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The commitment to green chemistry education at York: past, present and future

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The Department of Chemistry at the University of York, UK has been at the forefront of green chemistry education initiatives for several decades. As the MSc programme in Green Chemistry and Sustainable Industrial Technology celebrates the 25th cohort of students graduating in Summer 2026, this manuscript celebrates this milestone through showcasing the integration of green chemistry education into curricula at all levels at Chemistry at York from outreach in primary and secondary schools to undergraduate and postgraduate instruction through to delivering continuing professional development training to those working in the chemical and allied industries. The impact of becoming a signatory of the Green Chemistry Commitment *via* Beyond Benign is also highlighted. Through outlining the educational approach at Chemistry at York, it is envisaged that aspects of the portfolio of activities designed to support green chemistry instruction are transferrable for other institutions to adopt, no matter what stage of curriculum development they are at. Potential future directions for green chemistry education are also discussed in recognition of the evolving curriculum and ethos to transition away from an optional enviornmentally-focused idea to green chemistry acting as a core lens to be used when practicing chemistry.

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Sustainability spotlight

Training the next generation of scientists, engineers and policymakers to work in partnership to address global grand challenges requires instruction in green chemistry (SDG 4 and 17). Through adopting a holistic, green approach to solving chemistry-related problems, we can perturb the system and transition from our current unsustainable trajectory towards collectively developing a more sustainable bioeconomy where human health and well-being is prioritised (SDG 3, 12 and 15). This article presents a template for green chemistry instruction at multiple levels from primary school to professional development, through outlining a transferrable educational model at the University of York.

Introduction

The United Nations Sustainable Development Goals (UN SDGs) seek to address global grand challenges relating to, for example, poverty, climate change and access to clean water/sanitation.[1] While there is diversity in each of these goals, they are all interrelated and therefore cannot be considered as distinct issues.[2] Given this, such complex and multi-faceted goals will not be met by individuals working in isolation through one discipline but by diverse teams, collaborating internationally, embracing an interdisciplinary ethos to problem solving. More fundamentally, the three pillars of sustainability, the economic, environmental, and social components, by their nature, demand adoption of an interdisciplinary approach.

To equip society to tackle such grand challenges, it is critical that the next generation of scientists, engineers and policymakers are appropriately trained to adopt a holistic and interdisciplinary approach to solving sustainability-related issues. Quality education (Goal 4) is essential to achieving this competency. A systems thinking-based theoretical framework deployed within education environments could be used as an instructional model to facilitate this.[3–5]

Systems thinking

A systems thinking framework enables learners to take a holistic approach to analyse complex systems to understand the relationships between system components and behaviours that emerge from those interrelationships.[6] Integration of systems thinking approaches within chemistry education is starting to gain momentum, where, following the production of a dedicated special issue in the Journal of Chemical Education,[7] various resource portfolios and accounts of how to plan, implement and assess chemistry content through systems thinking are becoming available.[8–10] There also appears to be impetus and desire from staff and student perspectives to utilise systems-based approaches within chemistry instruction.[11–13]

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Using systems thinking in chemistry education: the case for green chemistry

Through the adoption of systems thinking within chemistry instruction, this will enable reactions and processes to be studied in tandem with one another as opposed to in isolation, encouraging students to critically evaluate where starting materials come from, how they are transformed and used and what happens at the end of their lifetime.[14] These considerations underpin how green chemistry is practiced in alignment with using the Twelve Principles of Green Chemistry to design and redesign chemical processes.[15] Indeed, through taking a holistic systems-based approach, this enables the Twelve Principles of Green Chemistry to be considered in conjunction with one another and supplemented by other frameworks/considerations such as life cycle assessment and green chemistry metrics to provide a more quantitative indication as to how green a particular reaction or process is.[16–18] Therefore, in order to enable society to transition from a linear to a circular economy, making use of integrated biorefinery systems, green chemistry education is critical to prepare the future workforce accordingly.

Use of systems thinking to teach green chemistry education is a developing area with a growing portfolio of resources available.[19–21] Such resources include laboratory experiments,[22–28] games,[29–31] activities,[32] learning platforms,[33,34] bespoke courses,[35,36] and programmes.[37,38] Furthermore, there is a clear mandate from the professional bodies such as the American Chemical Society[39] and Royal Society of Chemistry (RSC)[40] for higher education institutions to deliberately integrate green and sustainable chemistry into curricula to receive recognition. Another driver for the incorporation of green chemistry into curricular is changes to legislation surrounding the use of certain chemicals in various environments; educational and others. Such changes (which might be the restricted use of a solvent, for example) provide colleagues working in teaching laboratories with a clear directive to make a substitution/green modification to a teaching experiment to be compliant with policy changes.

The holistic approach taken by the Department of Chemistry at the University of York

The Department of Chemistry at the University of York has a long history of integrating green chemistry into instruction at all levels. The University of York is a research-intensive university and member of the Russell Group.[41] The Department of Chemistry is consistently ranked as a leading chemistry department within the UK, home to approximately 60 academic staff and over 900 students (undergraduate and postgraduate).[42] Within the Department of Chemistry, the Green Chemistry Centre of Excellence (GCCE) is a world-leading academic facility for pioneering pure and applied green and sustainable chemical research, specialising in renewable feedstocks, green synthesis, sustainable technologies and design for sustainable reuse/degradation/recovery.[43] Within this unit, green chemistry education represents a key portfolio of activities, embracing a research-led approach to instruction *via* outreach in schools, instruction for undergraduate and postgraduate students, through to continuing professional development training for industrialists and other relevant stakeholders.[44]

The focus on green chemistry education was initially championed by Professor James Clark where he was leading research at York from the late-1980s focused on 'clean technologies'. In 1996, he defined some of the goals of clean technology in the chemical industry as to 'increase process selectivity, to maximise the use of starting materials (aiming for 100% atom efficiency), to replace stoichiometric reagents with catalysts and to facilitate the easy separation of the final reaction mixture including efficient recovery (and hopefully reuse) of the catalyst'.[45] Around this time the RSC recognised the power of chemistry in solving environmental problems and following 'green chemistry' being coined in 1997, Clark led the RSC Green Chemistry Network (GCN) in 1998 to 'promote awareness and facilitate education, training and practice of environmentally-beneficial chemistry in industry, academia and schools.'[46] Through the establishment of the GCN (and associated awards portfolio), this played a highly significant role in positively changing the public perception of chemistry as a force for good where establishment of the highly successful RSC Green Chemistry journal followed in 1999. Through stimulating chemists to publish new environmentally friendly chemical processes, the journal also functioned to improve the public image of chemistry at the time and to this day.[47]

In 2001, the York team established a master's degree programme which was the first of its kind in Europe focusing on 'Clean Chemical Technology'. This programme was accredited by the RSC and enabled students to attain a master's degree in just one year through studying full-time.[48] While this programme has evolved over the years (and is now known as 'Green Chemistry and Sustainable Industrial Technology'[49]), it continues to feature a diverse cohort of international students as well as UK-based students, signifying the global demand from students to be educated in performing green chemistry. Further to being delivered by academic staff within and outside of the GCCE, the programme also features contributions from industrial partners within the chemical and allied industries, enabling students to receive instruction based on real world examples while expanding their network to assist with employability. Celebrating its 25th cohort of students this academic year (25/26), the programme level learning outcomes for this degree are to:

- Apply whole systems thinking and inter/trans-disciplinary approaches to the creative problem solving of complex global grand challenges using holistic green chemistry and sustainable industrial technology related interventions in concert with the UN SDGs.
- Apply a range of advanced research skills, principles, methodologies and approaches to be able to undertake cutting-

edge research, either laboratory or non-laboratory based, in the area of green and sustainable chemistry and allied sectors.

• Effectively communicate detailed, complex, green and sustainable chemistry research concepts to both experts and non-experts through the application of a variety of key transferable skills such as IT, scientific writing, oral presentations, posters, team-working, *etc.*

• Critically evaluate and debate research literature and explain its relevance to green chemistry frameworks, including and beyond the 12 Principles, development of circular biobased economies, UN SDGs and decolonisation of research.

• Critically evaluate the environmental impact and sustainability of chemical processes and products, through the use of relevant metrics and whole systems thinking.

• Apply holistic thinking to the commercialisation and innovation of green and sustainable chemistry through an understanding of intellectual property, environmental and circular economy law and business plan writing.

These learning outcomes are achieved through students completing modules, to include an extended research project, according to:

• Principles and Systems Thinking in Green and Sustainable Chemistry[50]

• Applications of Green and Sustainable Chemistry[51]

• Communication, Education and Public Understanding of Green and Sustainable Chemistry[52]

• The Business Case for Green and Sustainable Chemistry[53]

• Research Skills and Methodologies[54]

• Green and Sustainable Chemistry Research Project[55]

Rather uniquely, there is significant emphasis on training the students in conducting and facilitating green chemistry education activities. There is a strong ethos on empowering students to effectively communicate the research that they conduct through their research projects (and future careers), embracing the principles of research-led instruction, especially to assist with public understanding of green chemistry. Furthermore, the focus on the business case for green chemistry,[56] to introduce commercialisation routes through the role of environmental legislation governing manufacturing, the process of protecting inventions and bringing them to market, brings in significant industrial input to the programme and exemplifies the holistic systems thinking-based approach to consider the socioeconomic components to sustainability in addition to the environmental facets.

This programme continues to evolve with an emphasis on diversifying the international student cohorts. Efforts in this space have been focused on establishing progression agreements with partner institutions such that graduated students have the opportunity to complete this programme in 1 year of full-time study at a reduced rate.

Undergraduate instruction in green chemistry at the University of York

At the undergraduate level, it is relatively common in institutions (especially where there is a significant research effort in green chemistry) for there to be an optional module where students can elect to learn more about green chemistry. This has been the case at the University of York for well over a decade with the current offering comprising of a 20-credit module entitled 'Green and Sustainable Chemistry'.[57] This module is presently taught by academic colleagues engaged in research within the GCCE though historically, this has not always been the case with input from wider areas of the department akin to the aforementioned MSc programme. It is noteworthy that such a module is perhaps more easily convened by colleagues that are actively conducting research in green chemistry and related areas though this does not have to be the case. The University of York is in a privileged position in this regard given the significant research efforts in this area of strategic focus. The module as it stands comprises of the following topics:

• Principles and metrics of green chemistry.
• Sustainable solvents.
• Sustainable feedstocks.
• Sustainable catalysis and polymers.
• Heterogeneous transformations.
• Sustainable processing.

The assessment for this module is composed of a closed book assessment, representing 80% of the module with the remaining 20% serving as continuous assessment. The latter involves students making infographics for research-led instruction.[58] This assessment represents two of the above topics (sustainable catalysis and polymers together with heterogeneous transformations), which are therefore not contained in the examination along with the remaining topics. Students are provided with training from the Digital Skills, Creativity and Inclusion team on how to make an infographic. They are then placed into groups to review a research article linked to the lecture courses, where they have to produce an engaging infographic and associated list of key points to include a critical evaluation of the greenness of the work, while making links to overarching frameworks such as the UN SDGs.

In addition to a bespoke module on green chemistry, further interventions were made to infuse green chemistry into the curriculum over the years. This included the ability for students to conduct research projects (either as part of a 3 year bachelor's or 4 year integrated master's programme) in green chemistry under the supervision of appropriate academic staff. This also encompassed the possibility of doing research into green chemistry education more directly, such as by devising and evaluating the efficacy of creating new research-led resources for instruction.[59] This can either be conducted within the Department of Chemistry at York, through a research lab with one of our partners abroad, or within an industrial company. Such extended research projects are accompanied by prior open-ended problem-based learning mini-projects in green chemistry topics.[60] These team-based projects involve groups of approximately 6 students doing a green chemistry-based research project over 8 days where there is a significant exploratory component to the investigation though with wider constraints to follow than a more extended project. Practical chemistry training at earlier stages of the degree programme (*e.g.* years 2 and 3) evolved more gradually. Examples are largely based around more synthetic organic chemistry experiments where students are required to calculate various green chemistry metrics associated with their experiment as opposed to just determining yield and purity. More indirectly, laboratory experiments have been adapted in response to new legislation, restricting the use of certain chemicals. This has taken the form of, for example, substituting solvents of concern with greener alternatives. Indeed, students have taken the lead in investigating new possibilities either through conducting work as part of a research project through their degree programme or as part of a paid summer internship. While progress has been made through holistically considering the greenness of laboratory experiments at the early stages of the degree programme, changing the status quo in this regard has been more challenging.

Besides research and practical instruction, historically, students also have the opportunity to engage in green chemistry instruction through selecting from one of four green chemistry-based topics as part of the Group Exercises. This is a team-based exercise where students work in groups to solve an industrially-relevant problem and present their results *via* a team-based presentation, virtually or online.[61] More recently, the Group Exercises have been redeveloped as the Global Challenge Exercises, requiring all students to make sustainability-related considerations to solve real-world problems. This progress alone through moving from an option of 1 in 4 exercises to embedded throughout the activity represents increasing integration across of green chemistry and sustainability across the degree programme.

More holistically, if students curate their degree programme through completing credits through undertaking green chemistry-focused content (*e.g.* an option module, mini-project, research project *etc*), they have the ability to graduate with a named degree in ‘Chemistry, Green Principles and Sustainable Processes’ at the bachelor's or integrated master's levels.[62] As well as serving as a potentially helpful recruitment initiative for the department, such a named degree may also contribute towards enhanced recognition in the employability domain for students.

In recognition of the progress made in integrating green chemistry into curricula, there was still more that could be done. In 2022, the University of York signed the Green Chemistry Commitment led by Beyond Benign.[63] The Commitment acts as a signal of intent by higher education institutions to begin, continue, or optimise their bespoke green chemistry journeys to prepare the future workforce to address societal and environmental challenges as outlined by the UN SDGs.[64] Since signing the Commitment, this has had a transformative effect on green chemistry education at Chemistry at York. Prior to becoming a signatory, much of the curricula innovation was led by colleagues in the GCCE, directly engaged in green chemistry research. However, since signing the Commitment, we have witnessed a more powerful ‘collective effort’ of colleagues that are committed to enhancing green chemistry instruction in the department. Specifically, there has been (and is an ongoing) shift in colleagues that teach across all sub-disciplines within the department, reflecting on how they can incorporate green and sustainable chemistry into their lecture materials. In addition to signing the Commitment, further impetus for change has been provided by the recent inclusion of green and sustainable chemistry into accreditation criteria by the RSC.[36] In recognition that space in the curriculum is limited, should students be aware of well-used traditional processes as well as greener alternatives or will the latter suffice? This has proven to be a provocative question for instructors to grapple with. However, the fact that instructors are asking these questions and tackling how to integrate green chemistry holistically across the programme is significant progress. Indeed, becoming a signatory of the Commitment has also assisted in moving our laboratory curriculum forwards such that students are able to procure the necessary experimental skills in the early stages of the programme while embracing green chemistry more broadly.

Furthermore, in signing the Commitment, we have taken it upon ourselves to make our own green chemistry commitment to students. This occurs as one of the very first cohort-wide lectures to incoming first-year students where we introduce what green chemistry is and the role that green chemistry plays in solving global grand challenges according to the UN SDGs. As part of this, the approach that is used to deliver green chemistry education at York to empower the next generation to make sustainable change through chemistry, is outlined. By delivering this lecture to students early in the degree programme, it is believed that this helps to frame their mindset when approaching chemistry and to adopt a ‘green lens’ throughout their studies.

Outreach efforts in green chemistry education

Engaging the public and prospective students in green chemistry has always been a priority at Chemistry at York. Over the years this has taken the form of undergraduate students delivering outreach through, for example, conducting educationally-focused research projects with staff and sharing them with school students and the public. This has taken the form of making games[30,31] to creating green chemistry-oriented accounts on social media such that students become educators within their own right.[65] Undergraduate students can also complete educationally-focused projects in local schools where students have previously implemented a green resource/experiment into the curriculum. At the postgraduate taught level, through the MSc in Green Chemistry and Sustainable Industrial Technology, students have physically delivered outreach sessions to students and the public, while being assessed on their ability to do so. This has included delivery of practical laboratory classes and sessions as part of science festivals or in conjunction with local museums.

Various members of staff both within and without the GCCE routinely deliver lectures, taster teaching, practical classes, school visits, radio and television interviews, events such as Soapbox Science, Pint of Science and more to engage the public and school students in green chemistry. Innovative projects such as the creation and dissemination of a comic, Green Kid,[66] have been led by staff, together with the publication of a children's book, The Green Formula, which was done in collaboration with undergraduate students.[67]

Chemistry at York is particularly privileged to house the Centre for Industrial Education Collaboration (CIEC).[68] Through partnership with industry, the CIEC 'promotes excellence in primary science teaching and learning, increasing children's and teachers' awareness of STEM careers and industries, and raise children's science capital.' Through this, CIEC creates links with primary schools in the UK to enable teachers to engage children in conducting science investigations, focusing on topics that are relevant to the curriculum and industrial practices, of which green chemistry and sustainability-based concepts feature prominently.

Continuing professional development training in green chemistry education

Training for professionals at all levels has also been a focus of education efforts at Chemistry at York, specifically *via* the GCCE. This training has manifested as a blend of both online courses and face-to-face workshops.[36] On the former, as part of the CHEM21 project (Chemical Manufacturing Methods for the 21st Century Pharmaceutical Industries), which was Europe's largest public-private partnership dedicated to the development of manufacturing sustainable pharmaceuticals,[69] an associated learning platform was created. The Green Chemistry and Engineering Learning Platform is particularly focused on the uptake of green and sustainable methodologies in the synthesis of pharmaceuticals and is free for all to use.[70] More focused examples of online courses offered by colleagues in the GCCE include a solvent selection and substitution course, enabling users to identify and understand the properties of solvents such that solvent substitution can be approached in a systematic fashion, allowing performance to be maintained with benign solvents.[71] Students have also worked in partnership with colleagues in the GCCE to design focused online platforms such as *The Biorefinery Experience*,[72] which is free-to-use and where a systems thinking approach has been adopted to outline holistic and interconnected considerations in the design of a first generation sugarcane biorefinery. Users design their own biorefinery using real data and then redesign a biorefinery as a function of time, demonstrating holistic system understanding, retrospection, and prediction.[33]

Making a green impact beyond the curriculum

The foundations of green chemistry instruction at Chemistry at York have permeated elsewhere within the institution and beyond. Within the University, one example of this is through the collaborative creation across multiple departments of the York Interdisciplinary Modules (YIMS).[73] These modules offer students the opportunity to work collaboratively in multidisciplinary teams to solve, local, regional and global sustainability challenges. Modules such as the 'Future of Food'[74] directly align with GCCE research activities on the valorisation of unavoidable food waste, an area in which colleagues have actively published educational resources within.[24,26,28] Another YIM focuses on the 'Climate Crisis Action Lab'[75] where students collaborate to understand the background of a strategic issue related to the climate crisis presented by an external agency such as a non-governmental organisation. Part of the scientific evidence the students will need to investigate includes the chemistry of how substances behave in a given environment, the resulting impact on the wider ecosystem and the associated legal frameworks in place to prevent or deter negative impacts.

Expertise in green chemistry education has also informed initiatives from the GCCE Sustainability Team, which is considered a model team across the institution for reducing environmental impact and making our workplace more environmentally conscious and sustainable. This is achieved through voluntary collaboration between staff and students at the GCCE. Initiatives include practical interventions such as insulating reactions to reduce the time taken for the desired internal temperature to be reached, implementation of air condensers, transitioning from plastic to glass weighing boats and investing in equipment for solvent recycling. Other non-lab-based interventions have included establishing a garden using coffee waste as a fertiliser, developing a green chemistry outreach podcast and implementing a chemical inventory system to organise and, where relevant, share, chemical stocks in laboratories.

Owing to expertise within the GCCE, colleagues are regularly invited to facilitate training in green chemistry education outside of the institution whether it be *via* collaborative doctoral training centres, summer schools or training for industrial companies, for example. Indeed, influencing policy and setting the agenda for green chemistry education nationally and internationally also serves as a focus to evoke systemic change (*e.g.* through contributing towards a specialised manual on green and sustainable chemistry education and learning *via* the United Nations Environment Programme).[76]

Future directions for green chemistry education

Potential future directions for further integrating green chemistry into instruction at Chemistry at York include continuing to facilitate research-led teaching such that the most cutting-edge work is showcased to students at all instructional levels. This should take the form of both academic and industrial research, where continued partnerships with the chemical and allied industries to co-deliver the curriculum has synergistic advantages for all parties. One area of research that it is likely there will be enhanced integration in the coming years is the use of artificial intelligence and machine learning to conduct green chemistry. At a more fundamental level, increased adoption of students using Design of Experiments, particularly as part of more advanced practical laboratory courses (such as problem-based learning mini-projects), would seem likely, enabling students to be more efficient, sustainable and agile when exploring a reaction space.

In alignment with the University of York becoming a signatory of the Green Chemistry Commitment, a continued and sustained press to integrate green chemistry into all parts of the curriculum is likely to be a focus in coming years. In assisting to achieve this, the Green Chemistry Teaching and Learning Community (GCTLC)[77] platform will be an important source of global green chemistry education resources, developed by educators for use in all parts of the curriculum at all levels.

As part of chemistry instruction more broadly, it is not uncommon for lecture courses to be delivered in a format where the instructor provides a paper-based gapped handout and for students to annotate this as the lecture proceeds. Given large cohort sizes, the amount of uncollected printed handouts, the increasing integration of technology-enhanced learning methods and devices in higher education, coupled with the questionable assertion that handout annotation is the optimal pedagogic approach for chemistry instruction during lectures, it would seem likely that transitioning towards paperless instruction would be highly beneficial, not least from sustainability and financial perspectives. On this matter, it is likely there will be movement in both research and practical laboratory instruction environments where paper-based laboratory notebooks will be phased out. Indeed, the development and adoption of electronic laboratory notebooks (or an ELN) is becoming more prevalent. AI4Green4Students is one such example to foster sustainable laboratory practices.[78] Through this ELN, features include sustainability assessment, data documentation, and analysis. Initial adoption and trials are likely to take place in research laboratories and/or with relatively small cohorts of students (*e.g.* master's degree programmes). More broadly, it is likely that other innovations in sustainable lab practices will continue to be applied to teaching laboratories over the coming years to reduce energy usage, carbon footprint, waste generation and costs.[79] Certification programmes such as LEAF (Laboratory Efficiency Assessment Framework) or My Green Lab can provide a structured path for laboratory supervisors, technicians, and instructors to achieve 'green' status.[80,81]

Author contributions

This manuscript was conceived and developed by GAH.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this work.

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