Green Chemistry Education at the University of York: 15 years of experience

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ABSTRACT

The Green Chemistry Centre of Excellence at the University of York has been developing and teaching Green Chemistry curricula for over 15 years. The work now encompasses undergraduate and postgraduate teaching, and outreach activities for the general public and schools. The development of these materials is based on the principles that the material should be:

- embedded in the teaching of chemistry at the appropriate level
- based on current educational practice and informed by research
- developed so that they can be used, with appropriate changes, in other countries.

This article gives an overview of the green chemistry education work at the University of York, how it has developed and lessons to be learnt to help the incorporation of green chemistry elsewhere.

Key words: green chemistry, education, outreach.

Introduction

Over the past two decades Green Chemistry, as the development of more sustainable chemical practices and processes, has become a major advancement in the chemical sciences worldwide. Green chemistry is integral to the research and development of 'greener' products in both industry and academia. Driving forces for this adoption and interest in green chemistry have included concerns about a wide-range of environmental challenges, resource depletion, economic considerations, increases in regulation and funding for research, and an awareness that the intrinsic sustainability of products will be of ever-increasing concern for consumers.

The products of the chemical industry are ubiquitous in modern society and have greatly improved the quality of our lives; however, manufacturing these products in an environmentally compatible way is of critical importance. Solutions will only be found through collaboration between a multidisciplinary community of chemists, biologists, engineers, economists and legislators and with the support of the public. To promote uptake of green and sustainable methodologies amongst the chemical and chemical-using industries requires the exemplification of green chemistry in education and training material to influence and inspire the next generation of scientists.

The emergence of Green Chemistry Centres in rapidly developing countries is extremely important as they have a wealth of natural resources and waste that could be utilised to produce valuable chemicals, materials and fuels, but will require people with the expertise to develop them. Education in green chemistry is therefore necessary at all levels, from school to university and within industry and is also a valuable route to the engagement of a wider audience with chemistry.

The Green Chemistry Centre of Excellence

(GCCE) at the University of York (UK) is a world leading research centre which aims to promote the development and implementation of green and sustainable chemistry and related technologies into new products and processes. Originally established in 1999 as the Clean Technology Centre (CTC), the centre was awarded the status of Green Chemistry Centre of Excellence in 2005. Over the past 15 years the Centre has been instrumental in delivering excellence in Green and Sustainable Chemistry education and training across higher education (BSc, MChem, MSc and PhD) and industry, as well as developing outreach programme,[5] leading to the GCCE winning the ACS-CEI Award for Incorporation of Sustainability into Chemistry Education along with the Chemical Industry Education Centre at the University of York. We are therefore ideally placed to discuss Green Chemistry Education, its successes, challenges and opportunities.

Undergraduate courses

Updating undergraduate chemistry curricula to reflect the current needs of society for graduates that are trained in sustainability and able to implement green and sustainable chemical techniques remains a challenge worldwide. At the University of York the integration of Green Chemistry into the undergraduate curricula has been promoted by developing new undergraduate green chemistry practicals with examples of clean synthesis, renewable feedstocks, heterogeneous catalysis, continuous reactors and phase transfer catalysis (Table 1). With funding from the Royal Society of Chemistry, these experiments have been published for widespread use, with a booklet, teachers' notes and CD-ROMs with the materials sent to all UK Chemistry Departments. The experiments offer students much needed experience in several different green chemistry techniques, as well as further encouraging them to critically examine them through calculating a series of green chemistry metrics.

Following on from this initiative and, with the enthusiasm of undergraduate students for green chemistry, the Chemistry Department now offers optional modules in each year of the undergraduate course in Energy and the Environment, Greener Chemical Processing and Green Chemistry. These teach a broad perspective on sustainable chemistry and clean chemical technologies through case studies (e.g. on greener plastics) and practicals.

Our focus has now developed further, with the aim of integrating green chemistry and especially greener research techniques throughout the curricula and laboratories. We currently have a 'Sustainable Laboratories' programme, working with undergraduate students to substitute hazardous and non-sustainable chemicals used in their laboratory protocols. The project also aims to train laboratory technicians and demonstrators as “green chemistry champions” to further embed green chemistry principles in undergraduate laboratory teaching.

Table 1: Green Chemistry practicals developed with the Cutter Bequest

Practical	Target Audience
Synthesis of tetrahydrofuran by reactive distillation	1st year undergraduates
Alkylation of p-xylene with benzyl chloride using homogeneous and heterogeneous Lewis acid catalysts	2nd year undergraduates
Clean and efficient synthesis of 4-aminobenzoic acid from 4-nitrotoluene	2nd and 3rd year undergraduates
Synthesis of vanillin from petrochemical and renewable feedstocks	3rd year undergraduates and Masters students
Extraction and conversion of limonene to terepthalic acid via p-cymene	3rd year undergraduates and Masters students

Table 2: MSc in Green Chemistry and Sustainable Industrial Technology Outline

Module	Subjects Covered	Credit Value	Teaching Methods
Principles of Green Chemistry	Introduction to Green Chemistry	20	Lectures & Workshops
	Control of Environmental Impact of Chemical Processes and Products		Lectures & Workshops
	Alternative Reaction Media		Lectures & Workshops
	Catalysis for Green Chemistry		Lectures & Workshops
Application of Green Chemistry	Clean Synthesis	20	Lectures & Workshops
	Renewable Resources		Lectures & Workshops
	Energy Efficiency and Emerging Technologies		Lectures & Workshops
	Chemical Engineering and Clean Technology		Lectures & Workshops
Transferable Skills	Advanced IT Skills, CV and Interview Techniques	20	Workshops
	Green Chemistry Presentations		Workshops & Seminars
	Literature Seminars		Workshops
	Public Awareness		Lectures, workshops and presentation
Commercialisation of Green Chemistry	Greener Products	20	Lectures and Workshops
	Intellectual Property & Impact of Environmental Legislation		Lectures, Seminars & Workshops
	Commercialisation: Business Plan Development		Workshops
Green Chemistry Research Project	Masters Research Project (in collaboration with industry	100	Research Project

Msc in Green Chemistry and Sustainable Industrial Technology

The MSc in Green Chemistry and Sustainable Industrial Technology was the first of its kind in the world, established in 2001, and has since become the benchmark for similar courses in Spain, Greece, Bulgaria and the UK. The MSc is 12 month, including six months of taught courses developing in-depth knowledge about green chemistry and clean technologies followed by a six month intensive research project (Table 2). Over the past ten years, students graduating from the course have come from diverse academic backgrounds, work experience and nationality.

The foundations of any Green Chemistry course are without doubt provided by the 12 principles of green chemistry, which are as relevant today as when they were conceived by Anastas and Warner in 1998. However, in the past, Green Chemistry courses tend to have been heavily chemistry biased, but York among others, have broadened their syllabuses to encompass these other aspects. This is reflected not only in the content of the course at York but also in the expertise of its tutors, and is highly favoured by the students on the course. Students should become familiar with the fundamental philosophy and tools of green chemistry, which should incorporate understanding of the use of green chemistry metrics in order to calculate environmental impact of chemical processes; the control of environmental impact; as well as raised awareness of the legislative, financial

and social factors connected with reducing environmental impact.

It is also important that teaching material incorporates up-to-date industrial case studies which demonstrate green chemistry in application and the direct relevance of the course content. To achieve this at York, the course is run in collaboration with a wide range of companies and organisations that manufacture or use chemicals or are involved in chemicals management and policy, who are directly involved in the course delivery through lectures and workshops and visits to industrial sites (Figure 1). This is fundamental to the success of the course. The course also fulfils industry's need to equip students with the requisite tools, knowledge and experience and enable them to make an immediate impact on the development of environmentally benign products and processes.

From an industry perspective being 'green' is not enough on its own, and consideration of the economics and viability of new developments is important. In addition, the success of new technology is frequently related to the ability to communicate its' benefits and to developing society support. To enable the successful implementation of green and sustainable solutions chemists must also possess: transferrable skills; knowledge of the commercialisation of science; the ability to work effectively with people from a range of disciplines; and the ability to communicate science to a wider audience. To develop these skills two major components of the course are focused around transferable skills and the commercialisation of science (Table 2).

One of the most unique aspects of the course is the integration of a module on Public Awareness of Science. Students receive training in public engagement from York staff and external experts (Figure 2), work in teams to develop an idea for a green chemistry outreach activity and participate in the GCCE programme of outreach events throughout the year. This encompasses the development of educational material, running events, and

Figure 1: MSc students visiting an industrial site

hosting exhibitions and workshops for young children and the general public at National Science Centres, shopping centres and annual Festivals of Science. Through this programme of activities the students not only develop valuable transferable skills, but also contribute to the dissemination of green chemistry knowledge to a wider audience, in particular raising awareness of the role of green chemistry in improving the sustainability of products we enjoy as part of our everyday lives.

Just over half of the course is dedicated to the Green Chemistry Research Project. This enables the students to apply knowledge they have gained within the taught part of the course to an area of specific

Figure 2: MSc students learning about how to develop engaging science experiments

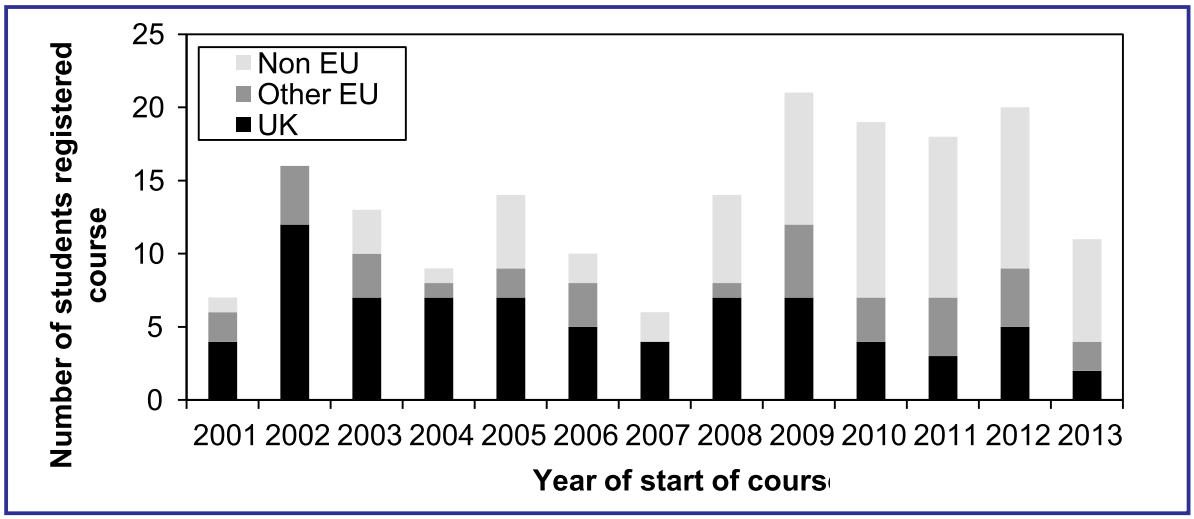

Figure 3: Number of students registered for MSc Course

interest to them, frequently in collaboration with industry. In addition they gain further knowledge about a wide range of techniques, develop their investigative skills and gain direct experience of working in a research environment. Past projects have covered diverse areas that the Green Chemistry Centre of Excellence has expertise in, examples of which are listed below:

- From food waste to bio-fuels and beyond
- Antioxidant Properties of Phenolic-rich Extract from Microwaved Biomass
- Utilisation of waste fatty acids for developing hydrophobic surfaces
- Supercritical extraction and fractionation of renewable feedstocks
- Catalysis for the formation of amide bonds
- Green oxidation of alcohols in water
- Biocatalytic routes to esters in supercritical carbon dioxide
- Starbons® as adsorbents for water purification
- Generation of high energy chars from biomass utilising microwaves
- The recovery of pharmaceuticals from waste streams
- From ash to bio-boards

The success of the MSc course can be recognized by the increasing number of students applying for the course year-on-year with a total of 168 graduates (Figure 3), although unfortunately this has recently been slightly affected by the levels of funding available. In addition the in-take from beyond the UK has gradually increased with students from Brazil, Brunei, China, Cyprus, France, Ireland, Lithuania, Malaysia, Malta, Nigeria, Oman, Spain, Tanzania and Thailand amongst many others. This is evidence of the global relevance of the course content, the lack of availability of similar courses and the desire from students to gain skills and knowledge in green chemistry.

The multidisciplinary nature of the background of the students who choose the MSc is also interesting. Although the majority come directly from Chemistry they also have degrees in Environmental Chemistry through to Pharmaceutical Science, Biochemical Engineering and Material Science. This benefits the course by adding in a broader range of expertise and perspectives and is eminently suitable for a subject area where interdiciplinarity is key. This multidisciplinarity is further exemplified by the post-MSc career paths, with the MSc preparing the students for careers in academia, industry, education, government and non-governmental organisations (Figure 4).

Outreach Activities

The Green Chemistry Centre of Excellence has embedded a programme of outreach activities within its work, recognising the importance of communicating with and engaging the public and

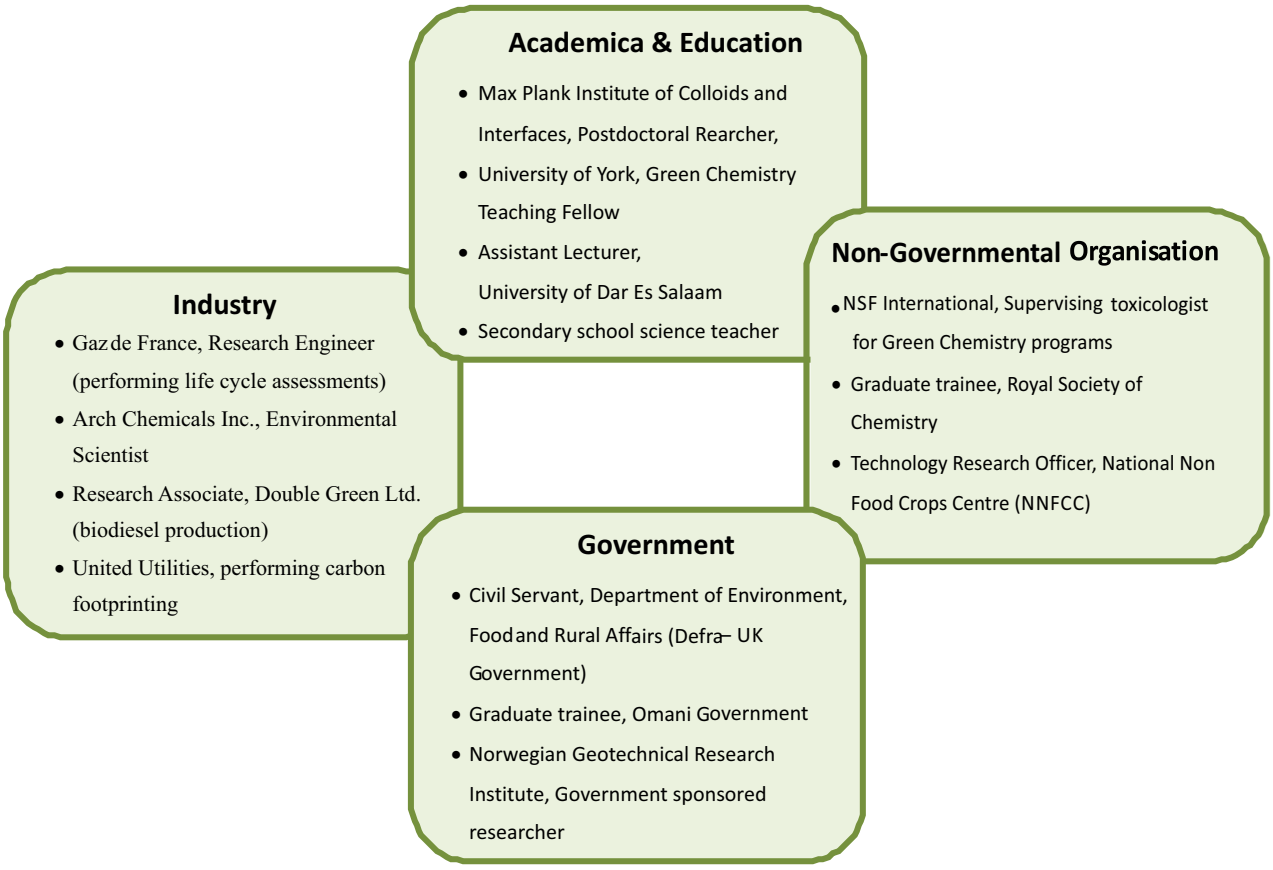

Figure 4: Examples of the career paths of recent MSc graduates

school students to promote the research at the GCCE, excite young people about the potential to study chemistry, and to demonstrate the positive impact that chemistry can have. We have developed and delivered a broad-range of outreach activities including:

- Developing educational websites (www.greener-industry.org.uk and www.sustain-ed.org), publications and organising exhibitions, for example, at the Royal Society, Royal Institution and National Science Week;
- Delivering hands-on green chemistry experiments for primary (age 5-11 years old) and secondary (age 12-18 years old) school students
- Delivering school and public lectures and participating in BBC Radio broadcasts;
- Running workshops at careers events and training courses for teachers

Collaboration with Chemical Industry Education Centre (CIEC) based at the University of York is also vital to stay relevant to the curricula content of schools and to understand the latest research in chemistry education. In addition the GCCE has worked the CIEC to develop educational materials for schools related to Green Chemistry. The fifth edition of the CIEC's *Essential Chemistry Industry,* for Grades 11-12 features units on Green Chemistry, Recycling in the Chemical Industry, Biofuels, Biotechnology, Biorefineries and Degradable Polymers.

Hands-on Green Chemistry Outreach Activities

We have developed simple hands-on outreach activities that can be performed with large number of students, in a short amount of time, and with minimal equipment. Many of these have been based on activities in the GEMs (Greener Education Materials for Chemists) database, including making glue from milk, and making plastic from starch, along

Figure 5: Members of the GCCE delivering outreach activities at various events

with new activities demonstrating research within the Green Chemistry Centre such as extracting limonene from oranges using a domestic microwave. These activities are run at a variety of large-scale science and public events such as Science & Engineering Week and the Yorkshire Show (an agricultural event) (Figure 5).

In addition, the GCCE has run longer hands-on experiments with secondary school pupils within the teaching laboratories at the University of York. AimHigher is a programme which aims to give pupils from disadvantaged backgrounds access to universities and experience of hands-on science. We developed a day-long series of experiments around the concept of the lifecycle and the production of cosmetics with experiments on extraction of fragrances, making plastic packaging from starch and producing biodiesel (Figure 6).

Figure 6:
Extraction of limonene using liquid CO_2

Fabs the Frog project

The 'Fabs the Frog – Discover and Explore Green Consumer products' project aimed to engage with the general public to increase their awareness of the role of green chemistry in improving the sustainability of consumer products, and explore its positive impact on our lives. The collaboration between the Green Chemistry Centre, Boots Ltd, EPSRC, Liquid Digital, Retec Interface and Glasgow and @Bristol Science Centres led to the creation of interactive touchscreen displays containing games, activities and videos demonstrating the lifecycle of products found in the bathroom such as shampoo and getting visitors to try and make a green bubblebath.

The touchscreens have had audience numbers of over 90,000 since 2009 and have been showcased around the UK at numerous venues and events including science centres, shopping centres, festivals of science, primary schools, and agricultural shows.

Conclusions: Lessons from Green Chemistry Education at the University of York

The development of Green Chemistry Education programmes at the University of York has been an ongoing process. We have started from small steps to develop a broad range of activities across the age-range and to build the philosophy of educating into the heart of our group. We are now working across the world through the Global Green Chemistry Centres (G2C2) programme to share our knowledge and experiences to enable the embedding of Green Chemistry Education throughout the world. Some key lessons from our experience include:

- Start with small steps, such as a talk to the public, and join in with existing activities at your university to minimize additional resources required;
- Utilise the experience and knowledge around you. Many universities have education departments and students eager to develop new skills; work with them to reach new audiences. In addition, there are many resources online, such as undergraduate practicals available through the GEMS database (Green Chemistry Education Materials);
- Work with early-career researchers including undergraduates, PhD students and post-doctoral researchers who can develop activities in green chemistry without the presence of a course. NESSE (Network of Early-career Sustainable Scientists & Engineers) supports early-career groups at universities who are holding talks, outreach

activities and symposiums to educate themselves about green chemistry and engineering;

- Where possible build in outreach and communication activities into research budgets as it can be difficult to gain separate funding and enables the combined benefits of promoting your research and public communication;
- Green Chemistry is a fantastic way to engage the public and students with chemistry in general. This can be further enhanced by making practicals, activities and talks relevant to people and local situations. For instance, take widely used experiments and modify them to local materials e.g. use corn starch instead of potato starch to make bioplastics;
- A successful green chemist requires a broad range of skills and knowledge. Alongside knowledge of green chemistry, we need to produce graduates with experience in commercialization, communication, engineering, biology and environmental legislation. This requires a broadening of our teaching and increasing interdisciplinary connections.

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