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Industry-Informed Workshops to Develop Graduate Skill Sets in the Circular Economy Using Systems Thinking

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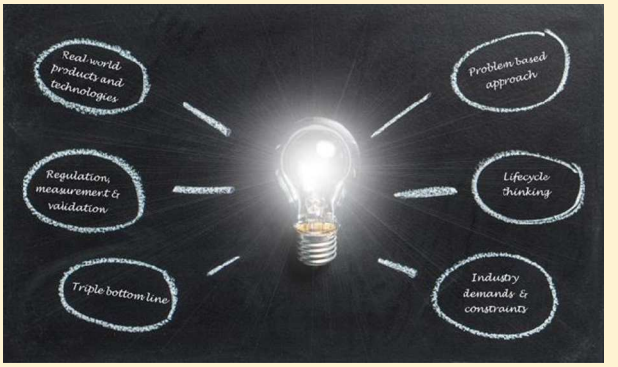
Supporting Information

ABSTRACT: Increasing demand for chemicals worldwide, depleting resources, consumer pressure, stricter legislation, and the rising cost of waste disposal are placing increasing pressure on chemical and related industries. For any organization to survive in the current arena of growing climate change laws and regulations, and increasing public influence, the issue of sustainability must be fundamental to the way it operates. A sustainable manufacturing approach will enable economic growth to be combined with environmental and social sustainability and will be realized via collaboration between a multidisciplinary community including chemists, biologists, engineers, environmental scientists, economists, experts in management, and policy makers. Hence, employees with new skills, knowledge, and experience are essential. To realize this approach, the design and development of a series of workshops encompassing systems thinking are presented here. After close consultation with industry, an annual program of interactive workshops has been designed for graduate students to go beyond examining the "greening" of chemical reactions, processes, and products, and instead embed a systems thinking approach to learning. The workshops provide a valuable insight into the issues surrounding sustainable manufacturing covering change management, commercialization, environmental impact, circular economy, legislation, and bioresources incorporating the conversion of waste into valuable products. The multidisciplinary course content incorporates industrial case studies, providing access to real business issues, and is delivered by experts from academic departments across campus and industry.



KEYWORDS: *Graduate Education/Research, Interdisciplinary/Multidisciplinary, Green Chemistry, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Applications of Chemistry, Industrial Chemistry, Systems Thinking, Sustainability*

INTRODUCTION

The RenewChem graduate training program was created to enhance the training provided to green chemistry doctoral students at the Green Chemistry Centre of Excellence (GCCE) at the University of York. By adopting a systems

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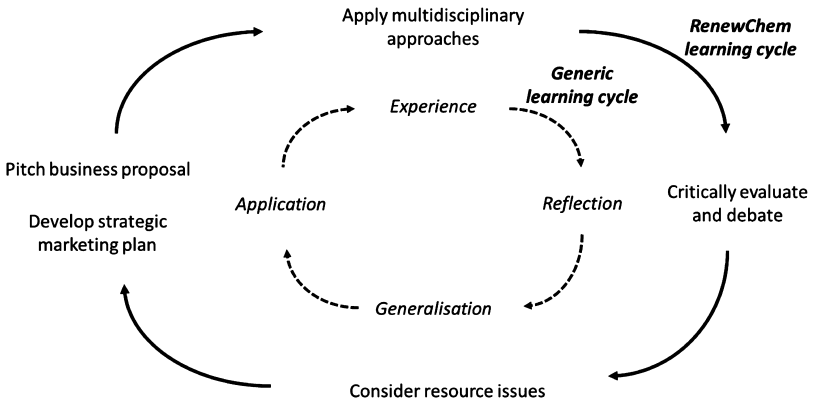

Figure 1. RenewChem key learning objectives inspired by the Kolb learning cycle.

thinking approach within a new annual workshop series, the GCCE is able to offer its students a more holistic, and multidisciplinary, approach to their training. Systems thinking is the ability to analyze and optimize complex and interlinked systems while understanding how one action can result in multiple changes over time. Systems thinking encompasses understanding of the interdependence of the components of systems at work and facilitates a greater, more integrated understanding of related subject matter as opposed to teaching disparate concepts.[1] Systems thinking improves student learning by promoting the consideration of a wide range of impacts, both positive and negative, within the framework of multiple interacting systems.[2] It also allows them to make predictions based on their understanding as to how system outputs may change, based upon variation of an input or parameter. Utilizing a systems thinking approach creates the opportunity for students to apply the knowledge they have acquired throughout their education in a real world or business context, during the workshops. This broader perspective prepares students more thoroughly for their future career paths and supports the move to a sustainable and circular chemical economy through promotion of a changed mind-set that embeds systems thinking at its core.[3]

BACKGROUND TO THE PROGRAM

During an industry focused event on "Green Careers", organized by the GCCE in 2015, industrialists highlighted the need for changes to current graduate training. Industrialists felt that, while the chemistry knowledge of most graduates was excellent, development of additional skills, knowledge, and experience would be vital for future employees to make an impact within sustainable manufacturing. The key areas identified were the following:

- Circular economy
  - This is an economy whereby items at the end of life are returned to the production process through some form of reuse or recycling, thus becoming feedstocks as opposed to the linear economy which operates along a feedstock to product to waste approach.
- Resource issues
- Regulation
- Triple bottom line
  - This is a company's performance with regard to financial, social, and environmental markers as opposed to the standard model which only considers profit and loss.
- Life cycle thinking (upstream and downstream)
  - This is a combination of circular economy and triple bottom line whereby the financial, social, and environmental impacts of each step of an item's life cycle from extraction through to end of life are considered, as well as how best to minimize such aspects by transitioning from a linear to a circular model.
- Measurement/validation
- Case studies—real world products and technologies
- End-of-life issues
- Industry's drivers and constraints
- Analysis—problem-based/logic approach
- Ability to work in/lead teams
- Enhanced communication skills

These views were supported by Voorhees and Hutchison[4] who stated "industrial employees are looking to hire students with expertise in sustainable processes and an understanding of systems thinking and life cycle".

In 2016, the GCCE established the RenewChem initiative as a noncompetitive industry club with the aim of steering the transition to green manufacturing and a circular economy within the chemical industries. The core foci of this initiative are cutting-edge research, education, and training. The main ethos behind the training was that students should gain exposure to a much broader range of influences and inputs outside of those found in traditional chemistry doctoral research. The aim of this was to elicit a broader understanding of the interaction between factors affecting the transition to a circular and sustainable economy, rather than solely focusing on research into a niche area of chemistry in isolation. Subsequently, an outline for a new series of interactive workshops was devised around the theme of "Sustainable Manufacturing for the Chemical Industry", using the information gained from the industry think tank exercise and in consultation with RenewChem industry club members. The following key learning objectives for the training were established to enhance the requisite skills and experience of the students.

- Apply multidisciplinary approaches to the creative problem solving of challenges within green chemistry considering industry demands and constraints as part of a dynamic global system.

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- Develop and present a strategic marketing plan for a green chemistry product to peers demonstrating commercial awareness and an appreciation for regulation issues. Pitch a business proposal to establish a sustainable chemical company following analysis and evaluation of real data for projected costs, feedstocks, processes, product streams, and revenues, and deciding optimal system parameters for a viable business.
- Consider resource issues and life cycle assessment outputs to rationally design and make a chemical product.
- Critically evaluate and debate case studies as part of a multidisciplinary team to develop an appreciation for the bioeconomy and circular economy.

The Kolb experiential learning cycle[5] is illustrated in the inner cycle in Figure 1. The learning objectives shown in the outer circular cycle align to Kolb's stages to provide an iterative cycle of learning through the course content. The consideration of resources and LCA outputs provides abstract concepts on which to base further experiences through generalization. Students can then move to application to test out the concepts through developing strategic marketing plans and pitching the analysis as a business proposal. Such concrete experiences are achieved through students applying a multidisciplinary approach to their learning. This allows the students time for reflection through critical evaluation and debate. The cycle can then repeat by providing further abstract concepts. For example, in pitching a business proposal, the students draw on the general theories presented and apply them to a new situation that they are not familiar with. This application draws them into the subtleties of the concepts and provides experience for them to reflect on. The other learning objectives have similar linkages around the cycle. Thus, the learning objectives are aligned with an accepted experiential learning cycle to guide the learning pathway for the students in a structured way.

INCORPORATING SYSTEMS THINKING INTO GREEN CHEMISTRY TRAINING

Green chemistry is defined by the United States Environmental Protection Agency as "...the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal."[6] Green chemistry inherently requires a systems thinking approach to make genuine improvements to the environmental, social, and economic performance of a product and its life cycle. Systems thinking in green chemistry requires consideration of the "bigger picture", i.e., looking beyond a reaction step or process in isolation. This includes examining the upstream reactions required for the production of a chemical, what happens during their use, and their end-of-life fate. Further factors include consideration of metrics in addition to those based on masses and efficiency to examine factors such as renewability, toxicity, and elemental sustainability, among others.[7] The authors of this paper also support the opinion that systems thinking within green chemistry should also encompass wider, multidisciplinary viewpoints. This comprises industrial/business perspectives as well as those of biologists, engineers, environmental scientists, economists, management experts, and policy makers in order to understand the interaction of green chemistry with other disciplines. This opinion is shared with S. A. Matlin et al.[1] who believe that the future teaching of chemistry should incorporate consideration of its "external orientation, connections and engagements with a host of different disciplines and the world at large". To incorporate these ideas, it was vital that these aspects were drawn together to create the RenewChem graduate training program. To make a change in the future toward a more sustainable and circular chemical industry, students ultimately need to learn from and interact with other academic disciplines and with industry, thus promoting a shift from the perspective that chemistry alone can solve the world's problems.[8]

THE RENEWCHEM GRADUATE TRAINING PROGRAM

To deliver a method to address the needs highlighted above according to the outlined learning objectives, an annual series of graduate workshops, covering a range of multidisciplinary and multisector viewpoints, was devised by the GCCE with the theme of Sustainable Manufacturing for the Chemical Industry. Contributions to the training came from academics at the University of York from the Department of Chemistry, the Department of Biology, the Department of Environment & Geography, and the York Management School, in combination with key industrial collaborators from a broad range of sectors and including Croda, Merck KGaA, GlaxoSmithKline, and Brocklesby Ltd. Through the RenewChem initiative, the GCCE recruited a new cohort of doctoral students sponsored by industry club members, for which this training was compulsory. In addition the workshop series was advertised campus-wide via an event management Web site, with free and open access (limited to 30 spaces) for any staff and postgraduate students to attend if they wished.

Workshop Design

Workshops were pitched at a level that is understandable to a general scientific audience, without going into too much detail in terms of the specific underlying chemistry. The intention is that the workshops introduce the students to a new topic and/or a new perspective to which they can apply their existing knowledge via the use of real world case studies. Utilizing case studies has the advantage of fostering the deployment of higher order reasoning to connect concepts and apply the knowledge gained to new contexts.[9] Students are challenged to think more widely in terms of additional factors that influence the scenario from the perspective of other disciplines. This wider thinking then enhances their broader understanding of additional important considerations within green chemistry, particularly in a real world setting, such as the business case for being green; meeting customer requirements while balancing performance, environmental impact, and cost; and marketing a green chemical. As well as embedding a systems thinking approach, the workshops are also based on collaborative and inquiry-based learning approaches in order to improve vital skills such as working in teams, problem solving, and critical thinking. This parallel combination of systems thinking and active learning approaches also ensures a deeper engagement with the course material. Through the requirement that students critically analyze and evaluate information, they are actively participating in the learning process resulting in a deeper understanding of subject matter.[10,11] Additionally, in order to ensure maximum take up by postgraduate students outside of the RenewChem program, the workshops were

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designed to be entirely self-contained, requiring no pre- or postwork. Attendance at the workshop series also counts toward the graduate training program requirement for all research students.

Workshop Content

The RenewChem graduate training program is currently in its third year and has covered a broad range of areas to date including the marketing of chemicals, environmental remediation of land, indoor air quality, formulations, biodiesel manufacture, waste biorefining, and the business case for becoming greener. For each of the workshops, staff within the GCCE work closely with the workshop facilitator to agree on the learning aim and content, as well as to aid the delivery of the workshops themselves. An overview of the workshops is summarized in Table 1. The workshops are highly interactive, typically involving a presentation from the facilitator for 30 and 90 min of group work, with opportunities for a significant amount of discussion and debate.

The “What is Green Chemistry?” workshop, facilitated by Dr. Helen Sneddon of GSK, aims to provide an introduction to modern day drivers and challenges for sustainable manufacturing with a number of recent case studies from within the pharmaceutical industry. Workshop participants review and analyze the 12 Principles of Green Chemistry,[12] and how some protocols do and do not meet these criteria. Participants then go on to explore solvents and reagents, the tools and guides that can be used in their selection,[13−19] and the uses of metrics.[20−23] In groups of 3−4, participants analyze some examples of literature research claiming to be green using the methods they have been equipped with during the workshop and discuss whether they believe them to be genuinely green. They also use the same approach to make decisions about a pharmaceutical case study, considering the advantages and disadvantages of two different systems and taking into account the control of product quality; solvent environment, health, and safety (EHS) issues; potential processing issues and throughput; waste disposal; cost; and solvent life cycle. The connection with systems thinking here is, for example, changing something as simple as the solvent employed has many secondary effects with regard to workup, disposal, cleaning, and regulation.

The aim of the “Green Chemistry Marketing to the Global Research Community” workshop is for participants to develop and present a strategic marketing plan for a green chemistry product to peers demonstrating commercial awareness and an appreciation for regulation issues. During this workshop, Dr. Jane Murray and Jeffrey Whitford of Merck KGaA discuss how the positioning, promotion, and economics of green chemistry products are critical to their successful uptake. The workshop then looks at the promotion of sustainable products through the employment of publications, conferences, and key tools. One example of such a tool is DOZN. This was developed by Merck KGaA as a quantitative green chemical analysis system that enables scientists to easily select the greenest product for their application.[24] Workshop participants plan, in groups of 3−4, the commercialization of a hypothetical green solvent, consider how to position the product in the marketplace, and develop a strategic marketing plan to pitch to the rest of the workshop. Participants then receive feedback on their pitch from both their peers and from Merck KGaA. The link to systems thinking is that researchers do not tend to think of their outputs in terms of the chemical market in general and

Table 1. RenewChem Workshops and Learning Aims

	Workshop Title	Facilitator (Affiliation)	Learning Aim
1	What is Green Chemistry?	Dr. Helen Sneddon (GSK)	Exploration of modern day drivers and challenges for sustainable manufacturing and their application to a pharmaceutical case study.
2	Green Chemistry Marketing to the Global Research Community	Dr. Jane Murray and Jeffrey Whitford (Merck KGaA)	Development and presentation of a strategic marketing plan of a green chemistry product to peers demonstrating commercial awareness and an appreciation for regulation issues.
3	Where There's Muck, There's Brass?	Dr. Liz Rylott (Centre for Novel Agricultural Products (CNAP), Department of Biology, University of York)	Critical evaluation and debate in order to develop an appreciation for different systems of cleaning contaminated land in order to return it to use in multiple applications.
4	Safer Chemicals for Healthy Buildings	Dr. Nicola Carslaw (Department of Environment & Geography, University of York)	Assessment of the various factors affecting indoor air quality and the potential for green materials to reduce indoor emissions.
5	Design of a Multiple Criteria Market Specific Formulation	Dr. Julia Creasey (Croda International Plc)	Consideration of resource issues and life cycle assessment outputs to rationally design and make a personal care product.
6	Running a Sustainable Chemical Company	Robert Brocklesby and Brian Dobson (Brocklesby Ltd.)	Pitching a business proposal to establish a sustainable chemical company following analyses and evaluation of real industrial data and deciding upon optimal system parameters for a viable business.
7	Business Case for Green	Prof. Peter Ball (Management School, University of York)	Assessment of environmental challenges for businesses with a different mind-set, viewing them as potential opportunities to add value and diversify.
8	Biorefining Waste	Dr. Joe Ross (Biorenewables Development Centre (BDC) University of York) and Pete Metcalf (Wilson BioChemicals Ltd.)	Exploration of all the factors that influence taking a new technology through to commercial reality and appreciation of the importance of demonstrator scale operations.

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marketing in particular. Being able to do so raises the potential impact of the discovery and thus furthers sustainability as a whole.

Contaminated land can pose significant implications in terms of environmental and health hazards and is very expensive; managing contaminated land in Europe costs an estimated €6.5 billion per year.[25] Dr. Liz Rylott of the Centre for Novel Agricultural Products (CNAP) within the Department of Biology delivered a workshop on the remediation of contaminated land entitled "Where There's Muck, There's Brass? (Remediating, with Added Value, Metal and Organic Wastes from Contaminated Land)". The aim of this workshop is for participants to critically evaluate and debate case studies as part of a team to develop an appreciation for different systems of cleaning land contaminated through anthropogenic activities in order to return it to use in multiple applications. Within this workshop some of the most common and also most difficult to remediate contaminants and pollutants are discussed as well as a range of methodologies for resolution of the issue, with varying levels of sophistication and cost.[26−29] In groups of 3−4, participants then go on to examine and appraise the various approaches, including exciting real world trials[30] and pilot studies.[31] These case studies encompass innovative, green applications for remediating land, while also investigating the generation of multiple revenue streams to enhance the financial viability of such projects. This links to systems thinking by making the students think about the full life cycle of a remediation strategy and how different approaches can best fit different scenarios with their various time lines and impacts.

The "Safer Chemicals for Healthy Buildings" workshop, delivered by Dr. Nicola Carslaw of the Department of Environment & Geography introduces the increasingly important topic of indoor air quality (IAQ). The indoor environment can be subjected to many sources of pollution, both from outdoors when air enters through doors and windows and also from indoor activities such as cleaning and cooking.[32] Recent energy efficiency measures in the building industry in response to climate change have made buildings more airtight. These measures have effectively shifted the balance of human exposure to air pollutants, whereby those generated indoors are now potentially more important than those generated outdoors. Another important issue is the rise in popularity of green building materials.[33] Such materials are green in the sense that they adopt sustainable and/or low energy methods of production, but very little is known about the emissions of air pollutants from these materials and how they affect IAQ. The aim of this workshop is to provide participants with the opportunity to assess the various factors affecting IAQ. The participants use results from an indoor air model to explore differences in IAQ that can arise when a building contains standard versus "green" materials (e.g., carpets, paints, and ceiling materials). Participants also discuss the implications for health, recommendations to improve IAQ in homes and other buildings, and what data is needed to improve future indoor air models. This workshop fits with systems thinking by exploring how a variety of different outside forces/trends, e.g., the 1970s oil crisis, the uptake of DIY, the advent of home 3D printers, the increased popularity of household air fresheners as well as personal care products, and other changes in lifestyle, etc., have inadvertently led to an increase in indoor air pollution while greener building materials produced principally to be more sustainable are helping to reduce it. Here the students get to consider unintended consequences over time through the prism of indoor air quality.

Dr. Julia Creasey and colleagues at Croda International Plc delivered a workshop on "Design of a Multiple Criteria Market Specific Formulation", with the aim of providing participants with experience in considering resource issues and life cycle assessment outputs to rationally design and make a personal care product. The workshop combines a prelaboratory session on developing formulations for personal care products, before participants are challenged to design, produce, and test their own formulations for a moisturizer. The formulation they produce must meet customer demands in terms of environmental impact, cost, and performance. Participants must decide upon the types and amounts of the different components (e.g., emollient, surfactant, etc.) required in order to meet these demands, and then make their formulations in the lab. Students then have the opportunity to revise and refine their choices to select an optimal formulation, providing them with an insight into genuine industry constraints when developing new products. Here systems thinking is encompassed by the problem solving that needs to be applied in order to meet various end user requirements, with the changing of one aspect having secondary effects with others. This workshop has the added complexity of solutions appearing to work on a spreadsheet but not in reality, such as the selection of the minimum number of the cheapest components which meet the other quantitative criteria that may look profitable but is unlikely to give a product with the desired qualitative properties. This then requires yet further holistic thinking and experimental iterations to achieve success.

The aim of the "Running a Sustainable Chemical Company" workshop is to provide participants with the experience of pitching a business proposal to establish a sustainable chemical company following analyses and evaluation of real data of projected costs, feedstocks, processes, product streams, and revenues, deciding on optimal system parameters for a viable business. Participants are provided with an insight into the workings and complexities of running a successful chemical SME (small and medium-sized enterprise with 250 or fewer employees) with a circular economy ethos; Brocklesby's principal business model is to take food waste and separate it into oils, carbohydrates, and proteins which are then used as feedstocks for other processes and products. Groups of 3−4 are tasked with taking real world wastes along with virgin oils and developing an outline business model considering factors such as processing technologies appropriate for their feedstocks, associated start-up costs, and running costs as well as the potential for additional product streams, while considering regulation and other drivers using data based on real industrial examples for the manufacture of biodiesel (available in the Supporting Information). Groups then pitch their business idea to the MD of Brocklesby Ltd., Robert Brocklesby, and receive associated feedback from an industry expert. Here systems thinking is evident in that, at each stage, the choices the teams make have secondary effects in terms of cost, complexity, and revenue streams. The ability to navigate the best path toward viability requires considering multiple drivers and is far from simply selecting the cheapest.

The transition of organizations to greener, more ecoefficient operations offers significant opportunities to reduce cost, increase quality, add more value to customers, and develop

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Table 2. RenewChem Workshops and Key Topics Covered

Key Topic Areas Addressed[a]	Topics by RenewChem Workshop[b]							
	1	2	3	4	5	6	7	8
Life cycle thinking (up- and downstream)	Covered					Covered	Covered	Covered
Industry's drivers and constraints	Covered	Covered			Covered	Covered	Covered	Covered
Case studies: real-world products and technologies	Covered	Covered	Covered	Covered	Covered	Covered	Covered	Covered
Measurement/validation	Covered			Covered	Covered			
Analysis: problem-based/logic approach	Covered	Covered	Covered	Covered	Covered	Covered	Covered	
Teamwork	Covered	Covered	Covered		Covered	Covered	Covered	
Resource issues		Covered			Covered	Covered		Covered
Regulation		Covered	Covered	Covered	Covered	Covered		Covered
Communication and marketing		Covered						
Circular economy			Covered			Covered	Covered	Covered
Triple bottom line			Covered			Covered	Covered	
End-of-life issues			Covered			Covered		Covered

[a]As outlined in Background to the Program section. [b]See Table 1 for workshop titles.

new business streams.[34] As businesses become greener, and ultimately work toward sustainability, opportunities arise to actually benefit the environment rather than minimize our impact on it. The "Business Case for Green" workshop, delivered by Prof. Peter Ball of the Management School at the University of York, presents the case for becoming greener, providing examples and insight into how business leaders are approaching the green challenge to create opportunities. Innovation in such leading companies can often be simple rather than based on new technology, and the aim of this workshop is to promote the assessment of environmental challenges for businesses with a different mind-set, viewing them as potential opportunities to add value and diversify.[35] An example of this is British Sugar whose primary business remains the production of sugar from sugar beet but who has also expanded into selling aggregate and soil cleaned from the root vegetable, renewable energy through anaerobic digestion of the residual pulp, and production of tomatoes (switched now to medicinal cannabis) using excess heat and CO_2 from their processes.[36] Using understanding gained from the initial lecture, participants go on to examine a case study based on a real-world scenario from a leading company. Working in groups of 3−4, the participants propose innovative ways forward to transition to greener, more ecoefficient operations and identify opportunities to reduce cost, increase quality, add more value to customers, develop new business streams, and provide a positive environmental benefit. The participants then gain feedback on the case study and their proposals for change, as well as a view of what could be the future make-up of company operations in the decades ahead. As an exemplar, this case study has been included in the Supporting Information for this paper. Systems thinking in the business case shows the impact of moving from a linear to a more circular economy approach, from the simple and mundane through to the complex or radical benefits for the triple bottom line: moving from showing progress, building confidence, and raising the company profile through to creating ambition, yielding rapid advances, and fostering long-term thinking.

Dr. Joe Ross of the Biorenewables Development Centre (BDC) and Pete Metcalf of Wilson BioChemicals Ltd. deliver a joint workshop on "Biorefining Waste". The aim of this workshop is for participants to gain insight into all the factors that influence taking a new technology through to commercial reality and appreciating the importance of demonstrator scale operations. The BDC specializes in the scale-up of new greener processes and products, in particular with regards to biorefining various types of waste including food, agricultural, and municipal solid waste (MSW). During the workshop participants explore case studies that exemplify this growing area of the bioeconomy and focus in particular on a pilot scale project that is operating in one of the warehouse units on the estate: a microautoclave fiber production plant for turning municipal solid waste (MSW) into biomass fiber that can be converted into chemicals or fuels. Participants are also given the opportunity to see the pilot scale facility in operation and observe how MSW is converted into biobased fiber for use in the manufacture of biofuels and other chemicals. This is an exemplar of a key tenet of green chemistry, that a waste is not a waste but a feedstock. Here the students consider the various value streams this resource then opens up and how that can positively feed back into the economy in general and the existing manufacturing chain in particular that the waste originated from.

Benefits of the Workshops

Throughout this workshop series, participants apply multidisciplinary approaches to the creative problem solving of challenges within green chemistry considering industry demands and constraints as part of a dynamic global system. The benefits of these workshops are manifold; from enhancing transferable skills such as team work and communication, through to embedding systems thinking in order to understand and approach their research activities from a more holistic perspective. The content of the workshop series to date has successfully fulfilled the key areas identified by industry for incorporation in graduate training to allow future employees to make an impact within sustainable manufacturing. All workshops were designed specifically to improve students' ability to work in and lead teams and enhance their communication skills, and the coverage of the remaining key areas identified is summarized in Table 2.

The workshops give participants exposure to researchers and industrialists from a range of multidisciplinary backgrounds with varied viewpoints. Further beneficial aspects of the program are that it demonstrates to students just how widely green chemistry is employed and the range of different career paths that could be open to them in the future. From the perspective of the workshop facilitators, there are also demonstrable advantages to participating in the workshop program (see Boxes 1−3).

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Box 1. Benefits to GSK

"We valued the opportunity to share our current thinking with the students. It is instructive to see which solvents and reagents they are already aware of as being problematic, and which may have issues they have not previous considered. This is something which is constantly evolving over time, and has a tendency to reflect media publicity as much as, or if not more so, than changes in legislation or toxicology data. The students were certainly engaged and I had follow up questions by email after my session." **Dr. Helen Sneddon, GSK Senior Fellow, Scientific Director Green Chemistry, GSK Medicines Research Centre**

Box 2. Benefits to Merck KGaA

"We welcome the University of York's modern curricula that helps develop the necessary skills for the next generation work force. The workshops provide an opportunity for a shared dialogue between academia and industry and enables us to align in addressing real world challenges utilizing the students' creativity and talent." **Dr. Jane Murray, Global Head of Green Chemistry, Merck KGaA**

Box 3. Benefits to Croda International Plc

"The workshops are a great opportunity to inspire and enthuse Masters students about the career opportunities available to them in industry. The students gain an insight into the challenges faced by an organisation in meeting customer and consumer demands for sustainability, without compromising on product performance. The group discussions can often spark thought provoking questions for us as a team. The day is also very good fun!" **Dr. Julia Creasey, Group Sustainability Specialist, Croda International Plc**

Additionally, through attracting a multidisciplinary audience, the workshops provide the students with networking opportunities and prepare them for working within a multidisciplinary environment in future. Last year the workshops were opened up to other local universities via the Northern Sustainable Chemistry network (NORSC) to widen networking opportunities further.

FEEDBACK AND EVALUATION

Feedback from workshop participants has to date been based solely on summative assessments focused mainly on qualitative data. In 2017, 49 individuals attended the workshop series and 44 in 2018, with most sessions attracting around 15−20 participants on average, primarily from the chemistry, the biology, and the environment & geography departments. The make-up of the workshops was predominantly masters and Ph.D. students, with a small number of postdoctoral research assistants and staff also taking part. Students have responded positively to the workshops with over 67% of participants rating the facilitators as excellent and over 90% rating the content as either good or excellent (with the remaining 10% stating they were "satisfactory"). Students particularly enjoyed the "interactive elements", "team working aspect", "interesting case studies highlighting real world problems", and the "multidisciplinary point of view". Students also praised the discussion topics, which "initiated good conversations" and stated that "the open discussion element encouraged widespread audience participation". Students also felt that the sessions were "thought provoking" and that "it was great to meet people from other disciplines and get their perspective". In terms of the level of the content of the workshops, participants have overwhelmingly responded that they were pitched at an appropriate level, which provides confidence that the idea to actively avoid complex scientific content was achieved, and rather, the workshops have focused on the other learning gains.

Now that the program has been established, evaluation as a whole is being focused on more closely with this year's workshops. A more rigorous assessment of a baseline vs postworkshop evaluation will be carried out to more transparently assess learning outcomes/gains to the students directly from participating in the sessions. This will take the form of a preworkshop questionnaire asking for the participants' understanding of a minimum of 3 areas which will covered in the workshop; e.g., in the Croda workshop this would be knowledge of (1) design of a new consumer product, (2) formulation science, and (3) evaluation of environmental, cost, and performance parameters. These will be asked again postworkshop to assess if these learning goals have been met. Additionally a series of open questions will be given in the postworkshop questionnaire to assess how engaged the students were, if the design of the workshop aided in their learning, and also how the workshop might be improved. Finally, there will also be a series of Likert questions to assess the development of transferable skills during the workshop. Assessment of skills such as critical thinking and holistic thinking are notoriously difficult to attribute directly to one event or activity, as they require a change in mind-set, which may grow over time, building upon a range of different experiences. Hence, this is why the series of RenewChem workshops from a number of different perspectives is preferential to a standalone event to bring about a paradigm shift to systems thinking for the graduates. Over the course of their graduate studies, students will have attended three workshop series. Hence, longer term gains can be looked at via assessment upon commencement and completion of the graduate program for new students. This will be achieved through a combination of formative and summative assessment as well as establishment of a baseline.

FUTURE PLANS

The strategy for this academic year will be to enhance the evaluation of the workshop program as outlined above, as well as to deliver new workshops on process intensification and waste management and a session on communication and networking. The workshop on process intensification will explore the numerous factors under consideration in order to maximize throughput while minimizing inputs (energy, mass, time, etc.) and will include exploration of an industrial case study moving from batch to continuous processing. The waste management workshop will explore waste management options from a range of different perspectives and examine waste reduction via a systems thinking approach including recycling and closing the loop. A workshop on communication and networking will also be run to equip participants with the tools needed to communicate strategically about their research to a broad range of disciplines/backgrounds. Participants will develop a set of key messages to describe their research and work in teams to develop a communication campaign to publicize a research finding.

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These new workshops will continue to focus on promoting a systems-based approach to solving problems, presented as real-world case studies from a multidisciplinary and multisector perspective, as well as promoting core skills vital to invoking systems thinking among graduates.

An additional future development may be to record the deliverable content of workshops where appropriate to enable them to be run virtually or as an outreach activity. RenewChem may also mirror the chemistry department's graduate teaching assistant training program with monitoring and logging of attendance coupled with presentation of a nonaccredited "homemade" certificate on successful completion.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00257.

Business case for green: case study exemplar (PDF, DOCX)

Running a sustainable chemical company: flow diagrams for potential process associated with producing biodiesel (PDF)

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Notes

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