its existence for over two decades, green chemistry remains a prominent subject in both research and education. This paper aims to provide comprehensive information on the state of the art, challenges, and future trends in green chemistry education. It explores effective teaching methods and discusses the implementation of green chemistry principles in specific fields such as organic chemistry and analytical chemistry.

Teaching Green Chemistry: Challenges and Solutions

Green Chemistry Awareness

The concept of green chemistry has gained increasing recognition worldwide, prompting academia, industry, and the public to prioritize sustainable practices and development (Monica, 2013). The international chemistry community faces mounting pressure to shift away from traditional approaches and embrace greener alternatives. Educational programs also need to be revised to address these concerns. Academic scientists are actively working to minimize pollution through the widespread adoption of green chemistry principles. Developing nations, where environmental awareness and responsibility were previously limited, are now actively embracing eco-friendly methodologies and products to protect the environment and promote sustainability (Oloruntegbe and Ayeni, 2009).

The design of chemical products has shifted from solely prioritizing economic interests to considering environmental and social factors. This change emphasizes the need to incorporate sustainability throughout the design process, including research, production, and waste recycling. Rather than addressing waste management as an afterthought, a holistic approach focuses on integrating sustainability from the initial design phase onwards (Zhang, 2017).

Educational Tools for Teaching

To promote the integration of pollution prevention in daily life and industrial processes, the development of green chemistry curriculum materials is crucial. The ACS website provides tools for laboratory use, curriculum ideas for teachers, and local government resources. This internet-based database offers a searchable collection of articles, books, courses, demonstrations, laboratory exercises, and other databases related to green chemistry. It aims to improve access to information and resources, enabling wider dissemination of quality materials and facilitating communication in the field.

Apart from online teaching tools, a range of educational resources including textbooks, reference materials, and lab manuals have been published in the field of green chemistry. These resources provide valuable information and guidance for educators and students. Additionally, computer-aided tools are available for specific purposes such as early design evaluation, allowing for the prediction of environmental properties and assessing the environmental impact of process designs. These tools contribute to the advancement of green chemistry practices and knowledge dissemination.

Green Chemistry Metrics Education

Green chemistry encompasses various aspects, requiring appropriate tools for assessing the degree of sustainability in methods and procedures. Green chemistry metrics provide a means to compare conventional chemical processes with their greener alternatives (Constable, 2002). Balancing chemical equations is the initial and crucial step in applying metrics, with material utilization efficiency serving as a fundamental tool. Additionally, the use of synthesis tree diagrams enables students to visualize and evaluate the mass efficiency of multi-stage chemical reactions, fostering a deeper understanding of complex processes (Andraos and Hent, 2015). This visualization tool allows students to focus on more complex, multi-stage chemical reaction.

Green chemistry education should extend beyond reaction efficiency and include aspects such as energy utilization, reagent toxicity, and solvent selection. Incorporating thermodynamics into the curriculum is essential for assessing energy consumption and exploring greener alternatives. Thermodynamics provides a comprehensive overview and establishes criteria for evaluating the sustainability of chemicals, fostering meaningful discussions in the classroom (Tobiszewski et. al., 2017).

Teaching responsible waste management practices is a crucial aspect of green chemistry education. Students should learn to quantify and identify different types of waste materials (Garrigues et. al., 2010). They should also be introduced to methods for quantifying waste and distinguishing between benign and harmful waste. By developing the ability to quantify and classify waste, students can shift towards more sustainable waste management practices, such as recycling, industrial synergies, and zero waste technologies, rather than relying on storage and dispersion methods (Zaman, 2015).

In addition to green chemistry metrics, it is essential to educate students on conducting economic assessments of chemical processes, substrates, and products (Kokubu and Kitada, 2015). Understanding the costs associated with greener alternatives can enhance their appeal. Furthermore, teaching advanced assessments such as life-cycle assessments (LCA) allows for the examination of mass and energy flows, providing insights into the environmental impact and engineering aspects of chemical processes(Gustafsson and Borjesson, 2007).

Teaching Methods

Green chemistry education aims to address the environmental and human impact of chemistry, emphasizing that chemistry knowledge can be part of the solution rather than the cause of environmental problems. Incorporating green chemistry across the curriculum is crucial for a sustainable future. Objectives in American and Chinese curricula align in improving chemistry knowledge, promoting renewable resources, and mitigating adverse effects on the environment and human health. This highlights the shared importance of green chemistry education in both countries (Bodlalo et al., 2013).

The incorporation of green chemistry into all levels of education, from elementary to graduate courses, is seen as beneficial for overall education. Expanding pedagogical materials in various chemical sub-disciplines and standardizing the terminology of green chemistry is essential for the direct application of the Twelve Principles. Teaching green chemistry faces the challenge of integrating it into the core material rather than presenting it as optional. Both standalone courses and integration with existing programs are acceptable, but adding an optional course to an already busy curriculum may require significant preparation and adaptation (Andraos and Dicks, 2012).

The adoption of problem-based learning (PBL) in chemistry education has influenced studying strategies, including in the field of green chemistry. PBL encourages students to explore multiple solutions, engage in negotiations, and utilize case studies to develop multivariate answers. This approach challenges students to shift their perspective from seeking a single '*green*' answer in chemistry to embracing comparative strategies and a decision-making approach (Edward, 2012).

Specific Field Education

Green Chemistry is gradually being incorporated into academic and industrial research laboratories, but its implementation in teaching labs has been hindered by a shortage of published materials. However, advancements in various chemistry fields, including organic and analytical chemistry, present opportunities to introduce Green Chemistry concepts in teaching labs. This extends beyond science disciplines, as even humanities aim to include Green Chemistry in educational programs, emphasizing its significance.

Organic chemistry

The past three decades have seen significant changes in the field of organic chemistry, particularly with the emergence of the microscale movement. This shift towards smaller-scale processes and syntheses has not only impacted the way organic chemistry is taught but has also influenced students' learning experiences (Horowitz, 2007). The adoption of microscale techniques has led to improved technical skills and manual dexterity among students. Moreover, it has expanded the range of experiments students can engage in, as certain dangerous, expensive, or challenging chemicals become more manageable on a microscale (Pavia et al., 2005). Unlike many educational reforms, the microscale approach has gained widespread acceptance and continues to have a lasting impact.

In the late seventies, the use of cookbook organic laboratories, where students followed instructions without understanding, was criticized (Horowitz, 2007). However, concerns and questions about engaging students in organic labs persisted. Organic chemistry educators responded with new approaches to promote student focus and thoughtfulness in the laboratory.

To address the issue of students mindlessly following instructions, an inquiry-based approach has been proposed for organic chemistry laboratories (Horowitz, 2007). Although such approaches are common in general chemistry labs, they are rarely implemented in organic labs due to the complexity of organic protocols and the need for extensive student knowledge and experience (Wink et al., 2004). In this approach, students engage in multi-week research projects where they modify existing protocols or design new ones to solve synthetic problems. The projects can be open-ended, allowing students to explore their own interests, or more focused, with the instructor providing a specific research question. These project-based approaches require students to conduct novel reactions and foster critical thinking about procedures and outcomes, effectively eliminating cookbook-style experiments (Horowitz, 2007).

The introduction of the new approaches in organic chemistry laboratories has also promoted collaborative learning (Cooper, 2005). This pedagogical advance emphasizes creating conditions where students can work together in small teams or groups. Collaborative learning helps foster independent thinking and is commonly used in project-based laboratories, where students are grouped into synthetic teams responsible for various tasks (Horowitz, 2007).

Analytical Chemistry

Teaching Green Analytical Chemistry involves integrating chemical knowledge with problem-solving models that prioritize data evaluation and environmental considerations. It emphasizes the evaluation of risks associated with chemical handling, miniaturization, automation, and the assessment of toxicity and characteristics of commonly used laboratory reagents and solvents, relevant to method development and application.

Education in green analytical chemistry aims to strike a balance between ethical and chemical aspects. It emphasizes the social responsibility of analytical chemists, focusing on ensuring accurate data, evaluating sample representativeness, method accuracy, selectivity, and considering risks to operators and the environment (Guardia and Garrigues, 2012). The goal is to emphasize the positive impact of chemistry in addressing health and environmental issues and to instil a sense of obligation in students to transmit this knowledge. Teaching green analytical chemistry focuses on concepts related to analytes at the molecular level, emphasizing their evolution and toxic effects. Integration and sustainability are key considerations, aiming to reduce the negative impacts of energy and reagent consumption in decision-making processes (Guardia and Garrigues, 2011).

Incorporating tools for transitioning from traditional analysis to green practices is a key aspect of green analytical chemistry. This includes evaluating method greenness, emphasizing miniaturization and automation, reducing energy and labor consumption, and discussing environmental risks and the responsibility of method developers and users regarding waste management.

In green analytical chemistry, the selection of methods is based on quantifying the amounts of reagents and solvents used, as well as assessing associated risks. Energy consumption and waste generation are also considered, aiming to save resources and explore opportunities such as online solvent and reagent recovery. The goal is to reduce costs and environmental impacts while maintaining analytical features like accuracy, sensitivity, selectivity, and precision necessary to solve problems effectively (Guardia and Garrigues, 2011).

Scaling down sample sizes, standards, and reagent usage can improve method sustainability, but it requires additional efforts to maintain sample and data representativeness. Automation enhances method greenness by reducing operator risks and enabling reagent and waste economy. Unused reagents can be stored and reused in future sessions, further contributing to sustainability.

The on-line treatment of laboratory wastes offers benefits such as reducing toxic accumulation risks, fostering student awareness, minimizing institution costs, and incorporating experiments in waste management. To enhance student education, aspects of thermal-, oxidation-, photo-assisted degradation, and biodegradation should be included at the end of measurement steps, alongside on-line solvent distillation for recovery. Strategies to reduce water solution wastes with toxic non-degradable mineral elements are crucial, achieved through precipitation and passivation of toxic ionic species resulting from the method (Guardia and Garrigues, 2012). This reduces costs and risks associated with waste transport and treatment while emphasizing the importance of degradation and passivation reactions at the molecular level, ultimately moving towards cleaner waste management.

Persistent Challenges and Emerging Trends: Opportunities for Enhancing Teaching and Research

Chemistry plays a vital role in sustainable development, and chemical educators must promote and support human identity development, which is connected to the environment. The goal is to enable students to learn how to shape society sustainably. The first step is to provide special attention to green chemistry education, and the second step is to integrate green principles into educational practice to benefit undergraduates (Zuin and Mammino, 2015).

Regrettably, there exist numerous deficiencies and opportunities for improvement in teaching and research. Primarily, the teaching methodology itself, including the approach to comprehending chemical laws and the manner of recording reactions, needs to be revised. The following points serve as examples of other areas requiring enhancement-

1. Improving students' understanding of organic chemistry involves balancing chemical equations, particularly in reduction and oxidation reactions, while connecting them with the actual reaction mechanism. It goes beyond a mere numbers game, helping students comprehend the underlying chemical explanations for the occurrence of specific by-products in reactions.
2. To enhance organic synthesis courses, it is crucial to include quantitative analysis and optimization, which are often overshadowed by a qualitative approach focused on reaction memorization. Improving mathematical skills among synthetic organic chemists is essential for adopting green chemistry practices.
3. While the pharmaceutical industry has traditionally served as a reference point for addressing the gap, other sectors of the chemical industry also offer valuable resources.
4. Unfortunately, the emphasis on mathematical skills in chemistry curricula is lacking, leading to a deficiency in understanding thermodynamics among synthetic chemists.
5. Instructors of traditional organic chemistry courses often exhibit weaknesses in teaching quantitative concepts to undergraduate students.
6. A crucial aspect of green chemistry education is the mandatory incorporation of metrics analysis, connecting traditional experimental results and their write-up. This integration serves as a distinguishing feature and enhances students' comprehension of specific

reactions. Furthermore, it fosters creativity in designing new experiments and optimized syntheses using novel reactions.

7. An essential aspect of training students in green chemistry is developing their ability to recognize green-washing in the chemistry literature. This involves identifying instances where green improvements are falsely emphasized based on a limited number of factors, while neglecting other crucial aspects. Addressing these issues highlights the need for improved training for instructors before effective training for students can be implemented.

In addition to gaps in education and teaching, there are gaps in literature and research. Many researchers focus on one principle of Green Chemistry when claiming a procedure is green, rather than adopting a comprehensive approach that considers all aspects of reagents, energy consumption, waste, and environmental impact. Examples in research include-

- The disclosure of reaction performance in patents is less common compared to journal publications, affecting the assessment of green chemistry ideas based on industrial examples from patents. Evaluations should encompass ionic liquid solvents synthesis, specialized catalysts, and ligands, which are often overlooked in green parameter assessments of synthesis.
- Typically, publications provide fragmented information regarding only a few parameters such as reaction time, power consumption, or temperature. However, the intrinsic efficiency of the microwave apparatus used is often disregarded, making it challenging to determine the actual energy consumption accurately.

In addition to the previously mentioned issues, there are gaps in educational literature. For instance, there is a lack of examples in the literature that inform about the recycling and reuse of catalysts, despite their heavy use in student laboratories (Edward, 2012). The success in these areas may result in a paradigm shift and the need to revise undergraduate textbooks (Andraos and Dicks, 2012). Furthermore, both research and teaching perspectives have given little attention to quantifying energy consumption and considering costs for appropriate methodologies.

Conclusion

This paper highlights the importance of incorporating green chemistry principles in higher education to equip future chemists with the necessary skills for protecting the environment and promoting sustainability. Green chemistry has transitioned from academic research to a widely adopted practice supported by academia, industry, and governments worldwide. Integrating green chemistry into existing courses presents challenges but can be achieved by incorporating key concepts into the curriculum. Various teaching methods, such as problem-based learning and collaborative learning, can be effective in promoting green chemistry education. The paper also discusses the implementation of green chemistry principles in specific fields, such as organic chemistry and analytical chemistry, emphasizing the need for incorporating sustainability throughout the design process and evaluating the environmental impact of chemical processes. Despite some persistent challenges, there are opportunities for enhancing teaching and research in green chemistry, including improving students' understanding of organic chemistry, emphasizing quantitative analysis and optimization in synthesis courses, and enhancing the integration of metrics analysis. Overall, green chemistry education plays a vital role in addressing environmental challenges and training future scientists for a sustainable society.

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