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Highlights of the Impacts of Green and Sustainable Chemistry on Industry, Academia and Society in the USA

Impacts of green and sustainable chemistry on US industries, analysis of green chemistry resources available in academia (higher education) within the USA, and a perspective on the role of green chemistry in US society over the past ten years

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Trends such as population growth, climate change, urbanisation, resource scarcity, conservation of energy and water, and reduction of waste and toxicity have led to the development of sustainable practices in industry, education and society. The desire to improve ways of living, the need for performance materials, and the urgency to close the gap between developed and emerging nations have propelled creative and innovative solutions based on green and sustainable chemistry to the forefront. This article provides an overview of the main impacts of green chemistry on industry, academia and society in the USA in the past ten years, as well as a summary of the drivers and barriers associated with the adoption of green chemistry practices. It also describes how researchers, policy makers, educators, investors and industries can work together to "build innovative solutions that transform and strengthen the chemical enterprise" (1) while addressing environmental and social challenges. The goal of this article is to understand why green chemistry is still primarily viewed as Joel Tickner, Director of Green Chemistry and Commerce Council (GC3), University of Massachusetts, Lowell, USA, puts it: as "an environmental activity rather than one that, as experience shows, yields economic benefit, and it has yet to be integrated into the fabric of the chemical enterprise, educational systems, or government programs" (1).

1. Historical Perspective: Paving the Way to Green Chemistry

The practice of green chemistry began in 1990 when the creation of the Pollution Prevention Act was seen as the USA's initiative to become directly involved in pollution prevention at the source (2). In 1995, former President Bill Clinton introduced the Presidential Green Chemistry Challenge Awards based on five (later changed to six) award categories: Greener Synthetic Pathways, Greener Reaction Conditions, the Design of Greener Chemicals, Small Business, Academic,

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and a new category created in 2015 based on a specific environmental benefit: Climate Change (for the reduction of greenhouse gas emissions). These awards are used as a marketing tool to communicate how green chemistry's contributions have impacted the world.

In 1998, John Warner and Paul Anastas published the book "Green Chemistry: Theory and Practice" providing tools, resources and applications of the 12 Principles of Green Chemistry (3). In 2001, the Green Chemistry Institute decided to join forces with the American Chemical Society (ACS) to become advocates of a more sustainable environment. In 2009, President Obama appointed Paul Anastas to the leadership of the US Environmental Protection Agency (EPA)'s Office of Research and Development. Anastas resigned from this position and chose to pursue his career at the Center for Green Chemistry at Yale University in 2012.

Following the 12 Principles of Green Chemistry provides a way to approach environmental challenges. The 12 Principles of Green Chemistry cover the topics of: pollution prevention; atom economy; less hazardous chemical synthesis; design of safer chemicals; the use of safer solvents and auxiliaries; design for energy efficiency; use of renewable feedstocks; reduction of derivatives; catalysis; design for degradation; real-time analysis for pollution prevention; and inherently safer chemistry for accident prevention, as mentioned in "Green Chemistry: Theory and Practice" (3). The philosophy of green chemistry is to produce substances in a way that does not harm the environment, health and society. A wise way to introduce green chemistry to future generations is to define it from a sustainable development point of view (4).

The concept of sustainable development began during the 1970s when the post-war environmental movement highlighted negative effects such as the direct impacts of pollution on the environment and health. In 1987, the desire to address sustainable development at a global scale became important to the United Nations. Through the Brundtland Commission, sustainable development was defined in the commission's report entitled 'Our Common Future' (5). This report encouraged individuals to become aware of the environmental and social issues. It was influential in discovering new approaches to protect future generations. In 1992, the United Nations Conference on Environment and Development, known as the 'Earth Summit' or the 'Rio Convention', was held by the United Nations in Rio de Janeiro, Brazil. Its focus was for the world to commit to a more sustainable development.

In 2002 the World Summit on Sustainable Development (WSSD) in Johannesburg, South Africa, led to a commitment to reduce global greenhouse gas emissions and to a suggestion that all governments around the world become unified in taking action towards sustainable development (5).

More recently it was devised by W. Cecil Steward, the President and CEO of the Joslyn Institute for Sustainable Communities, Lincoln, Nebraska, USA, to represent sustainable development using five domains of sustainability, which include the original three domains (environmental, economic and socio-cultural) and the domains of technology and public policy (**Figure 1**) (6).

The first domain, environmental sustainability, is based on assuming that the present environmental processes provide a way to keep society as stable as possible based on ideal-seeking behaviour. This domain relies on making the public aware of the limited amount of natural resources. Knowledge of the existence of renewable resources is another crucial tool that the human race must acquire to continue to thrive (6).

Properly harnessing and utilising the earth's natural resources is a key goal involving economic sustainability. The term 'economic' from a business

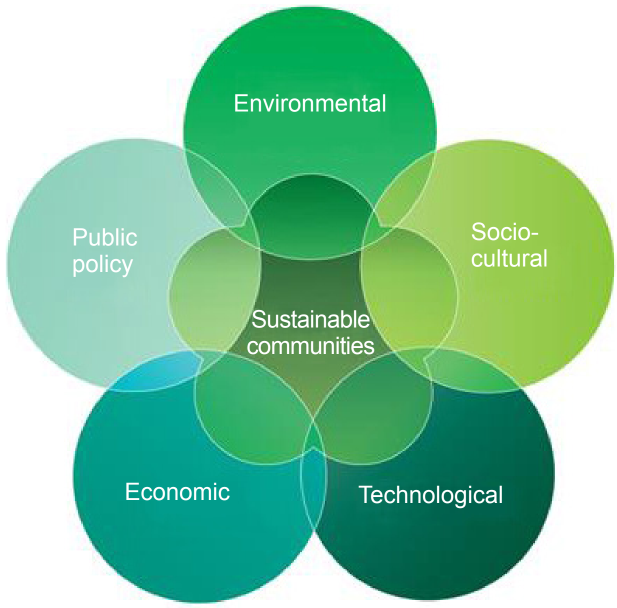

Fig. 1. Five domains of sustainable development (6). ECOStep: The Five Domains of Sustainability is a concept of W. Cecil Steward, FAIA, © 2017 Joslyn Institute for Sustainable Communities

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standpoint takes into account the value of resources (7). Ideally compatibility should emerge between improving the utilisation of natural resources more efficiently and making a profit from the end products. These strategies are defined as economic sustainability, which facilitates responsible usage of natural and manmade resources with no or minimal negative impact on the world. Observing sustainability from an economic perspective allows businesses to capitalise on the positive effects of change within society.

The socio-cultural domain pictures the necessity for a viable and sustainable future due to continued world population growth. Rising consumption levels undesirably impact environmental sustainability. In order to improve the standard of living, implementing strategies to educate society is vital to the foundation of a more sustainable future.

Technological advances have a direct impact on policymaking. Governments use policies to regulate industries and ensure their practices are not detrimental to the environment (6). As a society, implementing fit-for-purpose policies is vital to becoming sustainable.

When these five domains are considered in a harmonious way, the development of a society, a business or a nation willing to take steps towards a more sustainable future should be achieved. These domains provide an ideal platform as to how to structure a sustainable environment. Examples on how these domains have been exploited to impact industry, academia and society in the USA over the past ten years are detailed in the next section. The limitations on an article of this size mean that it focuses on the reduction or elimination of pollution and environmental toxics and on finding ways to reduce the consumption of nonrenewable resources, although this is only one of many areas where green chemistry can have an impact. Additionally, the geographical scope is also specific to the USA due to the limited length of this review.

2. Overview of the Impacts of Green and Sustainable Chemistry Initiatives

2.1 In US Industries

Before green chemistry became "a framework to do chemistry" (8), the US Congress passed the Emergency Planning and Community Right-to-Know Act (EPCRA) in 1986, which aimed "to support and promote emergency planning and to provide the public with information about releases of toxic chemicals in their community" (9). One of the outcomes of EPCRA was the establishment of the Toxics Release Inventory (TRI), which:

> "tracks the management of certain toxic chemicals that may pose a threat to human health and the environment. U.S. facilities in different industry sectors must report annually how much of each chemical is released to the environment and/or managed through recycling, energy recovery and treatment".

(A "release" of a chemical means that it is emitted to the air or water, or placed in some type of land disposal).

As mentioned in the 2015 TRI National Analysis, 21,849 facilities reported to TRI that they managed 27.2 billion pounds (12.2 million tonnes) of toxic chemicals related to production-related wastes through recycling, combustion for energy recovery, treatment or disposal (10). As shown in **Figure 2**, quantities of toxic chemicals released decreased while quantities of recycled toxic waste increased. As stated in the 2015 TRI National Analysis, "87% of toxic chemical waste managed was not released into the environment due to the use of preferred waste management practices such as recycling, energy recovery, and treatment".

The 2015 TRI National Analysis also highlights the total quantities of TRI chemicals disposed of or otherwise released by industrial sector (**Figure 3**).

About 3.4 billion pounds (1.5 million tonnes) of toxic chemicals were released, mostly by three sectors: metal mining (37%), chemical manufacturing (15%) and electrical companies (13%). Unfortunately the chemical manufacturing sector is among the leading sectors in both production-related waste managed (49%) as well as total releases (15%).

Throughout the development of the concept of green chemistry over the past 25 years, there have been many considerations on how green chemistry can help minimise toxic waste production and therefore prevent pollution. One way to manage and control toxic waste production is to continuously enforce a set of rules and regulations in order to keep our society and environment safe. These rules require many businesses and corporations to follow strict guidelines in order to meet environmental safety requirements that include "waste handling, treatment, control, and disposal processes" (11). However, these approaches are a costly factor for many businesses and corporations. Companies spend about $1.00 per pound (approximately 0.45 kg) to manage waste (8), which is a direct cost to the business. The major challenge faced by both industries and societies is to expand technological advances in

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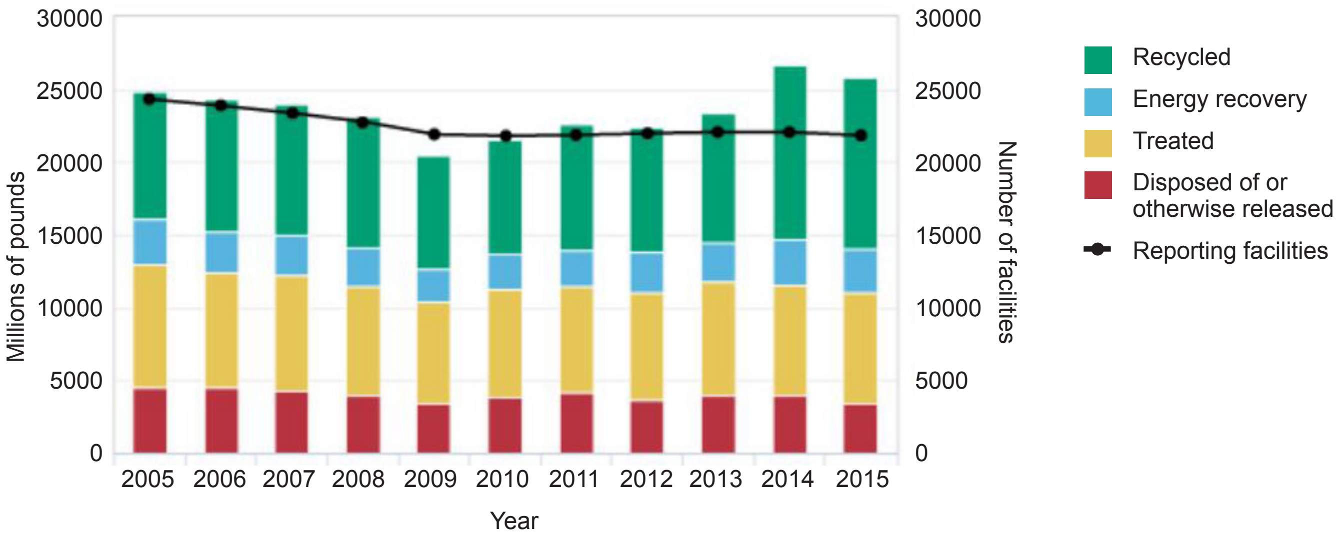

Fig. 2. Production-related waste managed by facilities reporting to TRI over 2005–2015 (10). US EPA's 2015 TRI National Analysis

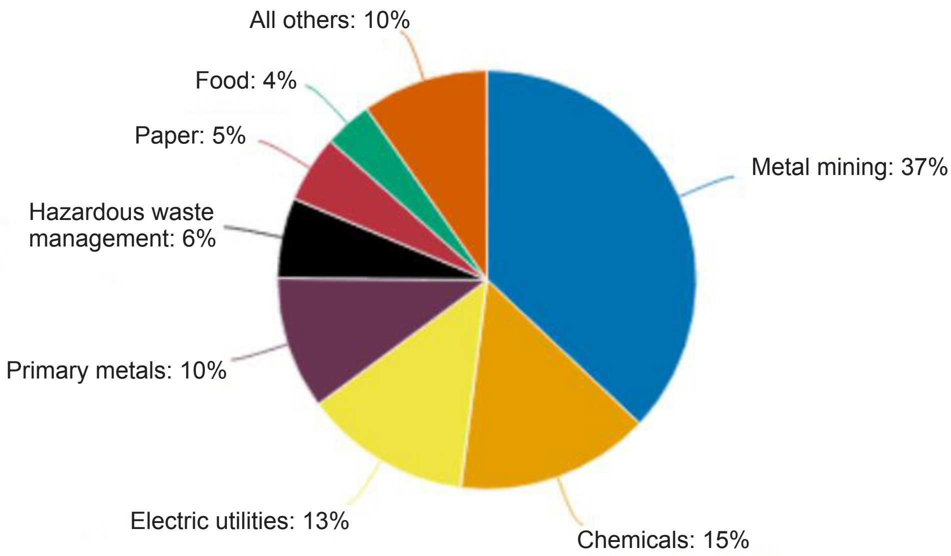

Fig. 3. Total disposal or releases by industrial sector in the USA in 2015: 3.36 billion pounds (1.5 million tonnes) (10). US EPA's 2015 TRI National Analysis

order to achieve more sustainable ways to improve the economy and the environment. As Paul Anastas defines it:

> "we wanted to begin a shift away from regulation and mandated reduction of industrial emissions, toward the active prevention of pollution through the innovative design of production technologies themselves. And we placed an emphasis on both the environmental and economic value, because we knew the concept would not be viable otherwise." (8)

The adoption of green chemistry principles could be seen as a wise means to reduce costs. The businesses and corporations that have implemented green chemistry within their design and manufacturing of chemical products and processes have seen major results on lowered environmental costs and increased sales and revenues. Examples of success stories on how some of the main chemical-based industries have benefited from the adoption of green chemistry principles are highlighted below. The examples given here are based on selecting some of the most

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recent winners of the Presidential Green Chemistry and Engineering Challenge Awards, selecting a variety of industrial sectors where a green chemistry alternative was successful, and ensuring that most of the categories of awards are represented. The authors are not affiliated with any of the industries mentioned below, nor did they receive funding from any of these companies.

Chemical giants and other large companies, such as The Dow Chemical Company, (now merged with E. I. du Pont de Nemours and Company (DuPont)), SC Johnson & Son, Shaw Industries Group Inc, Merck & Co Inc and Pfizer Inc have paved the way to define best industrial practices in green chemistry. Smaller companies such as Patagonia Inc, the Warner Babcock Institute for Green Chemistry LLC, Solazyme Inc (now TerraVia Holdings, Inc) and Verdezyne Inc have also engaged in the application of green chemistry principles.

According to the EPA and based on the winning technologies developed by the Presidential Green Chemistry Challenge Awardees (12):

> "Through 2016, our 109 winning technologies have made billions of pounds of progress, including:
>
> - 826 million pounds [375,000 tonnes] of hazardous chemicals and solvents eliminated each year – enough to fill almost 3800 railroad tank cars or a train nearly 47 miles [75 km] long
> - 21 billion gallons [95 billion litres] of water saved each year – the amount used by 820,000 people annually
> - 7.8 billion pounds [3.5 million tonnes] of carbon dioxide equivalents released to air eliminated each year – equal to taking 810,000 automobiles off the road."

The main industrial sectors where green chemistry has made an impact over the past ten years include but are not limited to: bulk and commodity chemicals, plastics, paints, coatings, pesticides, fuels and pharmaceuticals. Several companies exemplify what green chemistry at work is about. Taking some of the Presidential Green Chemistry and Engineering Challenge Awards winners as examples:

- Representing the bulk and commodity chemicals sector: Solazyme Inc (now TerraVia Holdings, Inc) based in South California developed the production of vegetable oils *via* the fermentation of microalgae. After finding out that microalgae have an inherent ability to produce oils, they used genetic engineering to develop an unlimited variety of triglycerides. Using Solazyme's triglycerides results in lower emissions of volatile organic compounds (VOCs), reduces the quantity of waste produced and lowers the environmental impact compared to traditional petroleum-based oils. Solazyme won the 2014 Presidential Green Chemistry Challenge Award in the Greener Synthetic Pathways category (13).
- In the biodegradable plastics sector: Verdezyne Inc, also based in Southern California, relies on "using the power of biology to make a positive impact on your products". Verdezyne took advantage of the well-known process of fermentation, using yeast to produce everyday products at a lower cost. Their yeast fermentation process works with renewable feedstocks such as low cost plant-based oils, which act as substitutes for petroleum-based products. Their products, such as adipic acid, are intermediates used in the production of nylons and plastics. Verdezyne won one of the Presidential Green Chemistry Challenge Awards in 2016 in the Small Business Award category (14). They recently diversified their 'green' products by partnering with Aceto Corporation to design Ferroshield™ HC, which is a nitrate-free mixture with anti-corrosion properties useful in several applications such as metal cleaners, engine coolants and aqueous hydraulic fluids.
- In 2016, the winner of the new Presidential Green Chemistry Challenge Award in the Specific Environmental Benefit: Climate Change category was Newlight Technologies who developed a low-cost thermoplastic named AirCarbon™ from methane, a potent greenhouse gas. Several well-known companies such as Hewlett-Packard Company, IKEA and Sprint have already adopted AirCarbon™ in the production of their packaging bags, furniture and cell phone cases (15).
- Representing the paint industry: one of the issues in the paint and coatings industry is the emission of large amounts of VOCs when oil-based 'alkyd' paints dry and cure. The well-known paint company Sherwin-Williams developed water-based acrylic alkyd paints with low VOCs that can be made from recycled soda bottle plastic (polyethylene terephthalate (PET)), acrylics and soybean oil. These paints exhibit the same properties as alkyd

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and acrylic paints but with low VOC content, low odour, and non-yellowing properties. In 2010, Sherwin-Williams claimed that the manufacture of this high-performance paint helped to eliminate over 800,000 pounds (360 tonnes) of VOCs (16). Sherwin-Williams won the 2011 Presidential Green Chemistry Challenge Award in the Designing Greener Chemicals Award category.

- Dow AgroSciences LLC participated in the improvement of many pesticides over almost two decades. In the 1990s they developed a biopesticide called spinosad to repel insect pests on vegetables. However, spinosad was not effective for insect-pest control in tree fruits and tree nuts. In 2008 they received the Presidential Green Chemistry Challenge Award in the Designing Greener Chemicals Award category for the design of spinoteram which is a high-performance insecticide efficient when applied to tree fruits, tree nuts, small fruits and vegetables. Spinetoram exhibits the same environmental benefits as spinosad while being less persistent in the environment compared to traditional organophosphate insecticides. Furthermore the toxicity to non-target species is low as well as its use rate (17).
- Two companies, Albemarle Corporation and CB&I Corporation, have developed a greener solid acid catalyst for the production of alkylate, which is a blending component for motor gasoline. The AlkylClean® technology replaces liquid acid, typically hydrofluoric acid or sulfuric acid, with an optimised zeolite-based catalyst. This catalyst eliminates the production of acid-soluble oils and spent acids and bypasses the need for product post-treatment. These two companies were the recipient of the 2016 Presidential Green Chemistry Challenge Award in the Greener Synthetic Pathways category (18).
- Several collaborators developed a greener synthesis of drugs for the treatment of high cholesterol. The latest to date was a collaboration between Codexis Inc and Professor Yi Tang of the University of California, Los Angeles, who used an engineered enzyme and a natural product to manufacture simvastatin, originally sold by Merck under the trade name Zocor® (19). Their efficient biocatalytic process avoids the use of several hazardous chemicals while eliminating waste and, most importantly, meeting the needs of the customers. Codexis and Professor Tang received the 2012 Presidential Green Chemistry Challenge Award in the Greener Synthetic Pathways category.

Communicating these success stories to the next generation of scientists, the students of today, and incorporating these real-world case scenarios in the K-12 curriculum and beyond is the key to generate a systemic interest in the field of green and sustainable chemistry (20, 21).

2.2 In Academia

As mentioned by Haack and Hutchison in a review article titled 'Green Chemistry Education: 25 Years of Progress and 25 Years Ahead' published in 2016, green chemistry was first depicted as a possible solution to improve laboratory safety, to address issues of inappropriate ventilation in laboratories and obsolete laboratory space, and to modernise the chemistry curriculum (22). Nowadays it seems essential for future citizens and leaders of the 21st century to be educated about the concepts of green and sustainable chemistry to participate in the creation of sustainable societies.

Supporters of green chemistry in academia have followed in the footsteps of leading societies such as the ACS, the US EPA and the Royal Society of Chemistry in the UK, to create reliable educational materials and programmes based on the application of green chemistry (2). Some of the educational green chemistry resources available for educators are textbooks, laboratory experiments, summer programmes, workshops, and more recently, the opportunity to continue training and research in green chemistry by enrolling into specialised Masters and PhD programmes.

The goal of this section is not to present an exhaustive list of all initiatives pursued in the academic world but to highlight the main current resources and to share some of the newest initiatives in academia in the past ten years in the USA. Literature and online resources dedicated to green chemistry have grown during this period, especially targeting undergraduate students.

Ten years ago, to discover how much content related to green chemistry was inserted in chemistry textbooks, two surveys were completed as a baseline by publishers' representatives (23). The first survey took place in 2006 at the ACS National Meeting and Exposition, and the second survey was in 2007 at the University of Scranton. For the first survey, nine publishers whose focus is the publication

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of undergraduate textbooks were chosen. These publishers were Benjamin Cummings, Prentice Hall, Houghton Mifflin Company, McGraw-Hill Publishing Company, W. W. Norton & Company, Thomson Corporation, W. H. Freeman and Company, John Wiley and Sons, and Jones & Bartlett Learning. A list of these publishers' undergraduate chemistry textbooks for both chemistry majors and non-chemistry majors was compiled. For the second survey, they gathered information from the same publishers above except for W. W. Norton & Company and Jones & Bartlett Learning. After analysing the data from the two surveys, it was determined that only 33 out of 141 textbooks examined from all of the publishers contained a mention of green chemistry.

Ten years later, textbooks dedicated to green chemistry occupy shelves at most college and university libraries (24–27). While these textbooks target science majors, several textbooks incorporating chemistry in the context of sustainability suitable for non-majors were recently published (28, 29). The wide dissemination of textbooks facilitated the development of single green chemistry-based courses as well as the infusion of green chemistry into typical major courses such as general, organic, inorganic, biochemistry, analytical and physical chemistry (30). Courses may be modified by choosing greener alternatives as replacements to traditional examples. For instance, in an organic chemistry laboratory, procedures can use renewable reagents, apply the metrics of atom economy instead of percent yield, limit the amount of organic solvents and use alternative energy sources such as a microwave. For inorganic chemistry, these alternatives can consist in highlighting reusable catalysts and reagents anchored on inorganic solid supports, decreasing the use of heavy metals and of solid acids and bases. For biochemistry, these alternatives can focus on biocatalysis, biosynthesis and the use of raw materials from renewable resources. For analytical chemistry, reducing the use of column chromatography or high-energy distillations is a step in the direction of green chemistry principles. For physical chemistry, a lesson on the thermochemistry of biodiesel, the use of kinetics and catalysis, and the benefits to using computational studies can be introduced.

However the most prominent place for green chemistry to be taught is still in a laboratory setting. The design of green chemistry laboratory exercises, mostly in organic chemistry, created a successful draw to this 'metadiscipline' (31). Several organic chemistry laboratory manuals are being used to 'green' the curriculum at many US undergraduate and graduate institutions (32–34).

Articles describing the implementation of green chemistry tools and strategies in the classroom or laboratory have seen exponential growth. Some journals publishing this type of content include the *Journal of Chemical Education*, *Science and Education* and *Chemistry Education Research and Practice* as well as *ACS Sustainable Chemistry and Engineering*. The number of articles devoted to examples on how to implement green chemistry in education has doubled since 2007 (22).

There are many online teaching resources that have emerged based on collaborations between advocates for green chemistry. The following resources do not represent an exhaustive list of tools and only a few examples are mentioned here. Some examples include: a database called Greener Educational Materials for Chemists (GEMs) which contains laboratory exercises, course syllabi and multimedia content and was created by the University of Oregon (35). The University of Oregon also created the Green Chemistry Education Network, allowing educators to continue their professional development through collaborating and fostering the integration of green chemistry in education. The non-profit organisation Beyond Benign, based in Wilmington, Massachusetts, USA, is "dedicated to providing future and current scientists, educators and citizens with the tools to teach and learn about green chemistry in order to create a sustainable future". It is focused on K-12 curriculum development and educator training, community outreach and workforce development (36). Another example is the iSUSTAIN™ Green Chemistry Index which is an online tool used to assess the sustainability of products and processes (37).

Mentoring and the creation of a green and sustainable chemistry community of practice is also taking place at conferences and workshops. National and international conferences on sustainability are bringing researchers together from all over the world. Examples of well-known conferences involving presentations of green chemistry educational materials are the national and regional ACS meetings, the Annual Green Chemistry and Engineering Conference and the Biennial Conference on Chemical Education in the USA, as well as international conferences such as the International IUPAC Conference on Green Chemistry, the International Symposium on Green Chemistry and

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the International Conference on Green and Sustainable Chemistry.

To foster critical thinking skills and engage students and faculty, workshops and awards are available. Each year the Green Chemistry Institute at the ACS offers workshops designed for students at the Annual Green Chemistry and Engineering Conference; Beyond Benign designed workshops for K-12 teachers' training as well as online courses for educators; the University of Oregon was one of the pioneers in offering weeklong Green Chemistry Education workshops for educators. Besides the Presidential Green Chemistry and Engineering Challenge Awards for professional chemists, students can also be actively challenged and participate in design competitions such as the People, Prosperity and the Planet (P3) Student Design Competition launched by the EPA in 2002 (38). The goal of this competition is to expand the breadth of participation by involving interdisciplinary teams of students interested in not only chemistry but also engineering, architecture, art and business. The University of Berkeley's Greener Solutions programme gathers both undergraduate and graduate students with local businesses and governmental agencies to come up with greener chemistry solutions in a real-world context (39).

Students have the opportunity to earn awards such as the Ciba Travel Awards in Green Chemistry, which are used for a student to travel to an ACS conference focused on green chemistry; the Joseph Breen Memorial Fellowship, which is for a student to present research on green chemistry at an international green chemistry conference; and the Kenneth G. Hancock Memorial Award, which recognises "outstanding student contributions to furthering the goals of green chemistry through research and/or studies".

Finally, it is possible for undergraduate and graduate students to specialise in the study of green chemistry and earn a degree in this discipline. While most institutions endorse some type of green chemistry programming (courses, laboratory curricula focused on green chemistry, workshops), some universities such as the University of Toledo, Ohio, are offering a BS or an MS degree with a minor in green chemistry and engineering, and Chatham University offers an MS in green chemistry focused on entrepreneurial skills. The University of Massachusetts at both Boston and Lowell offer a PhD in Green Chemistry.

Although progress has been made, it is important to keep in mind that the implementation of green chemistry in the curriculum needs to be tailored to the specific mission and type of institutions involved (four-year undergraduate institutions, community colleges, large research universities). One approach does not fit all. It is also essential that all stakeholders from academia and industry are involved in addressing emerging needs for new content related to toxicology as well as for metrics and best educational practices. To attempt to fill in the gaps, a Green Chemistry Education Roadmap Visioning Workshop took place in September 2015 to delineate "the Roadmap Vision and the set of green chemistry core competencies that every student with a bachelor's degree in chemistry, chemical engineering and allied sciences should attain by graduation" (40). While the roadmap vision is well established as follows: "Chemistry education that equips and inspires chemists to solve the grand challenges of sustainability", the "transformative potential of green chemistry" on society has not been explored yet since the societal impacts are often not taken into account when assessing the entire life cycle of newly designed green chemicals and processes (40). The next section attempts to give examples of how green chemistry is expected to play a role in addressing environmental and human health issues in a social justice context.

2.3 In Society

Even if the field of green chemistry inspires scientists to tackle sustainability-related issues on a global scale, the limited knowledge about the global risk associated with exposure of the human body to chemical pollution is leading to "an emerging perspective that addresses the confluence of social and environmental injustice, oppression for humans and nature, and ecological degradation" (31). Since the development of chemistry has left unintended marks on humans, especially in non-white and low-income communities, it is essential to consider the social consequences of high levels of environmental pollution by hazardous chemicals.

The US EPA defines 'environmental justice' as:

> "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies. EPA has this goal for all communities

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and persons across this nation. It will be achieved when everyone enjoys:

- The same degree of protection from environmental and health hazards, and
- Equal access to the decision-making process to have a healthy environment in which to live, learn, and work." (41)

The EPA recently decided to implement plan EJ 2020 which accounts for "improving the health and environment of overburdened communities". By 2020, they will:

- "Improve on-the-ground results for overburdened communities through reduced impacts and enhanced benefits
- Institutionalize environmental justice integration in EPA decision-making
- Build robust partnerships with states, tribes, and local governments
- Strengthen our ability to take action on environmental justice and cumulative impacts
- Better address complex national environmental justice issues." (42)

Environmental justice and social justice are mutually inclusive as demonstrated in the following definitions of social justice as:

> "A state or doctrine of egalitarianism (Egalitarianism defined as 1: a belief in human equality especially with respect to social, political, and economic affairs; 2: a social philosophy advocating the removal of inequalities among people)"

according to the *Merriam-Webster Dictionary* (43). The National Association of Social Workers states that "Social justice is the view that everyone deserves equal economic, political and social rights and opportunities" (44).

It has been stated that green chemistry "is one of the tools for improving the quality of human life and welfare". Consequently it seems appropriate to refer to the green chemistry philosophy as the spring board to change the negative perception associated with the chemical enterprise and to "reduce the level of social burden on the personnel and people living nearby" (45).

The successful implementation of green chemistry in industry, the role of green chemistry in increasing public well-being and sustainability leadership across disciplines, sectors, and cultures are essential to promote environmental and social justice. To help achieve this goal, the EPA created an interactive environmental justice online map across the USA called EJSCREEN which:

> "highlights low-income, minority communities across the country that face the greatest health risks from pollution. The analysis combines demographic and environmental data to identify where vulnerable populations face heavy burdens from air pollution, traffic congestion, lead paint, hazardous waste sites and other hazards." (46)

Applying the 12 principles of Green Chemistry to address social disparities affecting underprivileged populations can lead to many benefits such as the delineation of methodologies to provide:

i. cleaner air through decreasing the emission of hazardous chemicals during use (such as pesticides) or the unintentional release (during manufacturing or disposal) of toxic chemicals leading to health issues but also global warming, ozone depletion and smog formation
ii. cleaner water by preventing the contamination of drinking water with hazardous chemical wastes
iii. increased safety for workers using chemicals as part of their profession so that the use of toxic materials is minimised and the need for personal protective equipment is lessened
iv. safer consumer products such as the production of pharmaceutical drugs with less waste and the replacement of cleaning products and pesticides with safer alternatives
v. safer food based on the reduction of the amount of persistent toxic chemicals present in pesticides or as endocrine disruptors (47).

Aligned with the leadership approach of the EPA, scientists are motivated to determine that chemical exposures fluctuate with social disparities. The following section highlights examples where social injustices stemming from chemical exposure have been the subject of peer-reviewed research. An attempt to demonstrate how green chemistry principles can help address these social disparities is also presented.

2.3.1 Pesticides Exposure and Farmworkers

The population of farmworkers in the USA is severely affected by pesticides exposure. It is estimated that of the 2.5 million farmworkers in the USA, 60% of them and their dependents live in poverty (48). About 88% of all farmworkers are Hispanic and more than 78% of them are foreign-born without legal documentation and no higher education (49).

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Issues associated with the language barrier and the lack of health insurance coverage were brought up in a report titled 'Exposed and Ignored. How Pesticides are Endangering our Nation's Farmworkers' in 2013 (48). A study conducted by Washington State Department of Health showed that only 29% of pesticide handlers were able to read in English and to some extent in Spanish. Analysis of the blood work of pesticide handlers who could not read English showed significantly greater pesticide exposure compared to those who could read English to some degree.

Pesticide poisoning or exposure causes farmworkers to suffer more chemical-related injuries and illnesses than any other workforce in the USA (48). Worldwide, 25 million agricultural workers experience pesticide poisonings each year (50). Protective clothing does not provide adequate protection against pesticide exposure, especially when handling organophosphate and *N*-methyl carbamate pesticides. Since pesticide residues are often invisible and odourless, only a blood test would be useful to monitor exposure to these toxic chemicals.

In a thorough report titled 'Green Chemistry and Sustainable Agriculture: The Role of Biopesticides' by Peabody O'Brien *et al*. in 2009, the role of green chemistry applied to the agricultural world and biopesticides in particular was validated (51). Biopesticides are derived from plants or from microbial pesticides. They are less toxic, more pest specific, they biodegrade more quickly and do not affect the ecological balance.

Another approach is outlined in the Green Chemistry Principle #7: "Chemists should, whenever possible, use raw materials and feedstocks that are renewable". Green chemists are currently using agricultural waste products as renewable feedstocks and are synthesising biocatalysts to increase the "conversion of agricultural materials into high value products, including novel carbohydrates, polysaccharides, enzymes, fuels and chemicals" (3). As explicitly mentioned in the Peabody O'Brien report:

> "Green Chemistry and sustainable agriculture are inherently intertwined; farmers need green chemists to make safe agricultural chemical inputs. Green chemists need farmers practicing sustainable agriculture to provide truly "green" bio-based raw materials to process into new products." (51)

Additionally, as defined in the Green Chemistry Principle #10: "Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment" (3). The challenge to remove pesticide residues in the soil, water and air has led scientists at Carnegie Mellon University to develop specific TAMLs® catalysts targeting the degradation of pollutants from water without presenting endocrine disrupting activity (52).

Another example based on the control of pests affecting vineyards, the goal of research conducted by Jocelyn Millar at the University of California at Riverside was to "identify less-toxic pesticides that may be effective alternatives to organophosphates". Instead of using heavy loads of pesticides, the group developed a pheromone to control the vine mealybug population based on mating disruption. Their pheromone was not only successful in trapping the vine mealybugs but was also beneficial to attract the vine mealybugs' predators, which was an unexpected benefit to the preservation of the ecological balance and of the natural predator populations (51).

2.3.2 Exposure to Endocrine Disruptor Bisphenol A and Children

Bisphenol A (BPA), a synthetic organic compound used to make plastics and epoxy resins for a variety of common consumer goods, has been under scrutiny since 2008 when several governmental agencies investigated its safety, especially with respect to its use in baby bottles and 'sippy' cups. BPA and polyfluoroalkyl chemicals (PFCs) are oestrogen-like chemicals found to "disrupt reproductive development, body weight and metabolic homeostasis, and neurodevelopment, and to cause mammary and prostate cancer." Many comprehensive reviews regarding the impacts of BPA on health have been published (53–55).

While concerns about the potential hazards of endocrine-disrupting chemicals such as BPA are still debated, and after several countries have banned its use, a study published by Nelson *et al*. in 2012 addressed the population disparities in exposure to these chemicals. Their findings demonstrated that:

> "people with lower incomes, who may be more likely to suffer from other disparities in health and exposures, have a greater burden of exposure to BPA. The results for children are especially troubling. Children overall had higher urinary BPA concentrations than teenagers or adults, but children whose food security was very low or who received emergency food assistance - in

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> other words, the most vulnerable children - had the highest levels of any demographic group. Their urinary BPA levels were twice as high as adults who did not receive emergency food assistance. Concerns about health effects from BPA exposure are strongest for young children and neonates because they are still undergoing development. Results for BPA by race/ethnicity, adjusting for income, revealed that Non-Hispanic Whites and Blacks had similar urinary levels, and being Mexican American appeared to be highly protective." (56)

It is thought that:

> "eating more fresh fruits and vegetables is likely to be associated with eating less canned foods, which may explain the lower urinary BPA levels seen in Mexican Americans compared to other groups." (57)

Several companies are now selling BPA-free products but do not always inform what substitute is being used. It is even considered that some of the BPA-free alternatives may actually not be safer than their BPA-containing counterparts. Karen Peabody O'Brien, former Executive Director of the scientific foundation Advancing Green Chemistry, and John Peterson Myers, CEO and Chief Scientist at Environmental Health Sciences, both located in Charlottesville, Virginia, have suggested using green chemistry tools to create:

> "a new generation of non-petroleum-based materials from scratch, simultaneously protecting public and environmental health while reducing dependence on foreign oil" (58).

In 2014, Richard Wool and his research group at the University of Delaware achieved that by converting lignin fragments, a waste product of the papermaking and other wood-pulping processes, to a compound called bisguaiacol-F (BGF). BGF has the same shape as BPA, but does not interfere with hormones and retains the desirable thermal and mechanical properties of BPA (59).

2.3.3 Contaminated Drinking Water and Air in Poor Communities

The most recent example of social injustice was the water crisis in Flint, Michigan. When the town of Flint switched the source of water for its residents in 2014, corrosion inhibitors were forgotten to be added to the new water source, which caused lead levels to raise to 25 ppb (above the maximum level of 15 ppb set by the EPA). Residents complained numerous times about the strange taste and colour of the water but no further investigation was conducted. Thousands of children among the majority of the African American population of Flint were exposed to lead without being properly informed since this information was not made public. It was not until January 2016 that a federal state of emergency was declared (60). In March 2017, the EPA awarded US$100 million to the State of Michigan to upgrade Flint water infrastructure, especially lead service lines (61).

While the cause of the increased level of lead in Flint's potable water was due to corrosion in the lead and iron pipes that distribute water to city residents, green chemistry has been at work to provide environmentally friendly alternatives to chemical water treatment such as the use of nanomaterials (62), the use of 'green additives' (63) or the use of photocatalysts (64).

Some green chemistry advocates are concentrating their efforts to address the social and environmental (in)justice of chemical exposure using the concept of sustainable chemistry as framework in their academic research and outreach efforts. This has become a priority at academic institutions such as Bridgewater State University where Professor Ed Brush is starting a Participatory Action Research programme (65). In this programme the community will be involved in research projects targeting social injustice. His research students are interested in assessing the impacts of diesel particulate matter emissions on populations with a high risk of developing asthma such as females, children, people of colour and people of mixed race as well as those living in poverty or with low incomes. The plan is for students to collect data using air collectors and then report their findings related to diesel exhaust pollutants' impact on health. The ultimate goal is to delineate how green chemistry principles can be put to work to decrease the exposure of minorities to diesel exhaust pollution. It is expected that studies related to biofuels will inspire their green chemistry proposal to reduce social disparities due to exposure to emissions exhaust (66–68).

3. Conclusions

Advances in chemical knowledge and research have brought great progress to the field of green and sustainable chemistry. As mentioned earlier this article was written in the context of attracting attention to problems related to chemical pollution and resource depletion and it also proposes some alternatives related

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to the application of green chemistry. The overall goal was to demonstrate that the significant development of green and sustainable chemistry has opened up a new way of performing and teaching chemistry, demonstrating that green chemistry is applicable to all fields of research and that it should not be a tradeoff between cost and environmental impact. In industry, while the implementation of green chemistry is driven by government regulations, consumer awareness and higher demand for more environmentally benign products, the rate of adoption is slow. In 2015, T. Fennelly & Associates, Inc identified some possible accelerators of green chemistry adoption such as (69):

- Collaborative efforts relying on establishing price and performance trade-offs where transparency is addressed and where "open innovation" is welcome. The word "coopetition" has been used "as a model to drive competition and innovation" while simultaneously enabling the growth of green chemistry
- Compromise is a step in the right direction. When companies shift away from regulations and mandated reduction of industrial emissions towards active pollution prevention, continuous improvement of a product will be justified for its economic and environmental value
- Finally, continued and enhanced education in green and sustainable chemistry is crucial among the work force.

Even if the implementation of green chemistry practices in industry face adversity, strategies have been identified to accelerate the adoption of green chemistry such as: continued research and communication among all stakeholders; support for 'smart' policies that enhance green chemistry innovation and adoption; fostering collaboration; dissemination of information to the marketplace; and tracking of progress using metrics (1).

With educators passionate about the green and sustainable chemistry field, not only are institutions taking an interest in promoting the 'green' concept to their students, there are also plenty of resources available to encourage them to make a difference. The incorporation of green chemistry-based courses and the design of academic degrees in green chemistry is vital to establishing awareness and knowledge of environmentally benign chemistry. Students, who gain insight about how green chemistry can positively impact local communities as well as the entire world, enter the work force with a head start and a sense of ethical empowerment on how to solve existing challenges using green and sustainable chemistry principles.

Although many educational materials are available, challenges remain for academia, such as (22):

- The slow implementation of green chemistry in the undergraduate and graduate curriculum based on a "lack of uniform demand", which can be perceived as curricular conservatism from academic and industrial stakeholders
- "The resistance to infuse green chemistry into the main general and organic chemistry textbooks or the ACS standardized exams" which does not motivate departments to make changes in their curriculum
- The lack of expertise and confidence from inexperienced educators to help students learn about green and sustainable chemistry, and
- Finally, the presence of key gaps in terms of content such as the introduction of toxicology and metrics as well as well-defined curricular objectives and assessments.

Through the applications of green chemistry in industry and academia, it has been shown how green chemistry can make a difference in the sustainable development of human civilisation. While this article described some of the efforts undertaken in the USA, the scope of this article could be expanded by highlighting efforts outside the USA such as the commitment of the United Nations to develop 17 sustainable development goals to transform our world (70). Additionally chemical companies around the world such as Dow Chemical Company designed their own set of sustainability goals to help "redefine the role of business in society" (71).

Recognised as a means to aid society to live longer and better, green chemistry's focus on the humanistic level will drive modern society in the direction of global sustainability.

References

1. "An Agenda to Mainstream Green Chemistry", Green Chemistry & Commerce Council, Massachusetts, USA, 2015, 28 pp
2. 'Basics of Green Chemistry', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/greenchemistry/basics-green-chemistry (Accessed on 5th May 2017)
3. P. T. Anastas and J. C. Warner, "Green Chemistry: Theory and Practice", Oxford University Press, New York, USA, 1998, 135 pp

 © 2017 Johnson Matthey

4. M. V. Orna, *J. Chem. Educ.* 2009, **86**, (10), 1172
5. "Our Common Future: Report of the World Commission on Environment and Development", A/42/427, UN Documents, United Nations, Secretary General, New York, USA, 4th August, 1987
6. 'Essential Reading: The Five Domains of Sustainability: A Paradigm for Urban Management', Joslyn Institute for Sustainable Communities, Nebraska, USA: http://joslyninstitute.org/resources/the-five-domains-of-sustainability/ (Accessed on 29th June 2017)
7. M. Tatum, 'What is Economic Sustainability?', wiseGEEK, Conjecture Corp, Nevada, USA, 19th April, 2017
8. S. K. Ritter, *Chem. Eng. News*, 2016, **94**, (27), 22
9. 'Learn about the Toxics Release Inventory', Toxics Release Inventory (TRI) Program, US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/toxics-release-inventory-tri-program/learn-about-toxics-release-inventory (Accessed on 5th May 2017)
10. '2015 TRI National Analysis: Executive Summary', Toxics Release Inventory (TRI) Program, US Environmental Protection Agency, Washington, DC, USA, 17th January, 2017
11. P. T. Anastas and T. C. Williamson, 'Green Chemistry: An Overview', in "Green Chemistry: Designing Chemistry for the Environment", ACS Symposium Series, Vol. 626, American Chemical Society, Washington, DC, USA, 1996, pp. 1–17
12. 'Information About the Presidential Green Chemistry Challenge', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/greenchemistry/information-about-presidential-green-chemistry-challenge (Accessed on 5th May 2017)
13. 'Solazyme Wins 2014 Presidential Green Chemistry Challenge Award', Solazyme, Inc, Washington, DC, USA, 16th October, 2014
14. 'Verdezyne Wins Presidential Green Chemistry Challenge Award', Verdezyne, Inc, Carlsbad, CA, USA, 14th June, 2016
15. 'EPA Honors Winners of the 2016 Presidential Green Chemistry Challenge Awards', US Environmental Protection Agency, Washington, DC, USA, 13th June, 2016
16. 'Presidential Green Chemistry Challenge: 2011 Designing Greener Chemicals Award, The Sherwin-Williams Company, Water-based Acrylic Alkyd Technology', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2011-designing-greener-chemicals-award (Accessed on 18th May 2017)
17. 'Presidential Green Chemistry Challenge: 2008 Designing Greener Chemicals Award, Dow AgroSciences LLC, Spinetoram: Enhancing a Natural Product for Insect Control', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2008-designing-greener-chemicals-award (Accessed on 18th May 2017)
18. 'Albemarle and CB&I win EPA Green Chemistry Award for AlkyClean® Process Technology', Albemarle Corp, Charlotte, NC, USA, 14th June, 2016
19. W. W. Kromhout, 'UCLA's Yi Tang receives Presidential Green Chemistry Challenge Award from EPA', UCLA Newsroom, Office of Media Relations, California, USA, 19th June, 2012
20. J. W. Moore, *J. Chem. Educ.,* 2006, **83**, (8), 1111
21. C. Kitchens, R. Charney, D. Naistat, J. Farrugia, A. Clarens, A. O'Neil, C. Lisowski and B. Braun, *J. Chem. Educ.*, 2006, **83**, (8), 1126
22. J. A. Haack and J. E. Hutchison, *ACS Sustainable Chem. Eng.*, 2016, **4**, (11), 5889
23. M. C. Cann, 'Greening the Chemistry Lecture Curriculum: Now is the Time to Infuse Existing Mainstream Textbooks with Green Chemistry', in "Green Chemistry Education: Changing the Course of Chemistry", eds. P. T. Anastas, I. J. Levy and K. E. Parent, ACS Symposium Series, Vol. 1011, American Chemical Society, Washington, DC, USA, 2009, pp. 93–102
24. V. M. Kolb, "Green Organic Chemistry and its Interdisciplinary Applications", CRC Press, Florida, USA, 2016, 175 pp
25. A. E. Marteel-Parrish and M. A. Abraham, "Green Chemistry and Engineering: A Pathway to Sustainability", John Wiley & Sons, Inc, New Jersey, USA, 2013, 376 pp
26. C. Jiménez-González and D. J. C. Constable, "Green Chemistry and Engineering: A Practical Design Approach", John Wiley & Sons, Inc, New Jersey, USA, 2011, 696 pp
27. M. Lancaster, "Green Chemistry: An Introductory Text", 2nd Edn., RSC Publishing, Cambridge, UK, 2010, 340 pp
28. J. W. Hill, T. W. McCreary and D. K. Kolb, "Chemistry for Changing Times", 13th Edn., Prentice Hall, New Jersey, USA, 2011, 800 pp
29. C. H. Middlecamp, M. T. Mury, K. L. Anderson, A. K. Bentley, M. C. Cann, J. P. Ellis and K. L. Purvis-Roberts, "Chemistry in Context: Applying Chemistry to Society", 8th Edn., McGraw-Hill Education, New York,

 © 2017 Johnson Matthey

USA, 2015, 592 pp

30. M. E. Kerr and D. M. Brown, 'Using Green Chemistry to Enhance Faculty Professional Development Opportunities', in "Green Chemistry Education: Changing the Course of Chemistry", ACS Symposium Series, Vol. 1011, American Chemical Society, Washington, DC, USA, 2009, pp. 19–36
31. J. Sjöström, I. Eilks and V. G. Zuin, *Sci. & Educ.*, 2016, **25**, (3), 321
32. S. A. Henrie, "Green Chemistry Laboratory Manual for General Chemistry", CRC Press, Florida, USA, 2015, 384 pp
33. "Green Organic Chemistry in Lecture and Laboratory", ed. A. P. Dicks, CRC Press, Florida, USA, 2011, 298 pp
34. K. M. Doxsee and J. E. Hutchison, "Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments", Brooks/Cole, Cengage Learning, California, USA, 2003, 256 pp
35. 'Greener Education Materials for Chemists (GEMs)', Department of Chemistry, University of Oregan and CET Interactive Media, Oregon, USA: http://greenchem.uoregon.edu/gems.html (Accessed on 5th May 2017)
36. 'Our Mission', Beyond Benign, Wilmington, MA, USA: http://www.beyondbenign.us/home/about/about.html (Accessed on 5th May 2017)
37. K. Koster and M. Cohen, 'Practical Approaches to Sustainability: iSUSTAIN™ Tool for Green Chemistry Case Study', in "Treatise on Sustainability Science and Engineering", eds I. S. Jawahir, S. K. Sikdar and Y. Huang, Springer, The Netherlands, 2013, pp. 81–108
38. 'People, Prosperity and the Planet (P3) Student Design Competition', P3 Program, US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/P3 (Accessed on 5 May 2017)
39. 'Greener Solutions 2015', Berkeley Center for Green Chemistry, Berkeley, USA: https://bcgc.berkeley.edu/greener-solutions-2015/ (Accessed on 5 May 2017)
40. 'Education Roadmap', Green Chemistry, American Chemical Society, Washington, DC, USA: https://www.acs.org/content/acs/en/greenchemistry/students-educators/education-roadmap.html (Accessed on 5th May 2015)
41. 'Environmental Justice', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/environmentaljustice (Accessed on 5th May 2017)
42. 'Environmental Justice: About EJ 2020', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/environmentaljustice/about-ej-2020 (Accessed on 5th May 2017)
43. 'Social Justice', Merriam-Webster, Inc, Springfield, MA, USA: https://www.merriam-webster.com/dictionary/social%20justice (Accessed on 5 May 2017)
44. G. Dolan-Reilly, 'The Definition of Social Justice', Social Justice Solutions, New York, USA, 15th January, 2013
45. N. P. Tarasova, A. S. Makarova and F. I. Ingel, *Pure Appl. Chem.*, 2016, **88**, (1–2), 37
46. 'EJSCREEN: Environmental Justice Screening and Mapping Tool', US Environmental Protection Agency, Washginton, DC, USA: https://www.epa.gov/ejscreen (Accessed on 5th May 2017)
47. 'Benefits of Green Chemistry', US Environmental Protection Agency, Washington, DC, USA: https://www.epa.gov/greenchemistry/benefits-green-chemistry (Accessed on 5th May 2017)
48. 'Exposed and Ignored: How Pesticides are Endangering our Nation's Farmworkers', Farmworker Justice, Washington, DC, USA, 2013, 18 pp
49. 'Farm Workers and Immigration', National Farm Worker Ministry, Raleigh, USA: http://nfwm.org/education-center/farm-worker-issues/farm-workers-immigration/ (Accessed on 5 May 2017)
50. M. C. R. Alavanja, *Rev. Environ. Health*, 2009, **24**, (4), 303
51. K. Peabody O'Brien, S. Franjevic and J. Jones, "Green Chemistry and Sustainable Agriculture: The Role of Biopesticides", Advancing Green Chemistry, Charlottesville, USA, September, 2009
52. W. C. Ellis, C. T. Tran, R. Roy, M. Rusten, A. Fischer, A. D. Ryabov, B. Blumberg, and T. J. Collins, *J. Am. Chem. Soc.*, 2010, **132**, (28), 9774
53. C. A. Richter, L. S. Birnbaum, F. Farabollini, R. R. Newbold, B. S. Rubin, C. E. Talsness, J. G. Vandenbergh, D. R. Walser-Kuntz and F. S. vom Saal, *Reprod. Toxicol.*, 2007, **24**, (2), 199
54. L. N. Vandenberg, M. V. Maffini, C. Sonnenschein, B. S. Rubin and A. M. Soto, *Endocr. Rev.*, 2009, **30**, (1), 75
55. F. S. vom Saal, B. T. Akingbemi, S. M. Belcher, L. S. Birnbaum, D. A. Crain, M. Eriksen, F. Farabollini, L. J. Guillette Jr., R. Hauser, J. J. Heindel, S.-M. Ho, P. A. Hunt, T. Iguchi, S. Jobling, J. Kanno, R. A. Keri, K. E. Knudsen, H. Laufer, G. A. LeBlanc, M. Marcus, J. A. McLachlan, J. P. Myers, A. Nadal, R. R. Newbold, N. Olea, G. S. Prins, C. A. Richter, B. S. Rubin, C. Sonnenschein, A. M. Soto, C. E. Talsness, J. G. Vandenbergh, L. N. Vandenberg, D. R. Walser-Kuntz, C. S. Watson, W. V. Welshons, Y. Wetherill and R. T. Zoeller, *Reprod. Toxicol.*, 2007, **24**, (2), 131
56. 'NTP-CERHR Monograph on the Potential Human Reproductive and Developmental Effects of

 © 2017 Johnson Matthey

Bisphenol A', NIH Publication No. 08–5994, CERHR (Center for the Evaluation of Risks to Human Reproduction), US Department of Health and Human Services, National Toxicology Program, Durham, USA, 2008, 395 pp

57. J. W. Nelson, M. Kangsen Scammell, E. E. Hatch and T. F. Webster, *Environ. Health*, 2012, **11**, 10
58. L. Peeples, 'Toxic Chemical BPA Under Attack, but Alternatives may not be Safer, Experts Say', TheHuffingtonPost.com, Inc, New York, USA, 23rd February, 2012
59. 'Potentially Safer, Greener Alternative to BPA could come from Papermaking Waste', ScienceDaily, Rockville, USA, 16th March, 2014
60. J. Durando, 'How Water Crisis in Flint, Mich., Became Federal State of Emergency', USA TODAY, a division of Gannett Satellite Information Network, LLC, USA, 19th January, 2016
61. 'EPA Awards $100 Million to Michigan for Flint Water Infrastructure Upgrades', News Releases from Headquarters, US Environmental Protection Agency Media Relations, Washington, DC, USA, 17th March, 2017
62. C. Santhosh, V. Velmurugan, G. Jacob, S. K. Jeong, A. N. Grace and A. Bhatnagar, *Chem. Eng. J.*, 2016, **306**, 1116
63. E. Mavredaki, A. Stathoulopoulou, E. Neofotistou and K. D. Demadis, *Desalination,* 2007, **210**, (1–3), 257
64. V. Likodimos, D. D. Dionysiou, and P. Falaras, *Rev. Environ. Sci. Biotechnol.*, 2010, **9**, (2), 87
65. E. Brush, 'Exploring Social and Environmental Justice Through Green Chemistry Education, Research, and Outreach (GCE 119)', 20th Annual Green Chemistry and Engineering Conference, 14th–16th June, 2016, Portland, USA, online video clip, American Chemical Society, 15th June, 2016
66. D. An, Y. Guo, Y. Zhu and Z. Wang, *Chem. Eng. J.,* 2010, **162**, (2), 509
67. V. Kumar and P. Kant, *Petrol. Coal*, 2013, **55**, (3), 207
68. B. R. Kumar, S. Saravanan, D. Rana, V. Anish and A. Nagendran, *Energy Convers. Manage.*, 2016, **118**, 275
69. T. Fennelly & Associates, Inc, Minneapolis, USA, "Advancing Green Chemistry: Barriers to Adoption & Ways to Accelerate Green Chemistry in Supply Chains", A Report for the Green Chemistry & Commerce Council (GC3), University of Massachusetts, Iowa, USA, March, 2015
70. Resolution adopted by the General Assembly on 25 September 2015, 'Transforming our World: the 2030 Agenda for Sustainable Development', A/RES/70/1, United Nations, General Assembly, New York, USA, 21st October, 2015
71. 'Dow Launches 2025 Sustainability Goals to Help Redefine the Role of Business in Society', The Dow Chemical Company, Midland, MI, USA, 15th April, 2015

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