International Perspectives on Green and Sustainable Chemistry Education via Systems Thinking

Hurst, G.A. ; Slootweg, J.C.; Balu, A.M. ; Climent-Bellido, M.S. ; Gomera, A.; Gomez, P.; Luque, R.; Mammino, L.; Spanevello, R.A.; Saito, K.; Ibanez, J.G.

DOI
10.1021/acs.jchemed.9b00341

Publication date
2019

Document Version
Final published version

Published in
Journal of Chemical Education

JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: J. Chem. Educ. 2019, 96, 2794−2804

pubs.acs.org/jchemeduc

International Perspectives on Green and Sustainable Chemistry Education via Systems Thinking

Glenn A. Hurst,[†] J. Chris Slootweg,[‡] Alina M. Balu,[§] Maria S. Climent-Bellido,[§] Antonio Gomera,[‖] Paulette Gomez,[§] Rafael Luque,[§] Liliana Mammino,[⊥] Rolando A. Spanevello,[¶] Kei Saito,[□] and Jorge G. Ibanez*[,■]

[†]Green Chemistry Centre of Excellence, Department of Chemistry, University of York, Heslington, York YO10 5DD, United Kingdom

[‡]Van 't Hoff Institute for Molecular Sciences, Research Priority Area Sustainable Chemistry, University of Amsterdam, Science Park 904, 1090 GD Amsterdam, The Netherlands

[§]Departamento de Quimica Organica (NANOVAL), Universidad de Cordoba, E14014 Cordoba, Spain

[‖]Servicio de Proteccion Ambiental (SEPA), Universidad de Cordoba, E14014 Cordoba, Spain

[⊥]School of Mathematical and Natural Sciences, University of Venda, P. Bag X 5058, Thohoyandou 0950, South Africa

[¶]Instituto de Quimica Rosario, Facultad de Ciencias Bioquimicas y Farmaceuticas, Universidad Nacional de Rosario, Suipacha 531, S2002LRK Rosario, Argentina

[□]School of Chemistry, Monash University, Box 23, Clayton, Victoria 3800, Australia

[■]Departamento de Ingenieria Quimica, Industrial, y de Alimentos, Universidad Iberoamericana, Prolongacion Paseo de la Reforma 880, 01219 Ciudad de Mexico, Mexico

ABSTRACT: Various international perspectives from selected regions where substantial work is being done on green and sustainable chemistry education emphasize a systems thinking framework. Common to most of the perspectives is the inclusion of more global paradigms involving economic, environmental, political, and social aspects as fundamental issues in the formerly merely technical and scientific discussions, as well as the development of laboratory experiences, training sessions, written materials, discussion meetings, and conferences. We include bird's eye views from Europe (the Green Chemistry Centre of Excellence at the University of York, United Kingdom; the University of Cordoba, Spain; and the University of Amsterdam, The Netherlands), Latin America (the Universidad Nacional de Rosario, Argentina, and the Universidad Iberoamericana, Mexico), Africa (the University of Venda, South Africa), and Australia (Monash University).

KEYWORDS: *Continuing Education, Curriculum, Environmental Chemistry, General Public, Green Chemistry, Sustainability, Systems Thinking*

Green and sustainable chemistry education (GSC) is rapidly gaining acceptance throughout the world. However, purely scientific or technical approaches to specific subjects give rather limited visions of reality to students. More systemic thinking is therefore required to broaden students' perspectives and widen their ideas of possible useful actions in their lives as informed citizens and professionals. Systems thinking describes approaches that move beyond the fragmented knowledge of disciplinary content to a more holistic understanding that emphasizes the interdependence of components of dynamic systems and their interactions with other systems, including societal and environmental structures.[1a] Considerations of how present and future generations can live within the limits of the natural world, focusing on the material basis of our society and economy, are referred to as "the molecular basis of sustainability".[1b] In the present paper, we present different approaches that incorporate systems thinking in Europe, Latin America, Africa, and Australia. The North American experience is dealt with elsewhere in this issue.

EUROPEAN PERSPECTIVES ON GREEN AND SUSTAINABLE CHEMISTRY EDUCATION VIA SYSTEMS THINKING

Current efforts to meet the United Nations Sustainable Development Goals (UN SDGs, see below) by 2030 in the European Higher Education Area (EHEA)[2a] are traced back to the EHEA's creation by the Bologna Process (1999).[2b] The EHEA was launched at the Budapest−Vienna Ministerial Conference (March 2010) with a main goal of ensuring more comparable, compatible, and coherent systems of higher education in Europe.[2b,3] In order to join the EHEA, a country must sign the European Cultural Convention treaty.[4]

Higher education has previously been identified as an important tool for solving many systemic problems, and

Special Issue: Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry

Received: April 8, 2019
Revised: October 11, 2019
Published: November 19, 2019

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

Figure 1. Homepage of the CHEM21 online learning platform. Reproduced with permission from ref 12. Copyright CHEM21.

Agenda 21 recognizes that education is vital for achieving sustainable development.[2a] In view of a widespread de facto tendency away from sustainability, many universities have signed statements, such as the Talloires Declaration (1990) or the Copernicus Charter (CRE, 1993),[5] in which they pledge to emphasize sustainable development in their training programs, which was partly encouraged by the United Nations Decade of Education for Sustainable Development (ESD, 2005−2014).[6]

United Kingdom

There are examples of systems thinking that have been integrated within GSC teaching at multiple levels, from elementary school to high school, from undergraduate to postgraduate study, and even as part of continuing professional development. Much of this work has been pioneered at the Green Chemistry Centre of Excellence at the University of York. In 2001, Professor James Clark established there a master's degree program in green chemistry, which was the first of its kind in Europe and has been a benchmark for a number of graduate level courses internationally.[7−9] The value and applicability of systems thinking in green chemistry are embedded throughout this master's program via a top-down fashion, starting with program design. This was achieved through the creation of the following program learning outcomes (PLOs):[10]

- Critically evaluate and debate research literature and explain its relevance to the bio- and circular economy.
- Apply environmental-related metrics to chemical processes and products, enabling critical assessment of their environmental impacts and sustainability.
- Identify potential economic and technological drivers for change that may affect chemical manufacturing or user sectors, and advise accordingly through the use of skills and knowledge acquired in the program.
- Apply detailed understanding of intellectual property protection and commercialization of new inventions to the development of sustainable chemical products or processes.

These learning outcomes underpin the whole course, and through constructive alignment, module learning outcomes (and associated content and assessments) map onto the PLOs. Incorporating systems thinking into such outcomes provides instructors with the opportunity to teach green chemistry using this approach. At the postgraduate level, this has manifested as analyzing and evaluating the research literature to include case studies on the circular economy. To appreciate this economic system of minimizing waste and making the most of resources (in contrast to the traditional linear economy), students must consider all components of the system, such as resource input and waste, emissions, and energy leakage, together with their associated interdependencies and how to minimize them through slowing, closing, and narrowing energy and material loops. The former can be achieved via long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, recycling, and upcycling.[11] Similarly, through life-cycle assessment, students can consider product systems in their entirety from raw material extraction to processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Once the details of the system framework are understood, students can then quantify all inputs and outputs of material flows and, in doing so, assess how these material flows affect the environment. Furthermore, having students make evidence-informed generalizations about product systems allows them to predict how a process may be enhanced to minimize environmental impacts. In addition to analyzing existing systems, students can suggest improvements and predict the results of such changes. Moreover, in regard to empowering students with the means to design their own systems and respond to changes (e.g., in legislation) in dynamic ways, mimicking real life scenarios, students are required to submit a proposal and business plan for a spinoff company as a component of the assessment, affording students an opportunity while developing their commercial awareness in the context of a changing system. Although these interventions have been outlined in the context of implementation as part of a postgraduate qualification, application at lower levels, such as within an undergraduate program, is of course possible.

Systems thinking in green chemistry education is not restricted to face-to-face sessions but can be incorporated as part of blended and distance learning packages. An example of

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

this is the online platform constructed as part of Chemical Manufacturing Methods for 21st Century Pharmaceutical Industries (CHEM21), which is Europe's largest public–private partnership for the development of manufacturing sustainable pharmaceuticals. Through this collaboration, an online learning platform[12] was designed to train undergraduate and graduate students and medicinal chemists from the pharmaceutical industry in sustainable chemistry (Figure 1). The platform comprises a range of free, shareable, and interactive educational and training materials to promote the uptake of green and sustainable methodologies, with an emphasis on synthesis of pharmaceuticals.[13] A broad range of topics at introductory and advanced levels are covered, including process design considerations and life cycle impacts, together with the environmental fates of pharmaceuticals. For example, as part of process design, learners have to consider an entire system to select the optimum synthetic route using the best available techniques and technologies. In life cycle assessment, learners consider the impacts of primary manufacturing (e.g., the synthesis of an active pharmaceutical ingredient, API), secondary manufacturing (e.g., formulation, packaging, excipients, etc.), and end-of-life impacts (e.g., issues with contamination of human drinking water and effects on organisms other than humans exposed to APIs and their residues in water courses). Rapid feedback questions together with a blend of more detailed exercises requiring a deeper level of systems understanding are provided. The flexibility of the online learning platform for personal use and teaching purposes provides opportunities to foster independent learning but also opportunities for instructors to incorporate new research and industrial case studies into teaching, cover core concepts, extend learning, or even facilitate "flipped" lectures. To ensure that the most recent developments in research are incorporated into the platform for longevity, the ACS Green Chemistry Institute Pharmaceutical Roundtable has recently adopted the resource and will maintain it.

Laboratory experiments and more open-ended, problem-based learning miniprojects have also been designed to facilitate systems thinking in green chemistry. The design of such interventions has been achieved through adopting a *students-as-partners* approach.[14] Undergraduate students have worked with staff to substitute hazardous and nonsustainable chemicals used in their laboratory protocols through a "Green Reagents and Sustainable Processes" (GRASP) approach. This comprises students identifying potentially hazardous chemicals within an undergraduate experiment, substituting them with green alternatives, and implementing a refined version of the activity into the undergraduate curriculum. Much of the work has focused in polymer chemistry, in accordance with the 2015 ACS Committee on Professional Training Guidelines in undergraduate education in chemistry.[15] An example of such an experiment was the examination of the rheological properties of silly putty (poly(vinyl alcohol) cross-linked with borax).[16] Through this experiment, students could study the temperature dependence of kinematic viscosity, follow gelation, and investigate non-Newtonian behavior. However, students identified that borax is classified as "toxic for reproduction", category 1B under the Classification, Labeling, and Packaging regulations, and according to the Globally Harmonized System of Classification and Labeling of Chemicals (GHS), it poses a "serious health hazard" (GHS08). Hence, it is unsuitable for educational use. As such, through understanding the intricacies of this gel system, students applied the GRASP model and were able to effectively substitute the PVA–borax system with a green sodium alginate gel (basically seaweed) cross-linked with calcium chloride. In doing so, they designed an experiment to meet the original learning objectives from the PVA–borax system and implemented the resource to benefit future cohorts of students.[17] To embed systems thinking more deeply, students turned to a different system where they designed a laboratory experiment based on valorizing waste orange peel by extracting a pectin sol and, in combination with a sugar solution, formed a marmalade-based product in which the rheological behavior could be investigated.[18] This system allowed students to directly consider the life cycles of materials in a more systemic fashion. In doing so, students could reflect on where materials come from, how they are transformed and used, and what happens at the end of their life spans. At the elementary and high school levels, there are also examples of students making bioplastics from starch-based feedstocks as opposed to petroleum derivatives.[19] Issues with using oil to make plastics can be highlighted (e.g., oil is nonrenewable, there is a danger of oil spills, energy is required to drill for oil, lots of heat is required to separate crude oil, and oil-based products take thousands of years to biodegrade). As such, there is significant demand for bioplastic alternatives. Ongoing work expands the portfolio of resources to facilitate systems thinking in green chemistry at these levels.

In addition to laboratory experiments, problem-based learning miniprojects have been designed to foster systems thinking in chemistry using green systems. At York, upper-division undergraduate students study a smart pH-sensitive hydrogel used as a targeted drug delivery device in the stomach to combat *Helicobacter pylori* infections.[20] The green genipin-cross-linked chitosan hydrogel forms a welcome alternative to the traditional glutaraldehyde-cross-linked gel, making this system accessible for undergraduate use. Students have the opportunity to vary gel system parameters, such as the amount of cross-linking agent, the degree of chitosan deacetylation, the gelation time, and the gelation temperature, and to explore the effects on system outputs, such as swelling in various solvents (i.e., inclusion of the target environment), the reversibility of swelling, oscillatory behavior, the microporous structure, fluorescent properties, color and pigmentation, and the release of a model compound. Such an advanced and open-ended investigative project requires knowledge of the system together with the ability to predict the effects of modifying parameters on the system outputs and optimize accordingly. Other recent examples of experiments and laboratory-based projects with some elements of systems thinking outside of the United Kingdom have been summarized elsewhere.[21]

The Netherlands

A green chemistry course was recently developed at the University of Amsterdam for students who are enrolled in master's programs in Chemistry (i.e., Molecular Sciences track or Science for Energy and Sustainability track); Physics (Science for Energy and Sustainability track); or Science, Business & Innovation (Energy and Sustainability track) with the aim of combining different student groups in one classroom to stimulate systems thinking. The course, which uses the "flipped" classroom model, is all about acquiring knowledge of the general ideas of GSC and their importance in the development of sustainable chemical technology along the entire value chain.[22] Topics that are covered (using multiple e-

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

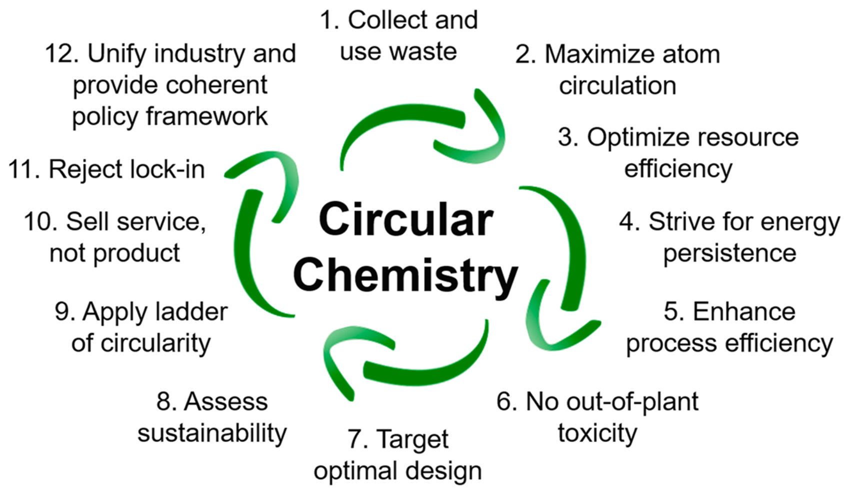

Figure 2. Twelve principles of circular chemistry. Reproduced with permission from ref 36. Copyright 2019 Springer Nature.

books) include the principles of green chemistry and green engineering,[23] evaluating the greenness of synthesis,[24] alternative feedstocks for synthesis,[25] biofuels,[26] fuels and chemicals from CO_2,[27] renewable materials,[28] the economics of GSC,[29] chemical leasing,[30] and sustainable chemical logistics.[31] The focus is on a transitional perspective on sustainable chemistry, discussing the need for smart governance,[32] a policy perspective,[33] and building of corporate social responsibility for developing a sustainability management system framework.[34] The course is organized around multidisciplinary teams to stimulate cross-disciplinary knowledge sharing. During in-class activities, each team provides a lecture on one of the topics listed above, followed by an in-depth plenary analysis of a related Green Chemistry Award, focusing on all aspects from lab to market. In addition, the student teams create exam-level tutorial questions, including answers, to apply their newly gained knowledge. They also write individual one-page essays about a new sustainability concept, such as "the chemical ladder of circularity", where they are challenged to create new knowledge, which is the ultimate aim of the green chemistry course. The course is concluded with a written exam.

When discussing circular economy in class,[35] the 12 principles of green chemistry were highlighted as suitable guidelines for chemistry research and R&D to contribute to a circular economy. The group realized that the green chemistry principles are designed for the optimization of linear production routes and focus on the conversion of raw materials and other (renewable) resources. However, for creating a circular economy, recycling is a key component, and therefore, waste should also be used as a valuable resource for the production of new molecules and materials. To promote life-cycle thinking and circularity in chemistry and advance the development of novel chemical products and processes that use waste as resource, the concept of circular chemistry was developed, and the 12 principles of circular chemistry were formulated (see Figure 2).[36] Circular chemistry aims to replace today's linear "take−make−dispose" approach with circular processes that optimize resource efficiency across chemical value chains and enable a closed-loop, waste-free environment. By making chemical processes truly circular, molecules and materials can be repurposed near-indefinitely, resulting in energy as the only input. Circular chemistry offers a holistic systems approach and stimulates systems thinking, which will contribute to realizing the circular economy and securing our sustainable future by addressing the UN SDGs.[6,37] On the basis of GSC teaching in Amsterdam, we can provide the following recommendations for teaching GSC globally: Chemistry is all about making molecules, and the principles of green chemistry provide an enabling framework for optimizing the synthesis and production of molecules and materials. After their use, these molecules and materials ultimately need to be reused or recycled, because in a circular economy, waste is a resource. To promote the development of molecules and materials from waste, the circular chemistry principles are now available,[36] highlighting that (circular) chemistry is all about *re*making molecules and materials as well.

Spain

An overview is now given of Spanish national and local initiatives that are currently implemented at the university level to train and educate professors and students toward sustainability.

In September 2002, the Association of Spanish University Rectors (CRUE) unanimously approved the proposal to create the Working Group for Environmental Quality and Sustainable Development (EQSD, now called the CRUE Sustainability Commission) to promote initiatives related to risk prevention, environmental management, participation, and awareness in universities, as well as interuniversity cooperation on these matters. They prepared the *Guidelines for the Inclusion of Sustainability in the Curriculum* in 2005.[38] This text, updated in 2011, laid down some general criteria and recommended actions to introduce competencies-based curricular sustainability in Spanish universities within the EHEA framework. This document advanced the development and expansion of these general guidelines by exploring the concept of sustainability and its application at universities. To facilitate understanding and the application criteria for the inclusion of sustainability in the curriculum, the document defines the sustainability concept and sets forth some generic principles and basic skills required to achieve sustainability in university teaching.[38]

Aside from the necessary networking among universities, there are also successful case studies on particular initiatives of universities to achieve improved sustainability for the environment. Examples are provided below.

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

Trebol Program (Certificate). Within the framework of sustainability of the European Universities in the General Direction of Prevention and Environmental Protection, the Trebol (i.e., the Spanish word for "clover") program is an initiative for improvement and environmental recognition in the centers, departments, areas, and services of the University of Cordoba, where environmental policies are gradually being integrated into the University's structure. This program contributes to saving resources and reducing the environmental impact of daily activities; it is designed to be applicable to any organizational unit (i.e., department, service, section, research group, laboratory, quality group, classroom, lecture, deanery, and secretary). It implements good practices in environmental matters, inserting systematized, organized, and continuous improvement into all processes and thus contributing to saving resources.

Four checklists make up the certification system at four levels, symbolized by a trebol leaf (from which its name derives). Each level comprises a series of actions corresponding to eight categories of environmental aspects: energy, waste, consumption, transportation, purchasing, laboratories, teaching, and participation. The plan is divided in this way to progress "leaf by leaf" until the four levels are achieved. The organizational units that reach each level obtain a certificate and an emblem of the leaf of the Trebol Program. This is a "do it yourself" program.[39]

Education and Social Innovation for Sustainability (EDINSOST) Project. EDINSOST, a government-funded project, involves the training of professionals as change agents in Spanish universities to face the challenges of sustainability. Over 50 researchers are actually engaged in it. Fifteen degree courses in the fields of education and engineering are implicated. These degrees are taught in 10 Spanish universities:

- Universidad Autonoma de Madrid (UAM)
- Universidad de Cadiz (UCA)
- Universidad de Camino de Jose Cela (UCJC)
- Universidad de Cordoba (UCO)
- Universidad de Gerona (UdG)
- Universidad Internacional de Cataluña (UIC)
- Universidad Politecnica de Cataluña (UPC)
- Universidad Politecnica de Madrid (UPM)
- Universidad de Sevilla (US)
- Universidad de Salamanca (USAL)

These 10 universities work on sustainability within the framework of the Sectorial Commission on Sustainability of CRUE (SCS) and in collaboration with other universities. The EDINSOST research methodology assumes an interpretive focus that uses both quantitative and qualitative techniques. The work is carried out in different degree courses at three levels of incidence:[40]

- Five bachelor's engineering degrees: Mechanical Engineering, Design Engineering, Electrical Engineering, Informatics Engineering, and Chemical Engineering
- Three degrees aligned with the three sustainability parameters (i.e., social, economic, and environmental): a bachelor's degree in Environmental Sciences, a master's degree in Scientific and Technological Sustainability, and a bachelor's degree in Administration and Business Management
- Six education degrees intended to train the future teachers of new generations of citizens: bachelor's degrees in Early Childhood Education, Primary Education, Pedagogy, and Social Education; a master's degree in Secondary Teacher Training; and an InterUniversity master's degree in Environmental Education

The EDINSOST project has four specific objectives:[40]

1. To define the Sustainability Competency Map of each one of the participating degrees and to establish a framework for its holistic incorporation into each degree.
2. To validate different didactic strategies for addressing sustainability from the constructivist and community pedagogical approaches.
3. To diagnose the status of the training needs (in terms of sustainability) of the teachers of each degree and to develop and test training proposals.
4. To diagnose the sustainability competency level of current university students and to develop and test other training proposals.

Training Courses for University Members on Curricular Sustainability. The university, as an institution dedicated to develop and transmit knowledge through research and teaching, plays a key role in the dissemination and application of possible solutions and alternatives to the socio-environmental problems present in our society (e.g., see the *COPERNICUS Guidelines for Sustainable Development in the European Higher Education Area* and the *Guidelines for the Inclusion of Sustainability in the Curriculum*).[5,38]

The University of Cordoba offers a doctoral program in Natural Resources and Sustainable Management aimed at learning the effects of environmental deterioration (referred to the loss of natural, domestic, or communal biodiversity) in order to establish mechanisms that result in integral management of the socio-environmental systems.[41] The Universidad Politecnica de Cataluña offers a master's degree in Sustainability Science and Technology, a doctoral program in Sustainability, and a doctoral program in Environmental Engineering, whose main goals include the development of working knowledge and understanding of the impacts of human activities and natural processes on the environment, as well as understanding of the interactions among society, economy, and environment (see the University Research Institute for Sustainability Science and Technology).[42]

The objective of the Sustainability Classroom program at the University of Cordoba is to mainstream principles of sustainability into the university community through the promotion of Curricular Sustainability,[38] which is understood as the process of incorporating sustainability criteria in the teaching and learning of students throughout all areas of teaching. The integration of curricular sustainability in higher education promotes among university graduates the development of skills related to sustainability, such as critical and creative thinking, problem solving, capacity for action, collaborative capacity, and systems thinking.[43]

The incorporation of sustainability into higher education is evaluated through competencies. The new EHEA proposes to go beyond the barrier of simple static knowledge of a specific subject, by planning the achievement of educational objectives through the acquisition of competencies (both basic and transversal) specific to each degree. Therefore, this sustainability-infusion process involves the student, along with the teacher, acquiring the knowledge and skills provided in each subject not in a passive way but in relationship to the socio-environmental reality in which they exist.[44]

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

Poland

In a related action, the University of Warsaw is about to launch a master's program in Sustainable Development that will cover a wide range of cutting-edge topics embracing the complexity of sustainability challenges and the leadership skills needed to design solutions and facilitate change in different types of communities and organizations (i.e., Alliance Copernicus).[45a]

The Centre for Bioeconomy and Renewable Energies of the University of Warmia and Mazury is highlighting sustainability schemes for biobased products in the framework of the circular bioeconomy. Here, applied research on economic systems with biobased value chains aims at material flows with near zero waste and pollution and integrates three fundamental areas of sustainable development: economy, environment, and society.[45b]

Germany

Among the many German institutions that promote GSC, the International Sustainable Chemistry Collaborative Centre (ISC3) is an independent, international institution promoting and developing sustainable chemistry solutions worldwide.[46a] It has a Research and Education Hub led by the Institute of Sustainable and Environmental Chemistry at Leuphana University (Luneberg). Together with the Elsevier Foundation and other organizations, they organized a recent GSC conference where a broad range of topics highlighted the role of chemistry in contributing to achieving the UN SDGs.[6,46b]

Lastly, in Europe and elsewhere, many university courses, regardless of the discipline, are taught in isolation with nominal global awareness and exposure and often without systemic references to the political, environmental, and economical aspects of reality.[1,47−49] On the other hand, the majority of universities within the EHEA framework are making important changes in this direction in their curricula and degree requirements.[50]

LATIN AMERICAN PERSPECTIVES ON GREEN AND SUSTAINABLE CHEMISTRY EDUCATION VIA SYSTEMS THINKING

GSC has been well received in Latin America (LAm), where the decades-old traditional divisions of organic chemistry, inorganic chemistry, physical chemistry, biochemistry, and analytical chemistry are not necessarily suited to globally address sustainable development goals.[51] In fact, reductionist and decontextualized perspectives still prevail, as the economic, political, social, and cultural aspects of chemistry are frequently not considered while teaching or performing research, but informal education actors (e.g., the press, nongovernmental organizations, museums, science fairs, etc.) have contributed to strengthening their integration.[52]

The Science−Technology−Society−Environment approach (CTSA, for its initials in Spanish),[53,54] whose origins date back to 1976 in England,[55] has been a major step in the direction of a more global systems thinking approach in LAm as it links scientific and technological issues to their contextual situations.[52] The CTSA methodology involves the steps of searching for reliable information, then linking it to sequential activities (either experimental or virtual) designed for the specific subject in focus; this enables students to make informed decisions as professionals and as citizens.[56,57] This series of concatenated activities promotes student interest in understanding the nature of science and scientific work, and links science with social and ethical issues as well as with everyday phenomena and applications.[52]

The introduction of GSC into the undergraduate curriculum in a transversal manner can increase a student's ability to think critically and more globally, especially if the CTSA dimensions are integrated as part of a system.[58] A complementary approach to reach wider audiences is to integrate the concepts of GSC and bioeconomy. The Knowledge Based Bio-Economy approach (KBBE) intends to improve the efficiency of processes; favor environmental, social, and economic sustainability; encourage the substitution of fossil fuels and raw materials; and promote the application of closed cyclic systems for recycling.[59] KBBE is grounded in biological processes, uses natural materials, minimizes the consumption of nonrenewable energy, and does not generate residues because those generated are employed as starting materials for other processes. The question of accessible land for food and nonfood crops directly impinges on the future availability of biomass feedstock for human needs and requires continuous analysis in the CTSA and educational arenas. In this sense, LAm plays a crucial role in the global food chain: it holds an important position as a world biomass supplier because the land quality and availability is higher than the world's average of 0.5 acres per capita. Nevertheless, this comparative advantage needs to be accompanied by innovative process intensification to meet the increasing demands for sustainable production.

For several LAm petroleum-based economies, the sustainable use of renewable natural resources through value addition using chemical, biological, or thermal processes is an ideal transition into bioresource-based economies; it greatly aids in addressing climate change and naturally leads itself into systems thinking analysis. These bioprocesses can manage bulky amounts of widely available and virtually free domestic, industrial, and agricultural wastes (e.g., residual stalks, straw, leaves, bagasse, roots, husks, nut or seed shells, waste wood, sawdust, manure from animals, and municipal waste such as waste paper and yard clippings)[60,61] to obtain fuels and valuable chemicals. Their use is carbon neutral, displaces fossil fuels, and helps reduce greenhouse gas emissions while closing the carbon cycle loop. As the debate on food versus fuel intensifies, one of the main industrial potentials of biomass wastes is the fact that they do not interfere with food production nor biodiversity and can provide added income to farmers.[62,63]

Even though most chemistry curricula in LAm may not explicitly include GSC, a transversal approach to its key concepts is increasingly considered.[52] Fortunately, some universities have now implemented degrees in Sustainable Chemical Engineering, Chemical Engineering in Sustainable Processes, Sustainable Development Engineering, Engineering in Energy and Sustainability, Sustainability, Sustainable Engineering, and the like.[51]

LAm chemistry organizations, funding agencies, and universities have been successful in emphasizing GSC at the local and international levels, including in research projects, the generation of graduate and undergraduate courses, book editions, journal articles, the organization of summer schools, workshops, contests, and outreach projects (including those for the general public as well as those for elementary, secondary, and high schools). Some (nonlimiting) examples of LAm educational and research institutions involved include:[64−68]

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

- Argentina: Universities of Buenos Aires, La Plata, Rosario, Córdoba, Rio Cuarto, Tucumán, Quilmes, Sur, and Litoral and the National Technological University
- Brazil: Federal Universities of Rio de Janeiro, Fluminense, and São Carlos
- Colombia: Pedagogical and Technological University of Colombia and Cauca University
- Costa Rica: Technological Institute of Costa Rica
- Ecuador: Polytechnic School of the Litoral
- Mexico: National Autonomous University, Monterrey Tech (ITESM), University of Guanajuato, University of Michoacan (San Nicolas de Hidalgo), and Iberoamerican University (to whom the ACS granted in 2011 an Award for Incorporating Sustainability into Chemistry Education)
- Peru: Pontifical Catholic University of Peru
- Uruguay: University of the Republic

Teachers and researchers from other LAm countries (e.g., El Salvador, Panama, Venezuela, and Cuba) have also participated in specific training facilitation and collaborative projects. A key question for the implementation of GSC in the undergraduate chemistry curriculum is how to create new subjects in the already crowded chemistry curricula. Awareness of the breadth of GSC and of the multiple uses of chemicals requires a multidisciplinary approach involving the sciences, pedagogy, the economy, e-learning, and ethics, among others. New objectives need global focal points. Planning requires a sustainable emphasis from the start. For example, at the Universidad Nacional de Rosario (Argentina) the undergraduate chemistry curriculum is now organized into two main subject groups: one dealing with the traditional disciplinary courses and a second group that includes epistemology and seminars on bioethics, sustainability, responsible use of chemicals, and ethical guidelines.[69] This naturally leads to examples of the misuse of chemistry (waste disposal, chemical accidents, and chemical weapons), and how the GSC concepts can improve industrial processes, emphasizing real examples presented in a very simple and understandable manner, especially for beginners, with a systems thinking vision.

International organizations have provided support in promoting GSC progress in LAm. For example, the American Chemical Society (ACS) and the Latin American Federation of Chemical Associations (FLAQ) have formally fostered collaboration among their respective communities, with GSC as one of the target areas addressing global challenges (e.g., energy, water, health, and food). Such a vision can also be thought of as a precursor to the systems thinking approach. In addition, the ACS Green Chemistry Institute has established and helped fund several local chapters in LAm and has provided many training opportunities. The ChemRAWN XIV ACS Green Chemistry Institute (ACS-GCI) International Green Chemistry Grants Program enabled training sessions to be developed with international attendance. The organization of the annual NSF Pan American Advanced Studies Institute (PASI) has boosted GSC systems thinking in several countries (e.g., Mexico and Uruguay).[70]

Global and local specific short training sessions (e.g., summer schools and workshops) including lectures, case studies, discussions, field trips, and poster sessions to reach younger scientists and students at all levels, greatly help to root key concepts, ideas, and projections; they also develop abilities to assess the greenness and sustainability of specific technologies.[71,72] The annual ACS-GCI summer-school program (established almost two decades ago) has also assisted and encouraged graduate students and postdoctoral researchers to establish working relationships. The International Union for Pure and Applied Chemistry (IUPAC) has sponsored funding for translation of educational materials into Spanish and Portuguese.[73]

In addition to the above, European institutions like the Organization for the Prohibition of Chemical Weapons (OPCW), winner of the 2013 Nobel Peace Prize, have strongly supported research and education in LAm in GSC and have offered various capacity-building opportunities. For example, OPCW's 11 member states from LAm and the Caribbean have worked together on chemical issues related to Safety, Security, and Environmental Protection, and they have urged the setting up of school and university curricula on GSC.[73] The United Nations declaration of a Decade of Education for Sustainable Development helped mobilize international educational resources to integrate the principles, values, and practices of sustainable development into all aspects of education and learning.[6,74] This educational effort fares well for a more sustainable future in terms of environmental integrity, economic viability, and a more equitable society for present and future generations. Also, the Italian Consorzio Interuniversitario "La Chimica per l'Ambiente" (Interuniversity Consortium "Chemistry for the Environment", INCA) has worked with IUPAC and representatives from several LAm countries to organize GSC events (e.g., the fourth. International IUPAC Conference on Green Chemistry in Foz do Iguaçu, Brazil, in 2012) and to produce a book titled *Green Chemistry in Latin America*, published as part of a Green Chemistry Series edited by IUPAC, where the main areas of interest include alternative energy sources, flow chemistry, alternative solvents, catalysis, biomass and biofuels, and education.[64]

Lab experiments have been developed in LAm at the precollege, postcollege, and college levels, mostly associated with sustainable agriculture, agro-resilience, green chemistry, and socio-environmental technologies, especially for biorational control. In many cases, these experiments use local materials, contexts, and interests, opening up the possibility of engaging student interest while being easily implemented elsewhere.[66] The principles of GSC at the higher education level, especially in the organic chemistry area, have been the object of increasing interest,[75,76] and metrics have been introduced.[77] Some LAm countries (e.g., Peru) have implemented a policy to support the development of GSC by providing financial support to selected master's programs.[66]

The issue of how to present GSC as a key factor for the global development of a nation remains a challenge, including the prevention of the environmental toll inherent to every transformation process.[78,79] GSC must be presented as far beyond mere pollutant treatment schemes and more as the avoidance of pollution and the promotion of an economy of time and resources, which requires systemic consideration of the whole system as opposed to isolated entities. Along with the increase in public awareness on sustainability issues, there is strong pressure on LAm industrial companies, research centers, and academia to put their focus on embracing the principles of GSC to produce safer chemicals and develop innovative technologies. All of these actions point at vigorous growth of GSC in LAm, and the wide range of interventions

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

gradually converges toward a more organized systems thinking approach.

AFRICAN PERSPECTIVES ON GREEN AND SUSTAINABLE CHEMISTRY EDUCATION VIA SYSTEMS THINKING

Reflections on the meaning and implications of systems thinking may focus on a variety of aspects. A fundamental one relates to the need of considering as many pieces of information as possible on the issue of interest, as well as the relationships among them. This is also a prerequisite to the design and implementation of initiatives and actions. In this way, education toward sustainable development covers a broad range of focuses and objectives, from the general (meant for all citizens) to increased specialization. The dissemination of information aimed at promoting sustainable behavior patterns is an example of the former, whereas Green Chemistry education is an example of the latter. All of them require the handling and understanding of many pieces of information, because of the complexity of environmental issues, of human and communities, and of chemical technology.

Two initiatives are exemplified for the African continent:

1. Green chemistry is the specialized response by chemists to the needs of sustainable development. Providing information and training to young chemists becomes a crucial component of the preparation of specialists capable of designing holistic approaches to make production processes cleaner and more environmentally benign. An encouraging example with a continental scope involves the first Postgraduate Summer School on Green Chemistry in Africa, an IUPAC-endorsed initiative that took place in Dar es Salaam, Tanzania (2019).[80]
2. The dissemination of information aimed at promoting sustainable behavior patterns may take a variety of forms. For instance, the book *Biomass Burning in Sub-Saharan Africa: Chemical Issues and Action Outreach* explores options aimed at promoting a shift from the traditional practice of burning huge amounts of plant materials in the open air to more sustainable practices.[81] It comprises technical information as well as materials and considerations for outreach activities, portraying possible options for joining together the investigation of the facts (i.e., experimental information and data) about specific environmentally unfriendly behavior patterns and the search for effective and respectful options, to actively engage citizens and communities in the design and implementation of environmentally benign behaviors, including the management of the necessary transference.

AUSTRALIAN PERSPECTIVE ON GREEN AND SUSTAINABLE CHEMISTRY EDUCATION VIA SYSTEMS THINKING

In order to give students a systemic GSC overview, a comprehensive sequence is introduced throughout the entire undergraduate curriculum at Monash University. A special case is the third year undergraduate Sustainable Chemistry course that highlights the development of chemical tools and practices that underpin the concept of a sustainable future. Here, three interconnected streams, Introduction to Green Chemistry, Sustainable Technologies, and Green Energy, systemically explore how humanity might meet the needs of the present generation while sustaining the needs of future generations to come. The interactive lectures aim to engage students via a range of case studies and class debates. In small groups, the student is charged with the responsibility of creating new green routes and procedures to transform current unsustainable practices that use traditional chemicals and syntheses. Findings are relayed to the class via an oral presentation.

A systems thinking approach is used here to explore the interdisciplinary connections with other fields of science, engineering, society, and politics. In addition, laboratory courses teach practical experimental skills in GSC to synthesize chemicals and materials. The program features fewer recipe-style experiments and more open-ended, inquiry-oriented miniprojects, giving students the freedom to design their own experiments and enhance their problem-solving skills. These laboratories are run in a >$50 million Green Chemical Futures building.[82]

In the fourth year undergraduate course (an honors course), a new Green Chemistry module covers more advanced topics in green chemistry (e.g., feedstocks and cradle to cradle design). A master's course in GSC is currently under development for introduction in the near future. This will cover not only Chemistry topics but also other topics, such as Innovation in the Chemical Industry, Manufacturing through Green Chemistry, and Entrepreneurship/Commercialization—Green Chemistry in Industry. This will also involve a research project (or internship) component that will be focused on GSC-related research.

CONCLUSIONS

GSC education via systems thinking is being implemented across the globe in widely varying forms. Science research and education are focusing more on each system as a whole and not just as a collection of parts. The interactions between a system and its environment (including the human components) are more routinely being emphasized.[83] Embracing the inclusion of economic, environmental, political, and social aspects as fundamental issues in formerly merely technical or scientific discussions is also becoming common; it is enlightening to note that these discussions are leading to more collaboration, democratic participation, and ethical action.[83] Educational interventions that facilitate systems thinking approaches are well suited to address such interconnected and interdisciplinary issues and are hence aligned with meeting the UN SDGs, propelling us to advance toward a more sustainable society. Laboratory components, training sessions, written materials, discussion meetings, and conferences are also becoming more and more common in many places. Because higher education is an important instrument for solving many systemic problems, the creation of the institutional consortia described herein constitutes in itself a move toward systems thinking. However, the degree of development of the different regions and their political decisions appear to be of paramount importance for the implementation of these systemic actions. It is noteworthy that Europe has stronger cooperation ties, and therefore, these approaches are becoming more homogeneous on this continent, along with the incorporation of sustainability throughout undergraduate curricula. Further cooperation is required to propagate the STICE approach elsewhere. Additional aspects that need further development include analysis of how a system's behavior changes over time, the

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

realization that variables that cause a specific behavior in a system are not variables that are correlated with its final behavior, and the study of how the organization and interrelationships among different parts of a system may result in unique emergent properties at the system level.[83]

AUTHOR INFORMATION

Corresponding Author

*E-mail: jorge.ibanez@ibero.mx.

ORCID

Glenn A. Hurst: 0000-0002-0786-312X
J. Chris Slootweg: 0000-0001-7818-7766
Rafael Luque: 0000-0003-4190-1916
Liliana Mammino: 0000-0002-3424-1975
Rolando A. Spanevello: 0000-0003-3701-5807
Kei Saito: 0000-0002-5726-8775
Jorge G. Ibanez: 0000-0003-3247-6751

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We acknowledge the leadership of Peter G. Mahaffy (Kings University, Edmonton, U.K.) and Stephen A. Matlin (Imperial College, London, U.K.) of the IUPAC-STICE project (Systems Thinking in Chemical Education). A.M.B. is grateful to SEPA and NANOVAL members at Universidad de Cordoba for fruitful discussions. P.G. acknowledges CONACYT-Mexico for a 3 year fellowship (#709621). A.G. acknowledges support by the EDINSOST Project.

REFERENCES

(1) (a) Mahaffy, P. G.; Krief, A.; Hopf, H.; Mehta, G.; Matlin, S. A. Reorienting Chemistry Education Through Systems Thinking. *Nature Rev. Chem.* **2018**, *2*, 0126. (b) Mahaffy, P. G.; Matlin, S. A.; Holme, T. A.; MacKellar, J. Systems Thinking for Education about the Molecular Basis of Sustainability. *Nature Sustainability* **2019**, *2*, 362−370.

(2) (a) European Higher Education Area. http://ehea.info/ (accessed Oct 11, 2019). (b) *The Bologna Declaration of 19 June 1999*; Joint Declaration of the European Ministries of Education; *The European Higher Education Area*, 1999. https://www.eurashe.eu/library/modernising-phe/Bologna_1999_Bologna-Declaration.pdf (accessed Oct 11, 2019).

(3) Agenda 21. *UN Department for Economic and Social Affairs, Division for Sustainable Development*. http://www.un.org/esa/dsd/agenda21_spanish/ (accessed Oct 11, 2019).

(4) *European Cultural Convention*; European Treaty Series No. 18; Council of Europe, 1954. https://rm.coe.int/168006457e (accessed Oct 11, 2019).

(5) *COPERNICUS Guidelines for Sustainable Development in the European Higher Education Area: How to incorporate the principles of sustainable development into the Bologna Process*; COPERNICUS-CAMPUS, 2006. http://www.ehea.info/media.ehea.info/file/COPERNICUS_Olderburg_2006/92/6/COPERNICUSGuidelines_587926.pdf (accessed Oct 11, 2019).

(6) *United Nations Decade of Education for Sustainable Development (2005−2014): International Implementation Scheme*; Document code ED/DESD/2005/PI/01; UNESCO, 2005. https://unesdoc.unesco.org/ark:/48223/pf0000148654 (accessed Oct 11, 2019).

(7) Summerton, L.; Hunt, A. J.; Clark, J. H. Green Chemistry for Postgraduates. *Educ. Quim.* **2013**, *24*, 150−155.

(8) Clark, J. H.; Jones, L.; Summerton, L. Green Chemistry and Sustainable Industrial Technology—Over 10 Years of an MSc Programme. In *Worldwide Trends in Green Chemistry Education*; Zuin, V. G., Mammino, L., Eds.; Royal Society of Chemistry: Cambridge, 2015; pp 157−178.

(9) Academic Programs in Green Chemistry. *American Chemical Society*. https://www.acs.org/content/acs/en/greenchemistry/students-educators/academicprograms.html (accessed Oct 11, 2019).

(10) Robinson, J. The York Pedagogy: What and Why, How and Why. *University of York Teaching and Learning Magazine*, 2015, pp 1−16. https://www.york.ac.uk/media/staffhome/learningandteaching/documents/propel/28280-Forum%20issue%20supplement%20LR%20final.pdf (accessed Oct 11, 2019).

(11) Geissdoerfer, M.; Savaget, P.; Bocken, N. M. P.; Hultink, E. J. The Circular Economy − A New Sustainability Paradigm? *J. Cleaner Prod.* **2017**, *143*, 757−768.

(12) CHEM21 Online Learning Platform. http://learning.chem21.eu (accessed Oct 11, 2019).

(13) Summerton, L.; Taylor, R. J.; Clark, J. H. Promoting the Uptake of Green and Sustainable Methodologies in Pharmaceutical Synthesis: CHEM21 Education and Training Initiatives. *Sustainable Chem. Pharm.* **2016**, *4*, 67−76.

(14) Healey, M.; Flint, A.; Harrington, K. Students as Partners: Reflections on a Conceptual Model. *Teach. Learn. Inquiry* **2016**, *4*, 1−13.

(15) *Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*; American Chemical Society: Washington, DC, 2015. https://www.acs.org/content/dam/acsorg/about/governance/committees/training/2015-acs-guidelines-for-bachelors-degree-programs.pdf (accessed Oct 11, 2019).

(16) Hurst, G. A.; Bella, M.; Salzmann, C. G. The Rheological Properties of Poly(vinyl alcohol) Gels from Rotational Viscometry. *J. Chem. Educ.* **2015**, *92* (5), 940−945.

(17) Garrett, B.; Matharu, A. S.; Hurst, G. A. Using Greener Gels to Explore Rheology. *J. Chem. Educ.* **2017**, *94* (4), 500−504.

(18) Mackenzie, L. S.; Tyrrell, H.; Thomas, R.; Matharu, A. S.; Clark, J. H.; Hurst, G. A. Valorization of Waste Orange Peel to Produce Shear Thinning Gels. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.8b01009.

(19) Making Plastic from Potato Starch, 2015. *Nuffield Foundation and the Royal Society of Chemistry*. http://www.rsc.org/learn-chemistry/resource/res00001741/making-plastic-from-potato-starch (accessed Oct 11, 2019).

(20) Hurst, G. A. Green and Smart: Hydrogels to Facilitate Independent Practical Learning. *J. Chem. Educ.* **2017**, *94* (11), 1766−1771.

(21) Summerton, L.; Hurst, G. A.; Clark, J. H. Facilitating Active Learning in Green Chemistry. *Curr. Opin. Green Sustain. Chem.* **2018**, *13*, 56−60.

(22) Schelland, J.; Mazur, E. Flipping the Chemistry Classroom with Peer Instruction. In *Chemistry Education: Best Practices, Opportunities and Trends*, 1st ed.; García-Martínez, J., Serrano-Torregrosa, E., Eds.; Wiley-VCH Verlag: Weinheim, 2015; pp 319−343.

(23) Marteel-Parrish, A. E.; Abraham, M. A. Principles of Green Chemistry and Green Engineering. In *Green Chemistry and Engineering: A Pathway to Sustainability*; Marteel-Parrish, A. E., Abraham, M. A., Eds.; American Institute of Chemical Engineers, Wiley: New York, 2013; pp 21−42.

(24) Constable, D. J. C.; Jiménez-González, C. Evaluating the Greenness of Synthesis. In *Handbook of Green Chemistry: Green Synthesis*, 1st ed.; Li, C.-J., Ed.; Wiley-VCH Verlag: Weinheim, 2012; Vol. 7, pp 35−67.

(25) Behr, A.; Johnen, L. Alternative Feedstocks for Synthesis. In *Handbook of Green Chemistry: Green Synthesis*, 1st ed.; Li, C.-J., Ed.; Wiley-VCH Verlag: Weinheim, 2012; Vol. 7, pp 69−92.

(26) Freund, E. A New Process for the Production of Biodiesel by Transesterification of Vegetable Oils with Heterogeneous Catalysis. In *Sustainable Industrial Processes*; Cavani, F., Centi, G., Perathoner, S., Trifiró, F., Eds.; Wiley-VCH Verlag: Weinheim, 2009; pp 439−448.

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

(27) Centi, G.; Perathoner, S. Perspectives and State of the Art in Producing Solar Fuels and Chemicals From CO_2. In *Green Carbon Dioxide: Advances in CO_2 Utilization*, 1st ed.; Cavani, F., Centi, G., Perathoner, S., Trifiró, F., Eds.; Wiley: New York, 2014; pp 1−24.

(28) Marteel-Parrish, A. E.; Abraham, M. A. Renewable Materials. In *Green Chemistry and Engineering: A Pathway to Sustainability*; Marteel-Parrish, A. E., Abraham, M. A., Eds.; American Institute of Chemical Engineers, Wiley: New York, 2013; pp 235−262.

(29) Meyer, D. E.; Gonzalez, M. A. The Economics of Green and Sustainable Chemistry. In *Green Chemistry and Engineering: A Pathway to Sustainability*; Marteel-Parrish, A. E., Abraham, M. A., Eds.; American Institute of Chemical Engineers, Wiley: New York, 2013; pp 287−323.

(30) (a) Moser, F.; Jakl, T. Chemical Leasing—A Review of Implementation in the Past Decade. *Environ. Sci. Pollut. Res.* **2015**, *22*, 6325−6348. (b) Sustainable Chemicals Service Solutions. *Chemical Leasing*. http://chemicalleasing.org/sites/default/files/20_CHEMICAL_LEASING_Basics.pdf (accessed Oct 11, 2019).

(31) Sörensen, K.; Vanovermeire, C. Sustainable Chemical Logistics. In *Management Principles of Sustainable Industrial Chemistry: Theories, Concepts and Industrial Examples for Achieving Sustainable Chemical Products and Processes from a Non-Technological Viewpoint*, 1st ed.; Reniers, G. L. L., Sörensen, K., Vrancken, K., Eds.; Wiley-VCH Verlag: Weinheim, 2013; pp 163−180.

(32) Loorbach, D. A. A Transition Perspective on Sustainable Chemistry: The Need for Smart Governance? In *Management Principles of Sustainable Industrial Chemistry: Theories, Concepts and Industrial Examples for Achieving Sustainable Chemical Products and Processes from a Non-Technological Viewpoint*, 1st ed.; Reniers, G. L. L., Sörensen, K., Vrancken, K., Eds.; Wiley-VCH Verlag: Weinheim, 2013; pp 217−232.

(33) Vrancken, K.; Nevens, F. From Industrial to Sustainable Chemistry, a Policy Perspective. In *Management Principles of Sustainable Industrial Chemistry: Theories, Concepts and Industrial Examples for Achieving Sustainable Chemical Products and Processes from a Non-Technological Viewpoint*, 1st ed.; Reniers, G. L. L., Sörensen, K., Vrancken, K., Eds.; Wiley-VCH Verlag: Weinheim, 2013; pp 21−32.

(34) Maas, S.; Reniers, G. L. L.; De Prins, M. Building Corporate Social Responsibility—Developing a Sustainability Management System Framework. In *Management Principles of Sustainable Industrial Chemistry: Theories, Concepts and Industrial Examples for Achieving Sustainable Chemical Products and Processes from a Non-Technological Viewpoint*, 1st ed.; Reniers, G. L. L., Sörensen, K., Vrancken, K., Eds.; Wiley-VCH Verlag: Weinheim, 2013; pp 45−53.

(35) Stahel, W. R. Circular Economy. *Nature* **2016**, *531*, 435−438.

(36) Keijer, T.; Bakker, V.; Slootweg, J. C. Circular Chemistry to Enable a Circular Economy. *Nat. Chem.* **2019**, *11*, 190−195.

(37) The 2030 Agenda for Sustainable Development. *United Nations*. https://sustainabledevelopment.un.org (accessed Oct 11, 2019).

(38) *Guidelines for the Inclusion of Sustainability in the Curriculum*; Association of Spanish University Rectors (CRUE), 2012. http://www.crue.org/Documentos%20compartidos/Declaraciones/Directrices_Ingles_Sostenibilidad_Crue2012.pdf (accessed Oct 11, 2019).

(39) Programa Trébol. *Universidad de Córdoba*. http://www.uco.es/servicios/sepa/es/programa-trebol (accessed Oct 11, 2019).

(40) Sánchez, C. F.; Segalas, J.; Vidal, E.; Martin, C.; Climent, J.; López, D.; Cabré, J. Improving Engineering Educators Sustainability Competencies by using Competency Maps. The EDINSOST Project. *Int. J. Eng. Educ.* **2018**, *34* (5), 1527−1537.

(41) Recursos Naturales y Gestión Sostenible. *Universidad de Córdoba*. https://www.uco.es/estudios/idep/doctorado-programas-recursos-naturales-y-gestion-sostenible (accessed Oct 11, 2019).

(42) University Research Institute for Sustainability Science and Technology Natural Resources and Sustainable Management. *Universidad de Córdoba*. https://is.upc.edu/en/teaching/phd-sustainability (accessed Oct 11, 2019).

(43) *BFUG Work Plan 2018−2020*; Swiss Federal Minitry of Education, Science, and Research, 2018. http://www.ehea.info/Upload/BFUG_AU_CH_63_7_Work_Plan.pdf (accessed Oct 11, 2019).

(44) Sostenibilización Curricular. *Universidad de Córdoba*. https://www.uco.es/aulasostenibilidad/Sostenibilizacion_Curricular/index.html (accessed Oct 11, 2019).

(45) (a) The University of Warsaw Launches new Master in Sustainable Development, 2019. *Alliance Copernicus*. https://www.copernicus-alliance.org/news-archive/233-university-of-warsaw-launches-new-master-in-sustainable-development (accessed Oct 11, 2019). (b) 6th International Environmental Best Practices Conference. *International Union of Pure and Applied Chemistry*. https://iupac.org/event/6th-international-environmental-best-practices-conference/ (accesed Oct 11, 2019).

(46) (a) International Sustainable Chemistry Collaborative Centre (ISC3) Homepage. https://www.isc3.org/en/home.html (accesed Oct 11, 2019). (b) 4th Green & Sustainable Chemistry Conference. *Elsevier*. https://elsevierfoundation.org/partnerships/research-in-developing-countries/greenchem/2019-elsevier-foundation-green-sustainable-chemistry-challenge-top-5/ (accessed Oct 11, 2019).

(47) McKeown, R.; Hopkins, C. EE Does not Equal ESD: Defusing the Worry. *Environ. Educ. Res.* **2003**, *9* (1), 117−128.

(48) Edwards, M. The Attention Paid by Science Education to the State of the World. Ph.D. Thesis, University of Valencia, Valencia, Spain, 2003.

(49) Gil-Pérez, D.; Vilches, A.; Edwards, M.; Praia, J.; Marques, L.; Oliveira, T. A Proposal to Enrich Teachers' Perception of the State of the World: First Results. *Environ. Educ. Res.* **2003**, *9* (1), 67−90.

(50) Edwards, M.; Álvarez-Sánchez, D.; Sánchez-Ruiz, L. M. Engineering Education and Competences for Sustainability Education in Spain. *Proceedings of the International Conference on Engineering Education (ICEE)*, Coimbra, Portugal, Sept 3−7, 2007.

(51) Soledad-Rodríguez, B. Teaching Sustainable Chemistry in Engineering Careers (in Spanish). *Rev. Quim.* **2018**, *32* (1), 12−17. http://revistas.pucp.edu.pe/index.php/quimica/article/view/19578 (accessed Oct 23, 2019).

(52) Panizzolo, L., Pistón, M., Terán, M., Torre, M. H., Eds. *Contributions of Chemistry to the Improvement of the Quality of Life*; UNESCO: Montevideo, 2012.

(53) Acevedo, J.; Vázquez, A.; Manassero, M. The Role of CTS Education in a Scientific and Technological Education for All (in Spanish). *Rev. Electron. Ens. Cienc. (REEC, Spain)* **2003**, *2* (2), 80−111. http://reec.uvigo.es/volumenes/volumen2/REEC_2_2_1.pdf (accessed Oct 11, 2019).

(54) Gil, D.; Macedo, B.; Martínez-Torregosa, J.; Sifredo, C.; Valdez, P.; Vilches, A. *How to Promote Interest in the Scientific Culture?*; UNESCO: Santiago, Chile, 2005.

(55) Gallego-Torres, A. P.; Gallego-Badillo, R. On the Technological Character of the New Didactics of Science (in Spanish). *Rev. Electron. Ens. Cienc. (REEC, Spain)* **2006**, *5* (1), 99−113. http://reec.uvigo.es/volumenes/volumen5/ART6_Vol5_N1.pdf (accessed Oct 11, 2019).

(56) Sanmartí, N. *Didactics of the Sciences in the Compulsory Secondary School Program*; Síntesis Educación, 2002.

(57) Ros-Clavell, I. Simulations and Role Playing as Strategies to Communicate Science: APQUA Project. In *Pinto Cañón: Didactics of Chemistry and Everyday Life*; Universidad Politécnica de Madrid, 2003; pp 233−238.

(58) Zuin, V. G. *Environmental Dimension in Chemistry Teacher Education*; Átomo: Campinas, 2012.

(59) Trigo, E. J.; Henry, G.; Sanders, J.; Schurr, U.; Ingelbrecht, I.; Revel, C.; Santana, C.; Rocha, P. Towards Bioeconomy Development in Latin America and the Caribbean. In *Towards a Latin America and Caribbean Knowledge Based Bio-Economy in Partnership with Europe*; Hodson de Jaramillo, E., Ed.; Pontificia Universidad Javeriana: Bogotá, 2014; pp 15−41.

(60) *Converting Waste Agricultural Biomass into a Resource: Compendium of Technologies*; United Nations Environment Programme, 2009. http://wedocs.unep.org/bitstream/handle/20.500.

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804

11822/7614/WasteAgriculturalBiomassEST_Compendium.pdf?sequence=3&isAllowed=y (accessed Oct 11, 2019).

(61) Corne, V.; Botta, M. C.; Giordano, E. D. V.; Giri, G. F.; Llompart, D. F.; Biava, H. D.; Sarotti, A. M.; Mangione, M. I.; Mata, E. G.; Suárez, A. G.; Spanevello, R. A. Cellulose Recycling as a Source of Raw Chirality. *Pure Appl. Chem.* **2013**, *85*, 1683−1692.

(62) Trautmann, M.; Löwe, A.; Traa, Y. An Alternative Method for the Production of Second-Generation Biofuels. *Green Chem.* **2014**, *16*, 3710−3714.

(63) Comba, M. B.; Tsai, Y.-H.; Sarotti, A. M.; Mangione, M. I.; Suárez, A. G.; Spanevello, R. A. Levoglucosenone and its New Applications: Valorization of Cellulose Residues. *Eur. J. Org. Chem.* **2018**, *2018*, 590−604.

(64) Tundo, P.; Rossi, R. H.; Romero, R. M. *Green Chemistry in Latin America*; Project Number 2002-064-1-300; IUPAC, 2004. https://old.iupac.org/projects/2002/2002-064-1-300.html (accessed Oct 11, 2019).

(65) Seidl, P. R.; Freire, E.; Borschiver, S.; Leite, L. F. Introducing Green Chemistry into Graduate Courses at the Brazilian Green Chemistry School. In *Worldwide Trends in Green Chemistry Education*; Zuin, V., Mammino, L., Eds.; Royal Society of Chemistry: London, 2015; pp 266−277.

(66) Zuin, V.; Anastas, P.; Mammino, L. Integrating Green Chemistry and Socio-sustainability in Higher Education: Successful Experiences Contributing to Transform our World. *Chem. Int.* **2017**, 21−24.

(67) Zuin-Gomes, V.; Marques, C. A. Green Chemistry Education in Brazil: Contemporary Tendencies and Reflections at Secondary School Level. In *Worldwide Trends in Green Chemistry Education*; Zuin, V., Mammino, L., Eds.; Royal Society of Chemistry: London, 2015; pp 76−92.

(68) Correa, A. G.; Zuin, V. G.; Ferreira, V. F.; Vazquez, P. G. Green Chemistry in Brazil. *Pure Appl. Chem.* **2013**, *85* (8), 1643−1653.

(69) Suárez, A. G. Education and Engagement: Key Elements to Achieve and Maintain a World Free of Chemical Weapons. *Pure Appl. Chem.* **2017**, *89*, 197−204.

(70) ACS/FLAQ Alliance. *American Chemical Society*. https://www.acs.org/content/acs/en/global/international/alliances/FLAQAlliance.html (accessed Oct 11, 2019).

(71) Anastas, P. T., Levy, I. J., Parent, K. E., Eds. *Green Chemistry Education*; ACS Symposium Series *1011*; American Chemical Society: Washington, DC, 2009. https://pubs.acs.org/isbn/9780841274471 (accessed Oct 11, 2019).

(72) Fellet, M. *Green Chemistry and Engineering: Towards a Sustainable Future*; American Chemical Society: Washington, DC, 2013.https://www.acs.org/content/dam/acsorg/membership/acs/benefits/extra-insights/green-chemistry.pdf (accessed Oct 11, 2019).

(73) Latin America and the Caribbean OPCW Member States Review Initiatives in Green Chemistry, 2018. *OPCW*. https://www.opcw.org/media-centre/news/2018/01/latin-america-and-caribbean-opcw-member-states-review-initiatives-green (accessed Oct 11, 2019).

(74) United Nations Decade of Education for Sustainable Development. *UNESCO*. https://en.unesco.org/themes/education-sustainable-development/what-is-esd/un-decade-of-esd (accessed Oct 11, 2019).

(75) Saqueto, K. C.; Zuin, V. G. Presented at the 4th International IUPAC Conference on Green Chemistry, Foz do Iguaçu, Brazil, Aug 25−29, 2012.

(76) Zuin, V., Mammino, L., Eds. *Worldwide Trends in Green Chemistry Education*; Royal Society of Chemistry: London, 2015.

(77) Machado, A. A. S. C. Holistic Green Chemistry Metrics for Use in Teaching Laboratories. In *Worldwide Trends in Green Chemistry Education*; Zuin, V., Mammino, L., Eds.; The Royal Society of Chemistry: London, 2015; pp 111−136.

(78) Spanevello, R. A. Dual Use of Scientific Knowledge and the Weapons of Mass Destruction. *Proceedings of the Academic Forum of the Organisation for the Prohibiton of Chemical Weapons*, The Hague, The Netherlands, Sept 18−19, 2007; Trapp, R., Ed.; Netherlands Institute of International Relations Clingendael, 2007; pp 139−144.

(79) Spanevello, R. A.; Suárez, A. G. Education and Outreach: Key Elements to Promote the Responsible and Peaceful Uses of Chemistry. In *Responsible Conduct in Chemistry Research and Practice: Global Perspectives*; Tratras-Contis, E., Phillips, D. J., Campbell, A. A., Miller, B. D., Brown, L., Eds.; ACS Symposium Series *1288*; American Chemical Society: Washington, DC, 2018; pp 69−81.

(80) *IUPAC Summer School on Green Chemistry 2019*. https://iupac.org/event/iupac-for-africa-postgraduate-summer-school-on-green-chemistry/ (accessed Oct 11, 2019).

(81) Mammino, L., Ed. *Biomass Burning in Sub-Saharan Africa: Chemical Issues and Action Outreach*; Springer: New York, 2019.

(82) Green Chemical Futures. *Monash University*. https://www.monash.edu/green-chemical-futures (accessed Oct 11, 2019).

(83) Orgill, M. K.; York, S.; MacKellar, J. Introduction to Systems Thinking for the Chemistry Education Community. *J. Chem. Educ.* **2019**, DOI: 10.1021/acs.jchemed.9b00169.

DOI: 10.1021/acs.jchemed.9b00341
J. Chem. Educ. 2019, 96, 2794−2804