IV. Enabling policies and action to support innovative solutions

About Part IV

Advancing a chemistry that is fully sustainable is dependent on scaling up innovative solutions; engaging new actors; and putting in place enabling policies. Innovative solutions complement long-standing measures to achieve the sound management of chemicals and waste, as discussed in Part III. They are an essential element in achieving the sound management of chemicals and waste. While the topics discussed in Part IV have been the subject of discussions and action taken at national and international level to varying degrees, they have by and large not received the attention warranted in the context of chemicals and waste. Opportunities therefore exist to explore their role in a beyond 2020 framework.

Relevant enabling policies and actions include education reform; support for technology innovation and financing; innovative business models; sustainable supply chain management; private sector metrics and reporting; fiscal incentives; and the empowerment of workers, consumers and citizens through information and participation rights. In exploring these topics, Part IV thus also draws attention to the contributions that can be made by a diverse range of actors, including entrepreneurs, academics, retailers, policymakers and citizens.

Contents

1/ Envisioning and shaping the future of chemistry 504

2/ Green and sustainable chemistry education: nurturing a new generation of chemists 515

3/ Strengthening sustainable chemistry technology innovation and financing 524

4/ Evolving and new business models 542

5/ Fiscal incentives to advance sound chemicals management and sustainable chemistry 555

6/ Sustainable supply chain management for chemicals and waste in the life cycle 564

7/ Sustainability metrics and reporting: measuring progress, strengthening accountability 575

8/ Empowering and protecting citizens, workers and consumers 586

References 604

1/ Envisioning and shaping the future of chemistry

Chapter Highlights

Innovations in chemistry, together with non-chemical alternatives, have significant potential to address societal needs and sustainable development challenges.

Sustainable chemistry is evolving as a holistic concept that embraces green chemistry, and that may serve as a reference for innovations in (or related to) chemistry.

The market for green and sustainable chemistry is growing in all regions, but is still modest compared to the overall chemistry market.

The Fourth Industrial Revolution, and digitalization of the chemical industry, provide opportunities to advance sustainability in the chemical industry.

A balance is needed between embracing the potential benefits of chemistry and recognizing challenges (e.g. the importance of addressing legacies).

1.1 Solutions shaped by chemistry are on the horizon

For more than a century the chemical industry has led innovations in areas including pharmaceuticals, plastics and consumer electronics that have transformed the way people live around the world. In particular, the period from the 1950s through the 1970s witnessed a wave of innovations in chemistry, with dozens of new chemicals and compounds discovered and commercialized. From 1980, however, new product development slowed down and few new blockbuster chemicals entered the market. During that time the global chemical industry focused on expanding to new markets, often selling chemicals invented long before such as polyvinyl chloride (PVC) (invented in 1913), polyethylene (1936) and polypropylene (1954). Return on investments from growth in new markets was more attractive than the return from innovation (Sarathy, Gotpagar and Morawietz 2017).

Today this situation is evolving. Lower profits from bulk chemicals, recent innovations in chemistry and advanced materials, and the challenge for the chemical industry to help meet the Sustainable Development Goals (SDGs) are creating new opportunities for chemistry to help meet society's needs. Examples are numerous and include the following:

- *Revolutionizing energy storage and battery development*: Fast-charging solid-state batteries, based on chemistry innovations, have the potential to revolutionize electric mobility. Not only can they be charged 10 times faster than traditional lithium-ion batteries, but they are safer as they cannot catch fire, are more reliable and are longer lasting.

© NASA/Dimitri Gerondidakis, a thin solid-state battery

- *Improving the biodegradability of bio-based plastics:* Biodegradable plastics, derived from agricultural or wood-based biomass, are compatible with home and municipal composting systems, have less environmental impact and can be incorporated into composting infrastructure. They can also form feedstocks for bioenergy and other circular economy applications.

- *Creating sustainable building materials:* Chemistry plays a key role in creating a new generation of sustainable and high-performing building materials. Examples include transparent wood, green concrete, wood foam insulation, and earthquake resistant bricks.

- *Turning carbon dioxide (CO_2) and wastes into chemical feedstocks:* Creating feedstocks that are not fossil fuel-based from CO_2 using renewable energy not only reduces greenhouse gas (GHG) emissions; it also advances circularity in the chemical industry by providing chemical feedstocks that are not derived from oil or bio-based materials.

- *Developing "advanced materials":* This involves developing materials and modifying existing ones to obtain superior performance in regard to one or more characteristics that are critical to the application under consideration, such as waterproofing textiles. These materials can also have completely novel properties, as seen, for example, in nanomaterials.

While such opportunities are promising, more thorough assessments are needed to obtain a full (or better) understanding of the sustainability aspects of these innovations, taking into account the criteria and tools discussed in Part III and in the remainder of this chapter.

Research across the disciplines of chemistry, biology and computer science is particularly promising. The 2018 Nobel Prize in Chemistry, for example, was awarded for path-breaking research on how chemists produce new enzymes, leading to new pharmaceuticals and cancer treatments and less waste. Another promising development is the use of advanced software and supercomputers to design molecules and assess the properties of chemicals, including their hazards. These developments have significant potential to advance the sound management of chemicals and waste, and to complement other measures in order to achieve sustainable production and consumption.

Chemistry is at the core of future industry sectors

The contribution of chemistry to a range of end markets was presented in Part I. Some of these markets are of particular relevance to shaping the future of sustainable development – from the transportation industry, to the construction industry and urbanization, to food and packaging, to waste management. For example, the transportation and construction industries have a range of requirements that can be met through chemistry and sustainable materials innovations.

Figure 1.1 Examples of how chemistry contributes to industries expected to play important roles in the future (adapted from World Economic Forum [WEF] 2017, p. 7)

		Projected growth rates for key innovations	Examples of relevant products from chemistry and advanced materials
Mobility	Electric vehicles	Annual sales of electric vehicles 2020: US dollars 4.9 million	Plastics, composites and battery technologies
	Drones	Market size for drones* 2015: US dollars 10.1 billion 2020: US dollars 14.9 billion	Plastics, composites and battery technologies
Mobile and smart devices	Smartphones and tablets	Mobile devices in use 2015: US dollars 8.6 billion 2020: US dollars $12.1 billion	Substrate, backplane, transparent conductor, barrier films and photoresists
	Flexible displays (e.g. wearable devices, virtual reality, TVs)	Market for AMOLED** displays 2016: US dollars 2 billion 2020: US dollars 18 billion	Substrate, backplane, transparent conductor, barrier films and photoresists
Connectivity and computing	High-speed internet	Fixed broadband speed 2015: 24.7 Mbps 2020: 47.7 Mbps	Chlorosilane for ultrapure glass
	More efficient and smaller integrated circuits	Processor logic gate length 2015: 14 mm 2020: 7 mm	Dielectrics, colloidal silica, photoresists, yield enhancers and edge bead removers

* Defence, commercial and homeland security sectors ** Active-matrix organic LED

Figure 1.1 shows how chemistry contributes to industries which are expected to play key roles in the future.

Innovations also include non-chemical alternatives

The concept of non-chemical alternatives is receiving wide attention, including by international policy bodies such as the United Nations Environment Assembly (UNEA), in research and innovation, in the private sector, and by non-governmental organizations (NGOs). Although a definition of the concept of non-chemical alternatives does not exist, the connotation is that innovations can often produce a desired function or benefits without an alternative synthetic chemical. For example, a retailer in Denmark launched a new fluorinated chemicals-free microwave oven popcorn bag made from cellulose that is impermeable to fat (Stieger 2015). The new product has become a commercial success. In the agriculture sector, the well-known concept of Integrated Pest Management (IPM) promotes a range of biological measures to eliminate or reduce the use of pesticides.

1.2 Green and sustainable chemistry: setting the standard

Lessons learned from innovations in chemistry

Some chemistry innovations, acknowledged for their positive contributions to society, were recognized years later to have unexpected and undesirable effects when additional knowledge became available. For example, dichloro-diphenyl-trichloroethane (DDT) was synthesized in 1874 and its use spread around the world once its insecticidal action was discovered in 1939. DDT helps fight diseases such as malaria, yellow fever and West Nile virus. At the time it began to be used, however, little was known about its detrimental impact on human health and the environment. Similarly, chlorofluorocarbons (CFCs) enabled the use of refrigeration by large populations. It was only years later that their damaging impact on the ozone layer was understood. Again, when celluloid was invented to replace ivory billiard balls in the 19th century (inspiring the development of further petroleum-based plastic products), it would have been impossible to foresee the vast volumes of plastic that would be produced and eventually released to the environment.

Green and sustainable chemistry as an evolving benchmark

As discussed in Parts II and III, knowledge, assessment tools and legislative instruments are available and used in many countries, albeit not globally, to ensure that new substances which may have adverse impacts on health and the environment do not reach the market. Furthermore, more detailed criteria are becoming available to assess the extent to which a chemistry innovation is fully compatible with the three pillars of sustainable development (economic, environmental and social). The concepts of green chemistry and sustainable chemistry provide promising guidance in this regard.

The term "green chemistry" was first used in the early 1990s. It gained momentum after it received support by the United States Environmental Protection Agency (US EPA) (Linthorst 2010). At the end of the 1990s Anastas and Warner defined green chemistry as "the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacturing and application of chemical products" (Anastas and Warner 1998). They also proposed 12 Principles of Green Chemistry (Box 1.1). In a related development in Europe, similar principles were included in the Council Directive on integrated pollution prevention and control (European Commission [EC] 1996). Research related to green chemistry has made possible a wide range of developments in the fields of bio-based chemicals, renewable feedstocks, safer solvents and reagents, atom economy, green polymers, and less toxic chemical formulations (Anastas and Warner 1998; Philp, Ritchie and Allan 2013).

As a spin-off from work on green chemistry, a set of nine Principles of Green Engineering, now known as the Sandestin Declaration, were developed in 2003 (Abraham and Nguyen 2003). Green engineering goes beyond baseline engineering quality and safety specification to consider broader economic, environmental and social factors (Anastas and Zimmerman 2003). Other important developments compatible with green chemistry took place in the same period. They include the European Communities Chemistry

Box 1.1 **The 12 Principles of Green Chemistry (Anastas and Warner 1998)**

1. *Prevention*: it is better to prevent waste than to treat or clean up waste after it has been created.

2. *Atom economy*: synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

3. *Less hazardous chemical syntheses*: wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. *Designing safer chemicals*: chemical products should be designed to affect their desired function while minimizing their toxicity.

5. *Safer solvents and auxiliaries*: the use of auxiliary substances (e.g. solvents, separation agents) should be made unnecessary wherever possible and innocuous when used.

6. *Design for energy efficiency*: energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. if possible, synthetic methods should be conducted at ambient temperature and pressure.

7. *Use of renewable feedstocks*: a raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

8. *Reduce derivatives*: unnecessary derivatisation (use of blocking groups, protection/de-protection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

9. *Catalysis*: catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. *Design for degradation*: 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.

11. *Real-time analysis for pollution prevention*: analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. *Inherently safer chemistry for accident prevention*: substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Council 1993 report on "Chemistry for a Clean World", conferences on the concept of Benign by Design (Linthorst 2010), and the development of related concepts such as cleaner processes, safer products, and the use of renewable feedstocks (Clark 2006; Mubofu 2016).

While the 12 Principles of Green Chemistry are widely used and cited, there is no agreement on how many of these principles must be fulfilled for a molecule or process to be qualified as "green" or how the different principles are to be weighed against each other (Zuin 2016). Therefore, a clear benchmark which determines whether a chemical is green does not exist. Despite these challenges, a number of accounts are available demonstrating how green chemistry has positively affected sustainability in several sectors (American Chemical Society [ACS] 2019; Erythropel *et al.* 2018).

Towards a more holistic approach: sustainable chemistry

The notion of sustainable chemistry was also developed in the 1990s, with the Organisation for Economic Co-operation and Development (OECD) playing an important role in advancing this concept (OECD 2012). The OECD has defined sustainable chemistry as "a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services" (OECD 2018). According to this perspective, sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. It also stimulates innovation across all sectors in order to design and discover new chemicals, production processes and product stewardship practices that provide increased performance and greater value, while meeting the goals of protecting and enhancing human health and the environment.

More recent discussions on sustainable chemistry have evolved beyond a focus on scientific and technical considerations towards a more holistic interpretation that takes into account the economic, environmental and social dimensions of sustainable development. For example, renewable feedstocks promoted by green chemistry may have sustainability trade-offs such as agricultural pollution. While sustainable chemistry embraces green chemistry principles, it covers broader considerations including (but not limited to) safe working conditions, human rights, ethics, new business and service models, and other related topics (Kümmerer 2017). Sustainable chemistry also emphasizes the role of chemistry in implementing the 2030 Agenda for Sustainable Development (Blum *et al*. 2017). A further development of the concept proposed by the German Environment Agency takes into account planetary boundaries (German Environment Agency 2016).

Based on a review of the literature and stakeholder interviews, a recent study by the United States Government Accountability Office (US GAO) on chemistry innovation "identified several common themes underlying what sustainable chemistry strives to achieve, including:

- to improve the efficiency with which natural resources […] are used to meet human needs for chemical products, while avoiding environmental harm;
- reduce or eliminate the use or generation of hazardous substances […];

Figure 1.2 **Dimensions of a chemical enterprise: towards sustainability (adapted from Hill, Kumar and Verma 2013, p. 27)**

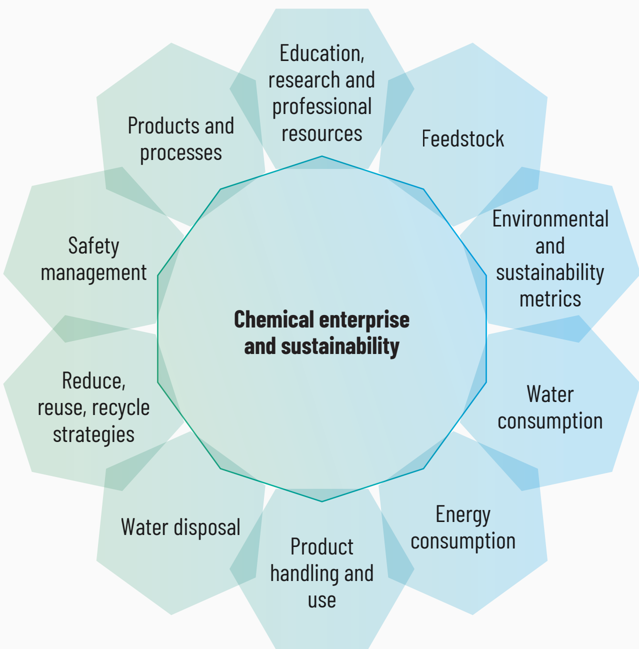
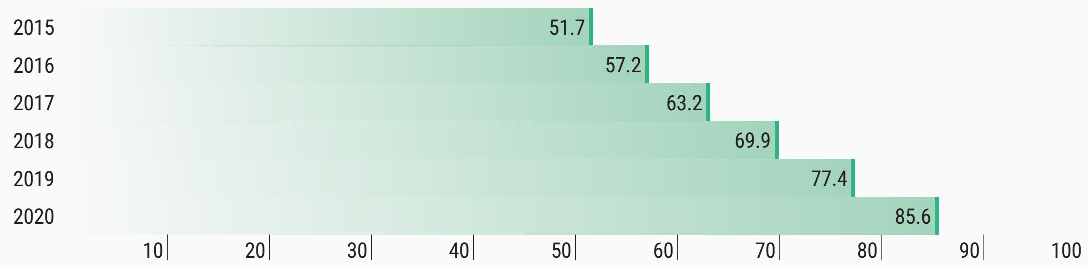


Figure 1.3 Market size of the global green chemistry industry, 2015-2020 (US dollars billion) (based on BCC Research 2016)



- protect and benefit the economy, people and the environment using innovative chemical transformations;
- consider all life cycle stages, including manufacture, use and disposal [...] when evaluating the environmental impact of a product; and
- minimize the use of non-renewable resources" (US GAO 2018).

From a sustainability point of view, a chemical enterprise has many interconnected dimensions, each of which needs to be considered (Hill, Kumar and Verma 2013). Some of these dimensions are shown in Figure 1.2. An assessment of the sustainability of a chemical enterprise would cover a range of factors and all three dimensions of sustainable development. It might raise questions such as: under which circumstances could the use of biomass for chemicals and biofuel production be a viable alternative to the use of fossil sources, taking into account the potential economic, environmental and social consequences of its use? or, to what extent would the reduction of vehicles' CO_2 emissions through the use of composite materials outweigh the environmental impact of the production and/or future recycling of these materials?

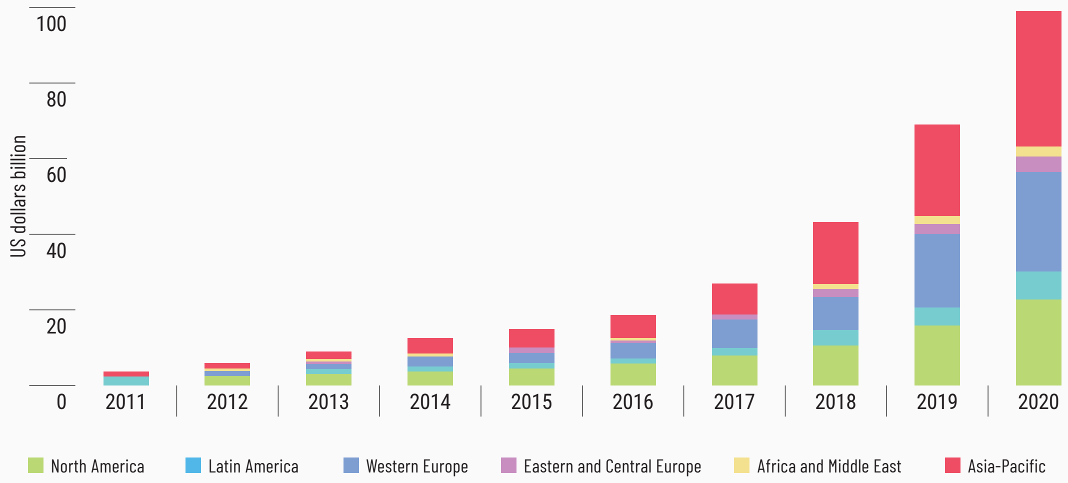
The market potential for green and sustainable chemistry

While differences still exist in the characterization of green and sustainable chemistry, forecasts have been published which predict growing markets for green chemistry worldwide. The global green chemistry industry was reported to have a market value of more than US dollars 50 billion in 2015, with the potential to grow to US dollars 85 billion by 2020 (Figure 1.3) (BCC Research 2016). It has been estimated that the global market for green chemistry (including bio-based chemicals, renewable feedstocks, green polymers and less-toxic chemical formulations) will grow to nearly US dollars 100 billion by 2020 (Bernick 2016). While this amount is substantial, it is modest compared with total global chemical industry sales of some US dollars 5.7 trillion (see Part I, Ch. 1).

Green chemistry markets are expected to show growth in all regions, with Asia and the Pacific, Western Europe and North America the key market growth regions (Pike Research 2011) (Figure 1.4).

Forecasts suggest that the growth rate for green and safer chemistry products is considerably higher than that for conventional products (American Sustainable Business Council [ASBC] and Green Chemistry & Commerce Council [GC3] 2015). Tightening regulations, and growth in consumer demand for more sustainable products – along with the rising costs of fossil fuels – all contribute to this trend (BCC Research 2016). In light of these developments, many chemical companies see benefits in developing sustainable products such as healthier food and environmentally friendly detergents. Sustainable products thus provide companies with new avenues of growth and establish a stronger connection with millennials, who are driving demand for these products (Bhattacharjee and Swamynathan 2017).

Figure 1.4 Global green chemicals market by region (US dollars billion), 2011-2020 (Pike Research 2011, p. 432)



International developments: towards a common understanding of sustainable chemistry

In 2016, at the second session of the UNEA, in Resolution 2/7 Governments recognized the concept of sustainable chemistry and initiated further work by the United Nations Environment Programme (UNEP), including the development of a report on how best practice in sustainable chemistry could help achieve the SDGs. Sustainable chemistry has also been among the topics discussed under the intersessional process on the Strategic Approach to International Chemicals Management (SAICM) and the sound management of chemicals and waste beyond 2020.

The 2019 report prepared by UNEP in response to that UNEA mandate notes the wide use of the sustainable chemistry concept by various stakeholders around the world (UNEP 2019). However, taking into account an analysis of submissions of sustainable chemistry cases by stakeholders, and the results of a survey of SAICM stakeholders, the report also notes that a common understanding of the sustainable chemistry concept does not exist at the global level. For example, one open question is the extent to which non-chemical alternatives are within the scope of sustainable chemistry. Given the interest of a number of stakeholders (including many from developing countries) in understanding and developing the sustainable chemistry concept further, the report suggests that practical guidance on sustainable chemistry be developed. Such guidance could be complemented by, or include, a simple definition of sustainable chemistry or a more elaborate definition if that is considered valuable. Such work might also further develop the compatibility of, and the relationship between, the green and sustainable chemistry concepts explored already, for example by Sheldon (2008), Kümmerer (2017) and Anastas and Zimmerman (2018). Together these concepts could be widely promoted, inspiring research, policymaking and private sector action compatible with, and in support of, the 2030 Sustainable Development Agenda.

1.3 Digitalization and the chemical industry: opportunities to advance sustainability

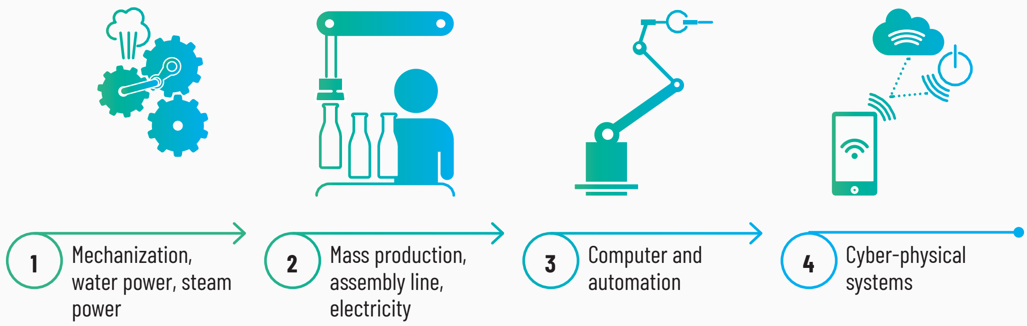
While in the past there was a focus on the invention of new molecules, future innovations in chemistry will likely be based on integrated solutions which are based on digital technologies.


© Suwin/Shutterstock, use of drones in agriculture

Industry 4.0 (Cisco 2017; EC 2017) and digitalization will impact a range of (if not all) aspects of the chemical industry: how it innovates and produces; how it conducts businesses and engages with actors across supply and value chains; and its productivity and safety.

Chemical manufacturing operations, in particular, are one of the largest and most readily accessible areas of opportunity for digitalization, from petrochemicals to pesticides. Most chemical plants continuously generate an enormous amount of data, but discard most of them. Managers could collect these data and interpret them in order to find ways to achieve higher yields and throughput, lower energy consumption, reduce pollution and foster effective maintenance. For many companies these are potentially easy wins that could be achieved using existing information technology (IT) and process control systems.

Figure 1.5 **The four industrial revolutions (adapted from Cisco 2017)**



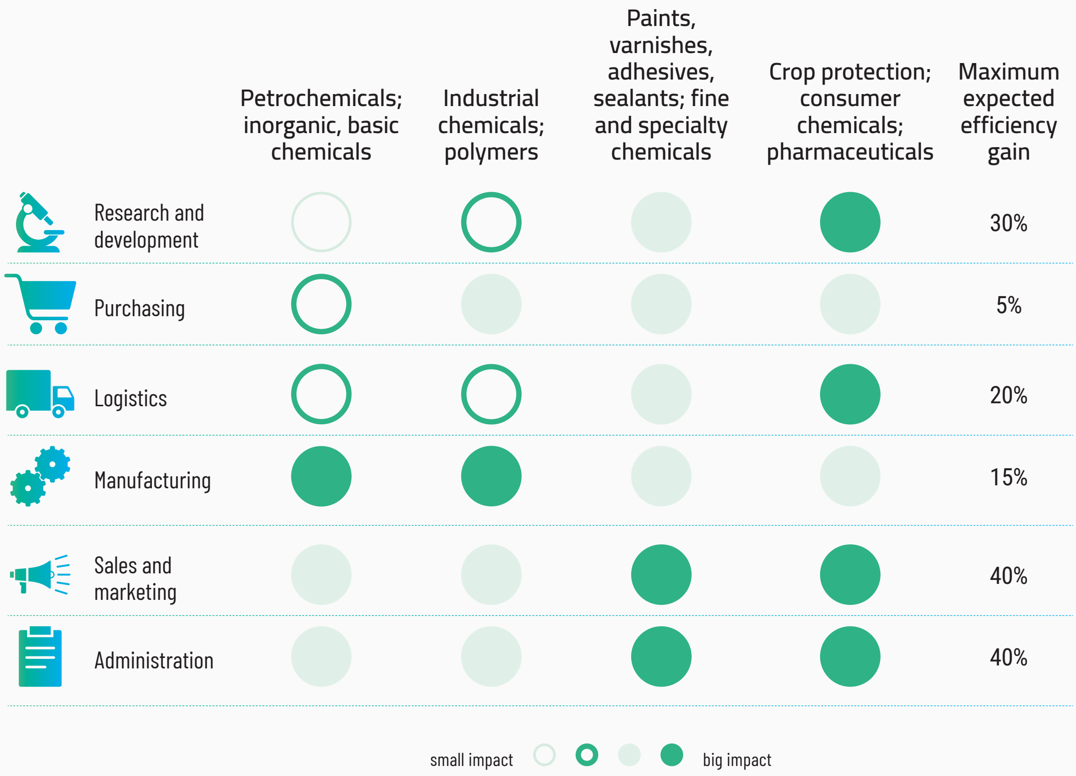
The Fourth Industrial Revolution refers to a new era in the interface of industrial production, digitalization and society which impacts a range of aspects of the chemical industry: how it innovates and produces; how it conducts business; how it engages with actors across supply and value chains; and its productivity and safety. While in the past there was a focus on the invention of new molecules, future innovations in chemistry, chemical safety and resource efficiency will likely be based on integrated solutions that are based on digital technologies. At the same time, digitization may also be associated with risks such as possible cyberattacks.

New integrated technologies are also on the rise. For example, drones and robots have started to play an important role in agriculture to minimize pesticides application, using global positioning system (GPS)-based systems.

While the chemical industry, according to a McKinsey & Company study (Jakobsen *et al.* 2017), has been perceived to lag behind in digitalization, the potential economic benefits are enormous. During the next decade or so, the digitalization of operations and commercial functions in the chemical industry has the potential for value creation of 4 to 6 per cent (Jakobsen *et al.* 2017). There is potential for companies to achieve a 3 to 5 percentage point improvement in sales through employing digitalization in production operations (Klei *et al.* 2017). This could unlock up to US dollars 550 billion (WEF 2017) in value in the next decades. Other important and related benefits include lower GHG emissions, reduced accident and injury rates, and greater value chain transparency (Cayuela and Hagan 2019).

Advanced analytics, the internet of things, and artificial intelligence can combine information from millions of sensors to boost not only operational productivity, but also energy efficiency, emissions reductions, and environmental and safety performance. For example, using drones and robots for certain operations could lower injury levels. Ultimately, the use of automation across processes and supply chains reduces manual interventions and paper-based documentation, thereby accelerating productivity and safety. Digitalization also enables more rapid experimentation, the discovery of new materials at lower cost, and better understanding of chemicals' hazardous properties (Figure 1.6). This means eventually exploring the enormous, and currently unexplored, chemical space (Kirkpatrick and Ellis 2004) of over 10^{60} conceivable compounds and filtering it to a manageable number that can be synthesized, tested and assessed for meeting sustainability criteria.

Figure 1.6 **Overview of the implications of digitalization in the chemical industry (adapted from Deloitte and German Chemical Industry Association 2017, p. 14)**



Considering potential trade-offs

While the opportunities of Industry 4.0 and digitalization for the chemical industry are significant, pervasive and will be long-lasting, there are also challenges. These include, for example, cybersecurity, possible data misuse and cybercrimes, as well as accountability challenges associated with decentralized production and markets. Digitalization will also require resources, such as energy or metals for hardware. Ultimately, however, Industry 4.0 and digitalization are here to stay. They will change the shape of the chemical industry from the current interplay of energy, materials, molecules and atoms to an interplay more focused on atoms and bits (Cayuela and Hagan 2019).

1.4 Enabling the potential of sustainable chemistry innovation

Advances in chemistry are occurring in the real world. They will continue to be one of the bases on which societies and economies are built. Chemical substances and materials, and their properties, actions and performance, will be at the heart of the processes and products that define our future. Innovation in chemistry (particularly in the fields of biotechnologies, advanced materials, nanotechnologies, energy and environment), and the growing global market for sustainable goods and services, are shaping the future of the chemical industry and creating new investment opportunities. The industry is in a position to help other sectors achieve their most ambitious objectives, from food to energy to resource security. Some leaders have already emerged in these sectors. They see this potential, and are ready and committed to help address sustainability challenges with and through chemistry.

The direction in which chemistry develops will depend on new leadership approaches in industry, and on how societies can work collaboratively with the chemical industry to support its transformation to sustainability. As the industry is subject to public scrutiny and demands for transparency and responsibility, educating and engaging with the public and all others to discuss the risks and benefits of the chemical industry and its opportunities for sustainability will be of value. New metrics for innovation, sustainability and accountability are needed, as well as programmes to mobilize scientific talent to embrace green and sustainable chemistry and scale up innovation. Furthermore, an ethical, value-driven approach to technological progress in the chemical industry is essential. For all this to occur, it will be paramount to find a balance in creating a discourse around the opportunities provided by chemistry – while not ignoring its risks. Finding such a balance will help to address the legacies of the past, as well as sustainability, and to mobilize the best and brightest minds in science to reap potential rewards. The following chapters in Part IV address these and related opportunities to scale up innovative solutions.

2/ Green and sustainable chemistry education: nurturing a new generation of chemists

Chapter Highlights

- Green and sustainable chemistry education (GSCE) is gaining momentum through its integration into relevant curricula, scientific journals and academic conferences.
- Despite significant advances in mainstreaming GSCE, major gaps remain in all regions.
- Institutions and networks are developing an increasing number of relevant tools and materials for use at the primary, secondary, tertiary and professional levels.
- While green and sustainable chemistry is taught selectively in countries across all regions, there is potential to scale up efforts, particularly in developing countries.
- Barriers to reform exist. They include professional and institutional resistance, and a lack of awareness.
- Mainstreaming GSCE in curricula at all levels includes disseminating best practices, utilizing existing networks, and strengthening partnerships.

2.1 A new way to teach chemistry

From chemistry to green chemistry, and green and sustainable chemistry education

Historically, toxicology and concerns about the protection of human health and the environment have received limited attention in chemistry classrooms. However, a paradigm shift towards pollution prevention took place in the second half of the 20th century, accompanied by growing awareness of the adverse effects of certain chemicals, as also reflected in regulatory action taken. A major milestone that can be seen as having accelerated the momentum towards green chemistry is the Pollution Prevention Act adopted in the United States (US) in 1990, which stated that "pollution should be prevented or reduced at the source whenever feasible" (US EPA 2017).

Chemistry education has reflected this conceptual transition during the last 20 years, and curricula in many countries have been revisited (Anastas 2015; Clark 2016). In 1997 a doctoral programme on green chemistry was introduced at a university for the first time. The early 2000s saw a proliferation of these new ideas, mainly under the label of "green chemistry", in the scientific community (particularly in the United States) (Cohn 2012). This was demonstrated, for example, by the Green Chemistry Institute becoming part of the ACS (ACS 2019a). Subsequently a growing number of universities incorporated

Table 2.1 Sustainable chemistry teaching: laboratory content (adapted from Aubrecht *et al.* 2015, p. 632)

Theme	Laboratory topic	Primary chemistry concepts	Connections to sustainability
Environmental degradation	Interaction of acid rain with minerals	Titrations, neutralization reactions, metal ion solubility	Sources and impacts of acid rain, ocean acidification, mitigation efforts
Energy production	Preparation and use of dye-sensitized solar cells	Semiconductors, doping, silicon and dye-sensitized photovoltaic cells	Solar energy, stabilization wedges approach to reduce greenhouse gas emissions
Green chemistry	Synthesis of a biodegradable polymer and recycling of polyethylene terephthalate (PETE)	Polymers, line-angle functional groups, infrared (IR) spectroscopy	Renewable feedstocks, biodegradability, "cradle to cradle" design, green chemistry

Aubrecht *et al.* (2015) described the content of a series of day-long field trips by high school students to a university where chemistry content was connected with sustainability issues. Experiments focused on environmental degradation, energy production and green chemistry.

green chemistry in their curricula, mainly for organic synthesis, and gradually incorporated the 12 Principles of Green Chemistry (ACS 2019b) in regular chemistry courses. Despite these advances, the number of schools and universities that have integrated green and sustainable chemistry in relevant curricula remains limited.

Today some elements of green chemistry education have been solidly established in many universities and are being promoted by companies, governments and NGOs worldwide. The expansion of the 12 Principles to wider dimensions with the label "sustainable chemistry education" in university and other curricula is a more recent phenomenon (Kümmerer 2017). While an increasing number of academic institutions have now embraced the concept of green chemistry, the concept of sustainable chemistry has been introduced less frequently (e.g. at the Leuphana University of Lüneburg in Germany). Thus there is still significant potential and need to further mainstream green and sustainable chemistry education (GSCE).

Green and sustainable chemistry education can be introduced in a wide range of institutions and curricula

The concepts and principles of GSCE can feed into education at various levels and in different settings, including high schools, universities and professional education. GSCE has been introduced at an increasing number of research institutions and universities. Various institutions have also developed tools and materials to allow the integration of green and sustainable chemistry at high school and even elementary levels (e.g. ACS 2019a; Beyond Benign 2019) in order to adequately address toxicology in the classroom (Cannon *et al.* 2017). For example, in the context of the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Decade of Education for Sustainable Development (ESD) (2005-2014) learning materials for secondary education and universities were developed that addressed topics related to green and sustainable chemistry (Burmeister and Eilks 2012; UNESCO 2014; Zuin and Mammino 2015). There is hope that this development will continue in the framework of the Global Action Programme on Education for Sustainable Development, which is the follow-up programme to the Decade of ESD (UNESCO 2018).

Eissen *et al.* (2008) reported the development of a new lab course for higher organic chemistry education. Aspects of the efficiency and sustainability of reactions, as well as toxicological and ecotoxicological knowledge, were added to the teaching content. Students were encouraged to plan, set up and reflect on organic laboratory activities, while taking into account any effects on people and the environment.

2.2 Education reform is gaining momentum, but significant gaps remain across regions

The extent to which GSCE has reached the general public, or has had a large-scale impact on behaviour patterns, is still limited (Mammino 2015; Beyond Benign 2019). Similarly, the inclusion of green and sustainable chemistry in university curricula has in many cases been confined to events, summer schools, short courses, one-off activities, and the inclusion of specific elements of GSCE in existing courses (Leitner 2004; Collins 2017).

There has been momentum in recent years to mainstream GSCE in academia. International conferences are also being organized on a regular basis, including in developing countries. Examples include the International Union of Pure and Applied Chemistry's (IUPAC) annual International Conference on Green Chemistry, the Annual Green Chemistry & Engineering Conference, the International Conference [on] Green and Sustainable Chemistry (the global green chemistry community); Elsevier's and Leuphana University's Green and Sustainable Chemistry Conference; and the Asia-Oceania Conference on Green and Sustainable Chemistry. Yet major international chemistry education conferences only incorporate green chemistry to a limited extent.

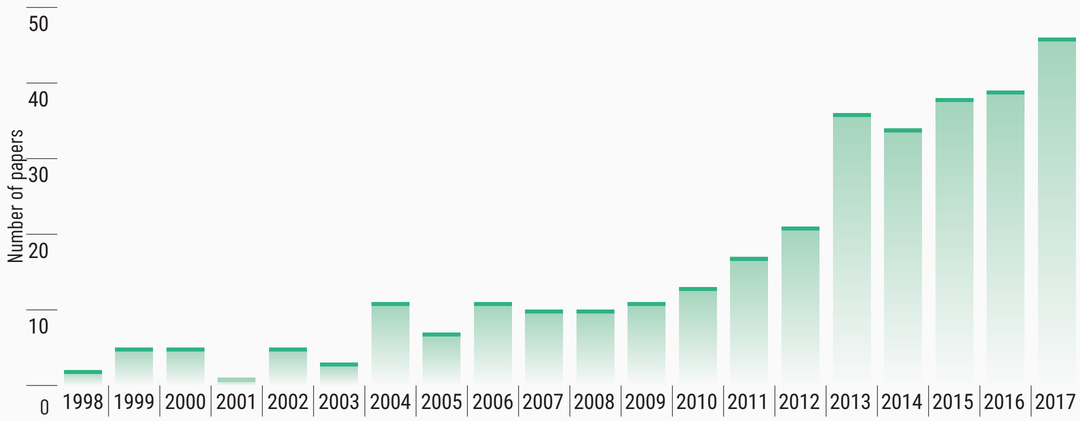
A growing number of academic journals focus on green and sustainable chemistry, including the Royal Society of Chemistry's (RSC) *Green Chemistry*, the ACS's *Sustainable Chemistry and Engineering*, VCH-Wiley´s *ChemSusChem,* and Elsevier's *Sustainable Chemistry and Pharmacy* and *Current Opinion in Green and Sustainable Chemistry*.

In a number of countries the concept of green – more than sustainable – chemistry has also

Box 2.1 **Examples of universities offering courses in green and sustainable chemistry**

City University of Hong Kong (China)
Federal University of Rio de Janeiro (Brazil)
Federal University of São Carlos (Brazil)
Fudan University (China)
Ghent University (Belgium)
King's University College (Canada)
Lomonosov Moscow State University (Russia)
McGill University (Canada)
Mendeleyev University of Chemical Technology (Russia)
Monash University (Australia)
Nankai University (China)
National University of La Plata (Argentina)
Queen´s University (Canada)
Queen´s University (UK)
Universidad Autónoma de Nuevo León (Mexico)
Universidad de Cordoba (Spain)
Universities of Porto and NOVA Lisbon (Portugal)
University of Amsterdam (The Netherlands)
University of Bath (UK)
University of Cape Town (South Africa)
University of Delhi (India)
University of Dodoma (Tanzania)
University of Massachusetts, Lowell (US)
University of Nottingham (UK)
University of Oregon (US)
University of Toronto (Canada)
University of Valencia (Spain)
University of Venice (Italy)
University of York (UK)
Yale University (US)

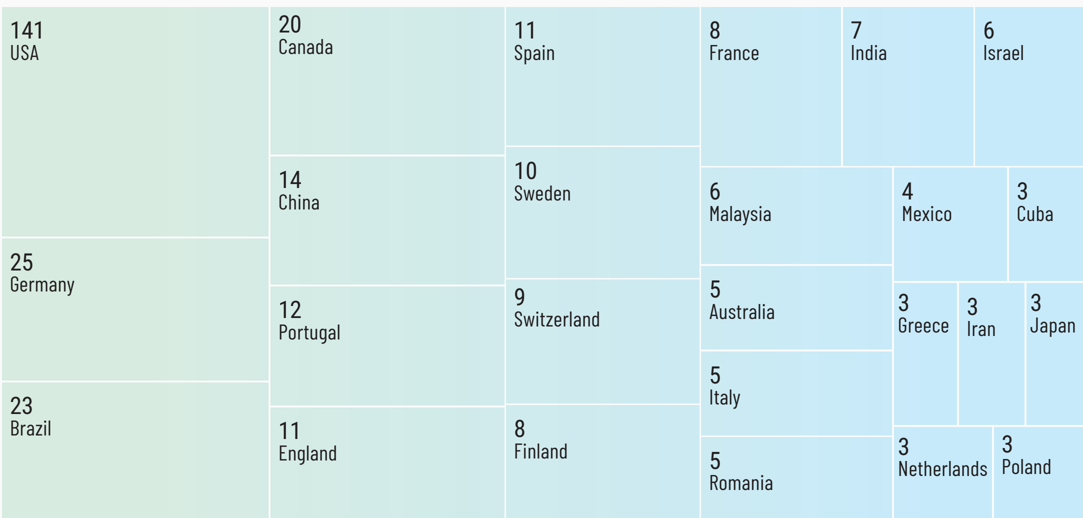
Figure 2.1 Number of papers published on GSCE, 1998-July 2018, concerning green chemistry education or sustainable chemistry education (adapted from Clarivate 2018)



been integrated in university curricula in the form of research programmes, courses and master's programmes. Universities offering courses in green chemistry include those listed in Box 2.1. Some of these courses are undertaken in partnership with the private sector. Green chemistry is also taught in regular courses. Based on an initiative of the German Federal Environmental Foundation, an entire laboratory course was developed to teach organic chemistry practically, based on ideas of green and sustainable chemistry. Today this course is available in more than 10 languages, including English, Spanish and Russian (Network Operations Portal 2018).

Most such initiatives have been taken in developed countries (Gross 2013; Juntunen and Aksela 2014; Kennedy 2016), although gaps remain (Kitchens *et al.* 2006; Hamidah *et al*. 2017). Yet an increasing

Figure 2.2 Number of papers published on GSCE, 1998-July 2018 (adapted from Clarivate 2018)



number are emerging in developing countries and countries with economies in transition in all regions. Green and sustainable chemistry education appears to be gaining momentum in China, in particular (Wang, Li and He 2018). An analysis found that more than 1,200 papers published in the journal *Green Chemistry* between 1999 and 2016 originated in China (Shuang and Yanqi 2018). The Indian Ministry of Education is piloting a programme in which all chemists will take a one-year course in green chemistry.

The number of papers addressing GSCE has grown in recent years. More than 300 papers are available in the literature from 1998. Most address the development of curricular materials; the assessment of student learning, and attitudinal outcomes from these curricula; and the use of multidimensional green chemistry metrics integrating broader societal factors and new pedagogical approaches. A significant share of these papers were published by scholars from developing countries or those with economies in transition, such as Brazil, China, India, Malaysia and Mexico (Figure 2.1 and Figure 2.2).

Diverse approaches and ongoing reforms

Depending on the institutional context, green and sustainable chemistry has been taught differently, with diverse approaches, materials and focuses (Box 2.2). Specific initiatives have also had an impact on behavioural patterns in a variety of communities (e.g. progressive greening of universities, companies and informal educational institutions) (Mammino 2015).

A variety of educational materials have been developed to convey the principles of green and sustainable chemistry in school chemistry education and academia (Eilks and Rauch 2012; Levy and Middlecamp 2015; Zuin and Mammino 2015; Welton *et al.* 2018). In view of the increasing attention being given to all three dimensions of sustainable development (economic, social and environmental), academics have responded by adjusting course content and materials to adequately consider the societal factors of sustainability (Burmeister and Eilks 2012; Armstrong *et al.* 2018). The case has been made for reconceptualizing GSCE through adjusting curricula and methodologies to "foster eco-reflexive chemical thinking and action" (Sjöström, Eilks and Zuin 2016; Sjöström and Talanquer 2018). Integrating this dimension could enable individuals to respond to complex challenges, in line with the principles of sustainable development (Figure 2.3).

In recent years momentum has been growing in the chemistry community to incorporate systems thinking. A number of authors have underlined this need, stressing the opportunities it would offer by empowering chemistry students to innovate for a sustainable future (Mahaffy *et al.* 2018). The IUPAC, which has a project on integrating systems thinking into chemistry education, notes that such an approach "draws

Box 2.2 Green chemistry and sustainability in professional education and training courses: a case study from Brazil

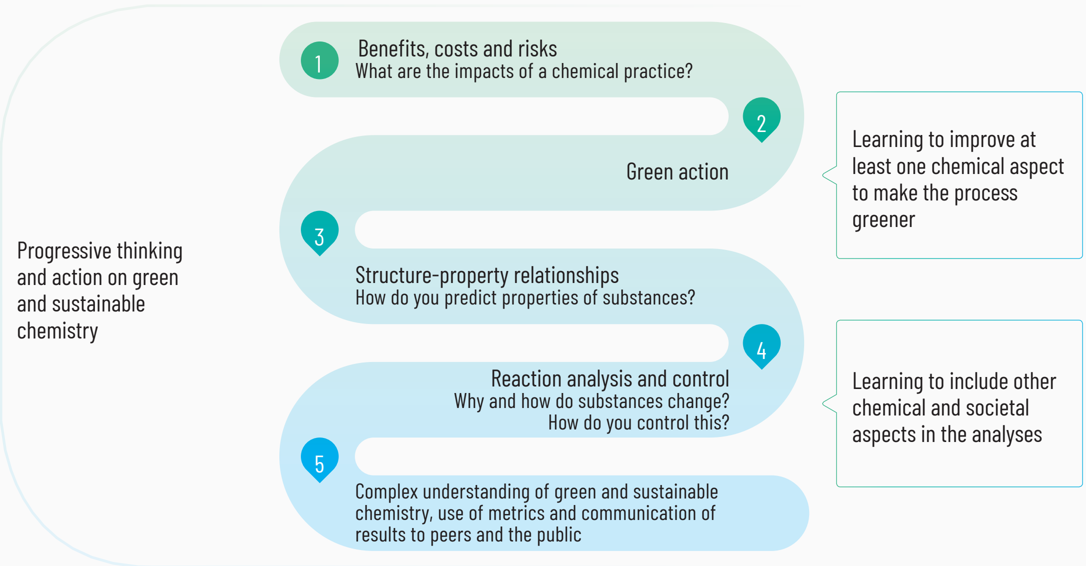
The National Service of Industrial Training, organized and run by industrial entrepreneurs through the National Confederation of Industry and state federations, was created to train qualified workers for Brazilian industry. Together with the Ministry of External Relations, it operates in Cape Verde, Guinea-Bissau, Guatemala, Paraguay, East Timor, Mozambique, Peru, Jamaica, and São Tomé and Príncipe. In 2015 the SENAI Green Chemistry Institute Brazil was launched. It is committed to increasing general global awareness and capacities for deployable green chemistry approaches, aiming at product design and processes that will have global environmental benefits throughout their life cycles. Under the umbrella of the UN Industrial Development Organization's (UNIDO) Green Chemistry Initiative, a pilot project will demonstrate that green chemistry works for applications on a large scale in the area of bio-based plastics production in Brazil. Other studies will look at advancing green chemistry and green engineering technology applications in developing countries and those with economies in transition (UNIDO 2018).

attention to a need to balance the benefits and impacts of chemical substances and the role they play in societal and environmental systems" (IUPAC 2018). Incorporating systems thinking in chemistry curricula would thus encourage students to use chemistry as a tool to find solutions for global challenges.

Chemical societies and green and sustainable chemistry education networks are advancing the integration of green and sustainable chemistry in curricula

Strengthening transnational, collective and multi-sectoral efforts towards a common agenda for

Figure 2.3 **Steps to promote GSCE (adapted from Armstrong *et al.* 2018, p. 62 and Sjöström and Talanquer 2018)**



Reprinted with permission from Elsevier.

GSCE – promoted by adequate pedagogical approaches – requires the engagement of existing networks, putting together champions and innovators in the field (Collins 2001; International Sustainable Chemistry Collaborative Centre [ISC3] 2018; Yale University n.d.). Strategic partnerships and the creation of networks of educators have been identified as key determinants of success (Haack and Hutchison 2016; Zuin 2016).

A number of national, regional and global networks have been established to advance the mainstreaming of GSCE in developed and developing countries, such as the Global Network of Chemistry Centres (2016) and the GC3 (n.d.). The GC3 has a long-running project to embed green chemistry in academic and professional education. It has also published a Policy Statement on Green Chemistry in Higher Education, featuring (among others) a commitment to advance green chemistry education and research across disciplines.

Many national chemical societies have founded sections, committees or networks for green or sustainable chemistry, including the German Chemical Society (GDCh), the RSC and the ACS, which is also implementing a Green Chemistry Education Roadmap seeking to address prevailing gaps in integrating green chemistry in relevant curricula (ACS 2019c). In 2017 the IUPAC formed an Interdivisional Committee on Green chemistry for sustainable development (Italian National Committee for IUPAC of the National Research Council of Italy 2016).

2.3 Overcoming barriers: key determinants of effective educational reform

Implementing green and sustainable chemistry education in developing countries

Making current chemistry practice green and sustainable is a relatively new concept in some countries, but one which is especially important to developing countries. The current curricula for the education of chemists and engineers in those countries barely considers environmental sustainability as a component. This makes it difficult to develop a consciousness of the implications of synthetizing chemicals with multiple applications, while also considering the life cycle of chemicals and their final fate in the environment (Barra and González 2018).

Currently a number of countries face several challenges regarding the design and implementation of GSCE, among which is a lack of scientists considering corresponding approaches. This is a barrier to awareness-raising by new professionals and scientists sensitized to addressing the issue. The language barrier with respect to the international literature might be a further hurdle for implementation of GSCE in certain countries. To date, few universities are proactively addressing the issue. Current curricula for chemists and engineers in many universities provide limited room for green chemistry principles and practices or sustainability issues. For example, there is a need to strengthen education in chemical synthesis and green chemistry principles to address molecular design and minimize impacts *ab initio* (i.e. starting from the beginning), in addition to a pursuit of material innovation including online pedagogical platforms and virtual activities (Haley *et al.* 2018).

Educating a new generation of chemists for the private sector

Embedding green and sustainable chemistry in academic and professional education across supply chains can contribute to building communities with a strong understanding of the chemistry, product design and sustainability nexus. Many initiatives prioritize the education of teachers and lecturers, as they can influence the knowledge and opinions of present and future generations (Karpudewan, Ismail and Roth 2012; Beyond Benign 2019; GC3 n.d.).

Mainstreaming GSCE not only into chemistry and engineering departments, but also into business and law schools, public administration and companies will be critical given these stakeholders' role in establishing, assessing and implementing technological, economic, financial and fiscal activities and policies (Box 2.3). Some

Box 2.3 The CHEM21 online learning platform (CHEM21 n.d.)

Regarding continuing professional development, the CHEM21 (n.d.) online platform established by the EU IMI CHEM21 project (Chemical Manufacturing Methods for the 21st Century Chemical Industries) was designed to provide a broad range of free, shareable and interactive educational and training materials to promote the uptake of green and sustainable methodologies in the synthesis of pharmaceuticals. Interactive elements include multiple choice quizzes with instant feedback, and downloadable problem-solving exercises (which can be carried out individually, or in groups, in a workshop setting) to encourage critical thinking on topics such as metrics, solvent selection and process safety (Summerton, Hurst and Clark 2018).

professional education programmes geared towards green management have been described, demonstrating that employees' attitudes to green management approaches became more positive and motivated through participating in new green management activities (including education programmes for other partners) (Lee 2009; University of Oregon 2018).

Overcoming professional and institutional resistance

The barriers to successful implementation of GSCE are significant and are quite similar globally. Lack of cultural and institutional openness to change, or professional conservatism, have been identified as critical obstacles (Vallée 2016). According to Matus *et al.* (2012), corroborated by recent research conducted with leaders in several sectors worldwide, a complex set of interconnected issues act as barriers to the effective implementation of GSCE and wider sustainability considerations. Most of these fall into the categories of inertia and resistance related to organizational and cultural change; insufficient financial, social and economic support; and lack of knowledge about green and sustainable chemistry among staff. Another challenge identified in the literature is the absence of the use of harmonized and clear definitions and metrics by academia and decision-makers (Matus *et al.* 2012).

Despite these challenges, a number of opportunities exist. Several stakeholders, including industry, academia, NGOs and policymakers, can make an important contribution by facilitating a shift in focus towards the design and use of safer chemicals and sustainable production processes. A number of local case studies have demonstrated the successful integration of green and sustainable chemistry, including in the private sector. In addition, a number of strategies, including distance learning with both blended and face-to-face approaches, have shown that there are a range of opportunities to overcome identified gaps, including transdisciplinary research and teaching, Industry 4.0 and big data systems (Zuin and Mammino 2015; Ellen MacArthur Foundation 2017). Moreover, tools have been developed to assist universities in assessing how well their curricula address sustainable development, as a means of identifying opportunities to capture sustainability issues in a more strategic manner (Lozano and Watson 2013). Holme and Hutchison (2018) describe the establishment of an overarching learning outcome for chemistry courses, noting that both the benefits and hazards of chemicals could trigger change.

The need to bring together policymakers, scientists and the private sector

Public support for green and sustainable chemistry requires a broader societal education in which stakeholders should be considered, including chemical producers, entrepreneurs, environmental justice groups, NGOs, downstream businesses, consumers, workers and professional associations. While motivated educators are necessary for the process of curriculum greening, they are not sufficient. It has been observed that this process can be significantly influenced by other constituents which can support them, providing resources such as educational materials and case studies (Centi and Perathoner 2009; Vallée 2016). For example, the ACS has been identifying tools to support work carried out in teaching laboratories, additional curricular materials for teachers, local government resources, and links to online networks, essentially for the United States (ACS 2019c). More recently, a new initiative to screen, assess, develop and apply international study programmes for sustainable chemistry education has been launched: the ISC3-Research Hub aims to offer scientific courses on a global level involving, for example, universities and public authorities, especially in developing countries and countries with economies in transition, in order to promote correlated programmes in their institutions (ISC3 2018).

2.4 Potential measures to scale up green and sustainable chemistry education

Building on existing initiatives, further efforts are needed at all levels to mainstream green and sustainable chemistry education into chemistry and other education curricula and teaching, including gathering and disseminating best practices and forging new and strengthened partnerships. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to further advance green and sustainable chemistry education:

- Develop appropriate local and global programmes for GSCE, and define fundamental pedagogical content, objectives, methods and evaluation processes.
- Gather and disseminate best practices for integrating GSCE in chemistry and other curricula at secondary, higher (university) and technical educational levels.
- Scale up the training on GSCE of teachers and lecturers across all educational levels.
- Enhance funding and cooperation, including through existing GSC networks, to further promote and implement GSCE in developed, developing and transition economies.
- Embed GSCE as a critical element of wider education reform, including through strategic collaboration with programmes such as the UNESCO Education for Sustainable Development initiatives.
- Engage stakeholders from all sectors in the development and implementation of effective strategies for GCSE, in order to prepare students to address global sustainability challenges.
- Further mainstream GSCE in professional education, including through public-private partnerships.
- Further advance a common understanding of green and sustainable chemistry concepts, including in the context of education.

3/ Strengthening sustainable chemistry technology innovation and financing

Chapter Highlights

Opportunities exist to scale up problem-solving oriented research and innovation in chemistry and related disciplines to support implementation of the 2030 Agenda for Sustainable Development.

Public research agendas, funding, and catalysing of support play important roles during early stages of the innovation process, as does private sector support.

To achieve the potential of chemistry start-ups to accelerate green and sustainable chemistry innovation, effective support mechanisms and innovative funding are important.

Engaging the financial services industry is important, but so far this source has not been fully tapped.

Collaborative innovation promises to focus research on problem solving by bringing together research institutions, the private sector, government and civil society.

An effective enabling environment for collaboration, including policies and incentives that nurture and do not stifle innovation, improves chances for successful outcomes.

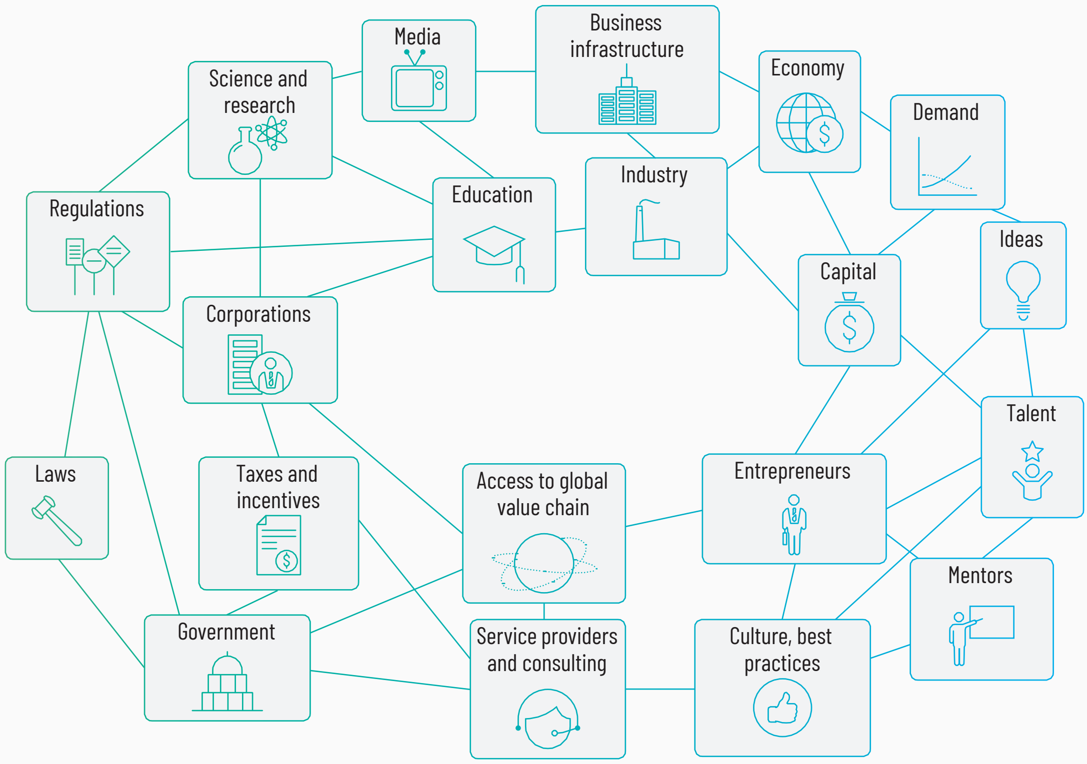
Significant opportunities exist for innovation in chemistry to help achieve the development goals and targets in the 2030 Agenda for Sustainable Development. The problems are diverse and challenging. To address climate change, energy supply and resource scarcity, for example, the functionality of chemicals and new materials is crucial. Yet chemistry innovation is complex and requires considerable resources and technical infrastructure, often more so than in other sectors such as IT. Laboratory equipment is costly, as are staffing, safety measures, waste treatment and other infrastructure needs. In the previous chapter the essential role of science and chemistry education was underlined. But what else is needed to drive innovation?

3.1 Opportunities and challenges in strengthening sustainable chemistry innovation

From basic research to research that solves societal challenges

Future research in chemistry, if undertaken to meet societal challenges, needs to be directed specifically towards that goal. This type of research may be fostered through the development research agendas of public and private actors, ideally together, that support implementation of the 2030 Agenda for Sustainable Development. The European Technology Platform for Sustainable Chemistry

Figure 3.1 Innovation ecosystem model (adapted from Ryzhonkov 2013)



(SusChem), for example, is a forum which brings together industry, academia, policymakers and wider society to establish research priorities directly linked to the 2030 Agenda (SusChem 2017).

There are many examples of innovations in chemistry that have not led to green and sustainable products. It is thus important for the actors engaged in research and innovation to take into account the guiding principles associated with green and sustainable chemistry and life cycle thinking. For example, start-up incubators and accelerators and funding mechanisms may integrate sustainability criteria in their selection process, in addition to economic viability criteria, especially if research is co-financed by public entities. In this context all actors concerned can benefit from interacting with end users and communities before developing start-ups that seek social use of new technologies or products, especially in sectors such as agriculture or sustainable mining.

The ecosystem for sustainable chemistry research and innovation

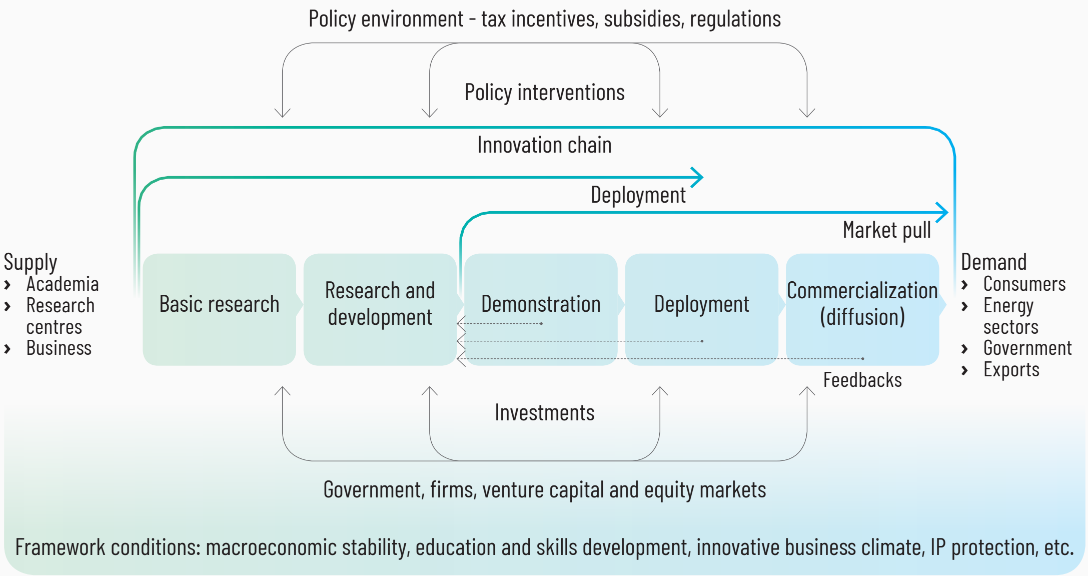
Chemistry research and innovation take place in a broader innovation system. An innovation ecosystem includes diverse actors and complex relationships. It also includes institutions (e.g. research and educational institutions, businesses, investors, centres of excellence, funding agencies and policymakers). This ecosystem requires material resources (e.g. funds, equipment and facilities), as well as human resources including students, faculty, staff, industry researchers and industry representatives (Jackson 2011). Figure 3.1 introduces the elements of the innovation ecosystem.

The technology innovation chain

The technology innovation process consists of three basic stages: invention, innovation and diffusion (Schumpeter 1954). Invention refers to the development of an idea; innovation is the stage at which an invention is turned into

a new product or process and brought onto the market; and diffusion or dissemination is the stage at which the new product or process obtains a larger market share. Figure 3.2 presents a slightly more detailed representation of the technology innovation process, including five stages: basic research; research and development; demonstration; deployment; and commercialization. This figure also features elements and actors in the broader innovation ecosystem. Within the system there are several underlying forces at play. They include a push force driving innovation through the research sector, and a pull force driving innovation through consumer preferences, market trends and government policies. As the research and innovation process advances towards commercialization, the role of research bodies and public investment decreases while that of the private sector increases.

Figure 3.2 Technology innovation chain and key enabling factors (adapted from International Energy Agency 2008, p. 170)



Technology readiness measuring systems and the Valley of Death

Throughout the innovation chain, decision moments (or gates) are built in to assess the status of the innovation and determine conditions for next steps. A Technology Readiness Level (TRL) measuring system has been developed to help measure the promise, maturity and usability of a new technology. Created originally by the National Aeronautics and Space Administration (NASA) in the United States (NASA 2012), it consists of nine levels, starting with the idea and basic principles and ending with successful mission and commercial application. To address specific needs, several institutions, venture capitalists and companies have developed complementary systems such as the Manufacturing Readiness Level, the Commercial Readiness Index and the Investment Readiness Level.

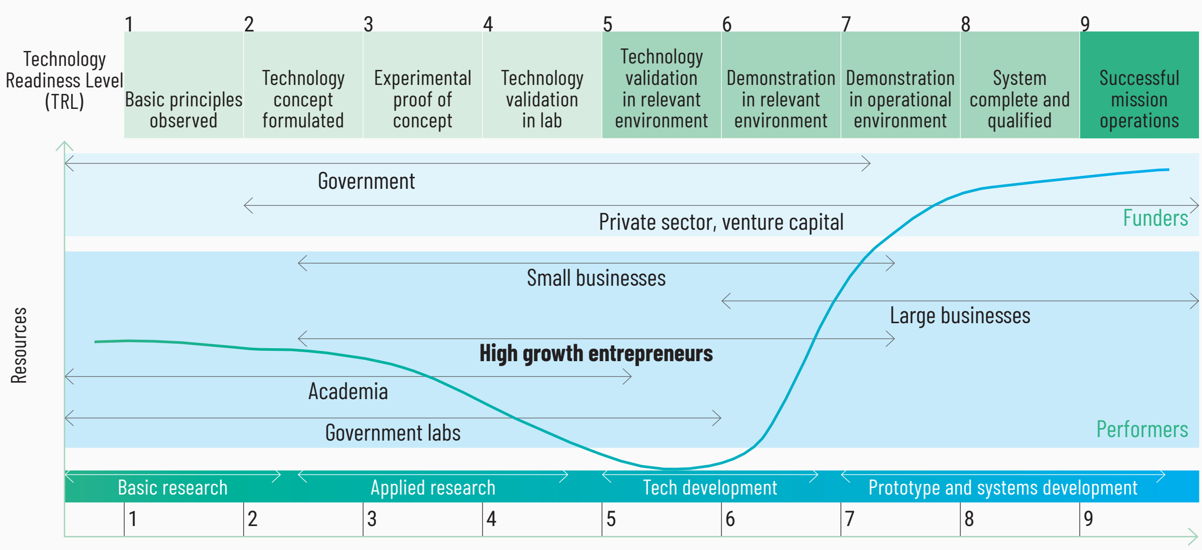
Many technology innovation initiatives are discontinued due to lack of resources, particularly at the stage of technology demonstration and development. The "Valley of Death" is the gap between the "research economy" (a product of academic research and industry-academia cooperation) and the "commercial economy", which transforms the research outcomes into commercially viable products (Figure 3.3) Strategies and approaches to fill the resource gaps between stages 4 (technology validation) and 7 (demonstration in the real world) include: 1) extending the availability of research resources to later stages of development, e.g. by incentivizing academic champions; 2) earlier commercial investment through reducing perceived risks, e.g. by prototyping, or brainstorming dialogues with investors on nascent technologies and potential capabilities; and 3) infrastructure investments designed to benefit the environment as a whole, e.g. through rapid prototyping of infrastructure, lowering start-up entry costs, and increasing successful attempt rates (Jackson 2011).

3.2 Key actors in advancing sustainable chemistry innovation

Universities/research institutions

Universities and other knowledge-generating bodies advance fundamental research on chemistry. Universities mainly carry out chemical science and engineering research from curiosity-driven, problem-based, empirical, theoretical and (nowadays) also computational angles. Sustainability chemistry research links the chemistry and engineering sciences, bridges curiosity-driven understanding and solving of

Figure 3.3 Stage of technology readiness and the Valley of Death (adapted from EC 2012, p. 18; Coyle 2011, p. 11)



hard problems, and brings in perspectives from other research disciplines such as toxicology, sociology and business (Whitesides 2015).

Universities no longer confine themselves to the traditional roles of teaching and research, but are increasingly engaging in entrepreneurial and business activities. They are expanding their roles by leveraging from fundamental research to entrepreneurial activities as "entrepreneurial universities" (Clark 1998; Etzkowitz 2002; Mirowski and Sent 2007; Etzkowitz *et al.* 2008) or "third generation universities" (Wissema 2009). In this case, universities are understood to be nucleuses for problem-solvers, inventors and entrepreneurs which are not only creating professionals (first generation universities), or professionals and scientists (second generation universities), but professionals, scientists and entrepreneurs (EC and OECD 2012). Examples of activities closely related to entrepreneurship are patenting, licensing and the establishment of start-up support systems, including spin-off venture formation (Klofsten and Jones-Evans 2000). This development is attributed to the pressure exerted on universities to commercialize their research findings in order to generate revenue which will cover some operating costs, including those of research.

The chemical industry

The chemical industry often carries out capital- and engineering-intensive applied research and development required for the commercialization of products or services (Whitesides 2015). It also fosters innovation contributing to sustainable development across sectors and regions (e.g. in the health and well-being, packaging, energy, mobility and other sectors) (International Council of Chemical Associations [ICCA] 2017; WEF 2018).

University-industry links are contributing significantly to innovation. In the field of chemistry several innovations have been (co-)invented and/or developed, including heterogeneous catalysis, the synthesis of monomers and production of polymers, small-molecule pharmaceutical chemistry, organometallic chemistry, electrochemistry and energy storage, materials science and surface science (Whitesides 2015). Direct private sector support for universities may include, for example, research funding, training partnerships and technical service contracts (Malairaja and Zawdie 2008). Strong industry-university partnerships could generate complementary strategies for technology development and commercialization, thereby reducing the market risk and optimizing

Box 3.1 Recommended actions for universities in low- and middle-income countries facing the challenge of transforming themselves into third generation universities

To strengthen universities in low- and middle-income countries in becoming "third generation universities", a number of actions have been identified by the UN Economic Commission for Europe (UNECE) and the UN Economic and Social Commission for Asia and the Pacific (ESCAP) (UNECE 2012). They include: 1) the preparation of plans to increase the contribution to innovation made by top research universities, based on a detailed assessment of existing constraints and possibilities; 2) the possible merging of existing research institutes with universities, as a result of a rating exercise that would take into account potential and existing synergies, complementarities between research programmes, and access to human and material resources; 3) the organization of centres of scientific and educational excellence in leading research universities, which would be appropriately equipped for the creation of high-level technology and encourage the involvement of students, among other actions identified.

resources for the creation of commercially viable product (Edmondson *et al.* 2012).

The financial services industry

The financial services industry is of importance in shaping investments and innovation. Experience in areas such as climate change has shown that it plays a decisive role in accelerating (or slowing) the transition towards sustainability. Actors in the financing sectors which affect the sustainability of chemistry-related innovation include both public finance entities (e.g. national/regional or multilateral development banks, export credit agencies, government enterprises/utilities) and private finance entities (e.g. pension funds, sovereign funds, mutual funds, insurance companies, hedge funds, banks, company capital expenditure).

The insurance sector, one of the world's largest investors, can endeavour to ensure that its direct investments contribute to sustainable chemistry innovation. In the banking sector lending decisions can direct funding towards sustainable projects and technologies. Similarly, cutting finance for destructive practices and companies can play an important role in steering the chemical industry and its downstream users towards sustainability. Institutional investors can exert influence by redirecting their investments towards more sustainable practices and companies, and using their influence as shareholders to demand that companies act sustainably.

Governments

Governments play an important enabling role in fostering chemical innovation (UNECE 2012; United Nations Economic Commission for Africa [UNECA] 2016a; UNECA 2016b) and helping correct market failures to produce innovation. Governments may provide financial incentives, finance infrastructure or directly finance innovation projects (Lopes da Silva, Baptista Narcizo and Cardoso 2012). They may also ensure that innovation barriers are removed by stimulating the demand side (UNIDO 2017). Government can play a particular a role in fostering sustainable chemistry innovation through national industrial policies or national programmes. These functions are in line with the perceived role of government as a facilitator providing enabling instruments and favourable conditions, rather than making specific choices and declarations (UNECE 2012; UNECA 2016a; UNECA 2016b).

Other actors

NGOs and the general public have traditionally not been engaged in research or been recognized as stakeholders in the innovation process. However, it is now recognized that these groups can make a significant contribution. For example, innovation-focused dialogue among stakeholders may be undertaken in developing new regulatory frameworks or as a response to awareness-raising of NGOs. This approach requires new interaction channels, but may bring in new sustainable chemistry considerations to implement the SDGs (WEF 2018).

3.3 Profiting from the potential of sustainable chemistry start-up companies

The importance of chemistry start-ups for sustainable development

Start-up companies, including those focusing on sustainable chemistry, play an important role in contributing to sustainable economic development (US GAO 2018; WEF 2018). Where they attain their growth ambitions, they contribute significantly to innovation and the creation of jobs and wealth in the larger economy. Start-ups invest heavily in R&D and are more likely to export their goods and services (Storey 1994; Baldwin *et al.* 1995; Kirchhoff *et al.* 2007; Wu and Atkinson 2017). If they are created as international new ventures, they can also act as catalysts for technology transfer across regions and value chains (Oviatt and McDougall 2005). Similarly, they have the potential to apply specific local knowledge that is relevant in less developed parts of the world.

Sustainable chemistry start-ups play an important role in scaling up chemistry innovation.

They develop new, potentially disruptive ideas and attempt to put innovative products on the market. Breakthrough technologies in sustainable chemistry have significant market potential and could transform how the industry perceives performance, function and synthesis (ASBC and GC3 2015).

Sustainable chemistry start-ups are based in many countries. An example of a collaborative start-up network is the GC3 Start-up Network in North America (GC3 n.d.a). The winners of the 2018 Elsevier Foundation Green and Sustainable Chemistry Challenge, for example, from Nepal and Italy, developed novel approaches to sourcing guava leaves and fish bones in order to create new preservatives and fertilizers (Elschami and Kümmerer 2018). Other examples of sustainable chemistry start-ups recognized internationally include:

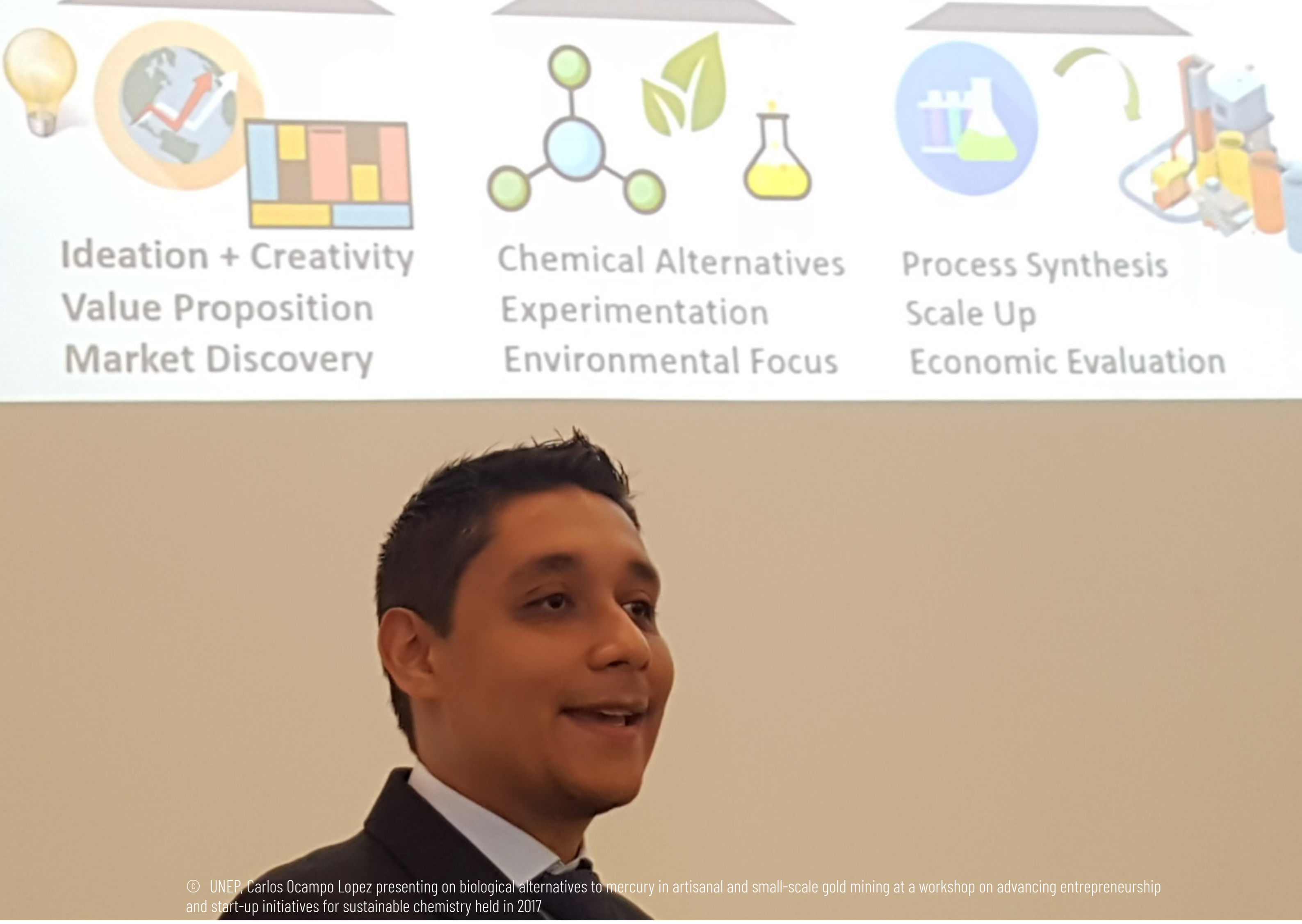
- an Indonesian start-up that uses seaweed in the production of plastic-free packaging (Langenheim 2018);
- starts-ups from Peru and Singapore that use nanotechnology-empowered water purification filters (OECD 2016); and
- a Kenyan start-up that is providing alternative building materials and products made from recycled plastics (Mbaka 2018).

Challenges of chemistry start-ups

Start-ups active in the area of chemistry, including those working on sustainable chemistry, face challenges. Difficulties may occur in regard to securing access to finance, marketing, partnerships, commercialization, and access to research infrastructure. Other difficulties include high costs and logistical challenges in feedstock supply, capital requirements to build a commercial scale plant, and technical challenges in making cost-competitive products (Sworder, Zhang and Matheson 2018). Access to finance is challenging, as start-up firms are often built on intangible rather than tangible assets and face a high risk of failure (Söderblom and Samuelsson 2014). Start-ups in developing and emerging economies face particular challenges (Sworder, Salge and van Soest 2017), including lack of basic laboratory infrastructure and of access to capital. However, developing countries may also offer opportunities, for example owing to their lower market density and the opportunity to leapfrog to advanced technologies. Box 3.2 describes start-up challenges identified by sustainable chemistry entrepreneurs (UNEP 2017).

A range of stakeholders and organizations engage in supporting sustainable chemistry start-ups through various stages of the innovation chain, with complementary roles based on their motives for collaboration (Wilson 2015). These stakeholders include universities, research

 First and second prize winners of the 2018 Elsevier Foundation Green and Sustainable Chemistry Challenge, Prajwal Rabhindari and Dr. Alessio Adamiano



© UNEP, Carlos Ocampo Lopez presenting on biological alternatives to mercury in artisanal and small-scale gold mining at a workshop on advancing entrepreneurship and start-up initiatives for sustainable chemistry held in 2017

Box 3.2 Insights from entrepreneurs on challenges for sustainable chemistry start-ups (UNEP 2017)

Representatives of some 15 sustainable chemistry start-ups from around the world met in Berlin, Germany, in 2017 to identify opportunities and challenges. They discussed, among others, the following:

- *Innovation culture in universities:* Few universities provide chemistry students with training in business, marketing, and other relevant subjects; universities seldom encourage students to create start-ups; co-operation across faculties can support interdisciplinary thinking; there is a need for curriculum reform, as sustainability considerations are still not integrated in standard chemistry courses.
- *Research infrastructure:* More incubators are needed to facilitate sustainable chemistry start-ups; barriers for spin-offs from universities are too high; there is a need to strengthen partnerships between academia and industry/the private sector.
- *Intellectual property, patents and licensing:* Patenting and licensing processes are often lengthy, costly and complicated; where patents are in place, they are often not turned into a product or service; licensing agreements with universities may sometimes hinder entrepreneurship.
- *Business planning and access to finance:* Sustainable chemistry entrepreneurs often lack business expertise (e.g. in developing a business plan); networks and partnerships are crucial to establish a multi-disciplinary team and gain access to capital.
- *Upscaling, marketing, commercialization:* The time it takes for a product/service to become profitable is often lengthy; a thorough analysis of the market is a prerequisite for success (e.g. innovation should be based on market demand); start-ups need realistic milestones and targets.
- *Enabling environment/effective regulation:* Regulations may sometimes create unnecessary burdens for entrepreneurs; registration processes may be too costly and lengthy for start-ups with little capital; an incentive system could help (e.g. tax reductions).

institutions, corporations, business associations, NGOs, funding organizations and governmental institutions.

Initial coaching and technical support services

In the early development stages, start-ups need to have the right entrepreneurial skill sets. These include: 1) technical skills (necessary to produce the business's product or service); 2) managerial skills (essential for the day-to-day management and administration of a company); 3) entrepreneurial skills (skills for recognizing economic opportunities and acting effectively on them); and 4) personal maturity skills (e.g. self-awareness, accountability, emotional and creative skills) (Kutzhanova, Lyons and Lichtenstein 2009). A basic knowledge and skill set may include learning on topics such as entrepreneurship, scholarship, business modelling and business planning. There is an emerging market for online education platforms that provide full courses and certified modules of university lectures to support start-ups (Yuan and Powell 2013).

The United States Department of State's Global Innovation through Science and Technology (GIST) has supported the development of start-ups, including many initiatives in green chemistry (GIST 2018). This initiative seeks to "empower young innovators through networking, skills building, mentoring, and access to financing to develop start-up solutions that address economic and development challenges". Through training, competitions, resources and interactive online programmes, the initiative supports innovators and entrepreneurs from more than a hundred emerging economies in establishing successful start-ups. This is done through competitions, start-up trainings, and interactive online programmes. The first programme developed by GIST in Latin America was in Medellín, Colombia in 2015. It provided training, an innovation competition, and access to finance in the United States.

Some entrepreneurially oriented universities have set up infrastructure to attract investment for the development of promising high-tech projects (Lockett, Jack and Larty 2012). Dedicated staff provide coaching and technical assistance through technology transfer centres or innovation and commercialization offices (Sergey, Alexandr and Sergey 2015). For example, the Center for Sustainability at Aquinas College in the State Michigan in the United States operates a "*Proof of Concept Center*" providing assistance to green chemistry start-ups (e.g. in licensing and patenting processes).

Obtaining recognition is important for start-ups early on in the process, in order to achieve market visibility and gain a reputation. Start-ups may benefit from participating in award schemes and thematic challenges, early-stage start-up

Box 3.3 Selected sustainable chemistry awards and pitching events targeting start-up

Thematic challenges and awards

- The Elsevier Foundation Green and Sustainable Chemistry Challenge, launched in 2015, is a thematic challenge. Chemistry-related ideas with an impact on sustainable development can be submitted.
- The ISC3 Innovation Challenge, launched in 2018, calls for applications by start-ups pioneering in thematic sustainable chemistry topics that change annually, such as sustainable buildings and living. Its best practices awards are lighthouse examples of sustainable chemistry innovation.

Start-up pitches and investor forums

- The GC3 is a multi-stakeholder collaborative based in the United States which promotes sustainable chemistry innovation. It selects start-ups every year to present their sustainable chemicals, materials, products and manufacturing technologies to large companies at its Annual Green & Bio-Based Chemistry Technology Showcase & Networking Event.
- NIW Startups is part of the annual Nairobi Innovation Week in Kenya, where early-stage start-ups (classified into categories such as clean tech, agriculture and food security) present their ideas to an international jury.

pitches and investor forums, and by seeking media coverage as described in Box 3.3.

Institutional support mechanism/venturing tools

When start-ups advance along the technology innovation chain, more institutional support mechanisms and venturing tools become available. Table 3.1 provides a broad overview.

Both incubator and accelerator type organizations provide nascent firms with advice, business services, networking facilitation and, occasionally, financial support to help them develop and launch their companies (Bøllingtoft and Ulhøi 2005; Hoffman and Radojevich-Kelley 2012; Dempwolf, Auer and D'Ippolito 2014). While incubators "incubate" ideas and set up a business model and company, accelerators "accelerate" the growth of an existing company (Forrest 2018). Figure 3.4 shows key characteristics of these two concepts and how they overlap.

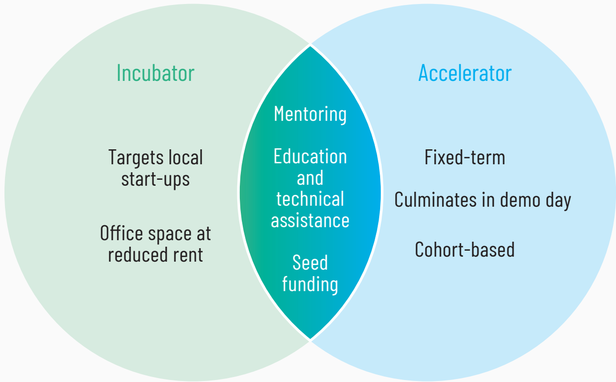
Organizations develop institutional support mechanisms with various subsets of services based on different venturing tools, all with distinct or similar observable characteristics (Dempwolf, Auer and D'Ippolito 2014). Examples include:

- the Center of Studies and Research in Biotechnology (CIBIOT) at Universidad Pontificia Bolivariana, Medellín, Colombia, an initiative that contributes to sustainable chemistry by building capacities in technology transfer projects with technical novelty, market-oriented, scalable and social innovation characteristics;
- the John Warner Chemical Invention Factory of the Technical University of Berlin (Germany), an incubator-like start-up development centre opened in 2018, which provides state-of-the-art laboratories, research infrastructure, scientific mentors and networking opportunities;
- the Think Beyond PlasticTM early-stage innovation accelerator, an accelerator which

Table 3.1 **Institutional venturing tools (adapted from OECD 2012; Dempwolf, Auer and D'Ippolito 2014; Root 2017)**

Venturing tool	Description
University technology innovation offices	Universities help start-up projects turn first ideas into inventions and innovations, e.g. by providing access to research infrastructure, technical equipment and support in patenting.
Incubators	Incubators take in young start-up companies and provide them with affordable space, shared offices and other services. This helps narrow down the business idea and connect to funders.
Accelerators	Accelerators give developing companies access to mentorship, investors and other support that help them become stable, self-sufficient businesses. This is usually cohort-based and
fixed-term.	Large enterprises organize start-up support, with a view to improving corporate competitiveness following their own strategic or financial objectives. This can include business incubation or acceleration. It usually addresses more mature start-ups at later stages of development.
Corporate ventures	Large enterprises organize start-up support, with a view to improving corporate competitiveness following their own strategic or financial objectives. This can include business incubation or acceleration. It usually addresses more mature start-ups at later stages of development.
Governmental/NGO support	Public or non-profit venture development organizations provide a portfolio of services to start-ups, with the intention of creating positive economic, social or environmental impacts.

Figure 3.4 Venn diagram of incubator and accelerator characteristics (adapted from Dempwolf, Auer and D'Ippolito 2014, p. 14)



supports sustainable chemistry start-ups from different world regions; and

- Accelerace (Denmark), a late-stage innovation accelerator that is part of the Danish national Scale-up Denmark initiative, which is scaling up start-ups within tech, food tech, clean tech, life sciences and welfare technologies.

A wider range of venturing tools are shown in Figure 3.5. This figure highlights the relevance of venturing undertaken at various stages of the innovation chain. Some tools are more relevant for start-up support early on, while others (e.g. corporate venture capital, strategic partnerships and acquisitions) are more relevant at later stages.

Financing instruments and mechanisms

In most cases, start-ups require funding from investors because their own financial resources are not sufficient to cover various costs at the different development stages. For example, large amounts of capital are often needed for technical equipment, laboratories, access to research infrastructure, patent fees and salaries. One of the most important decisions entrepreneurs

Figure 3.5 Venturing tools supporting start-ups at different innovation phases (adapted from IESE Business School 2017, p 21)

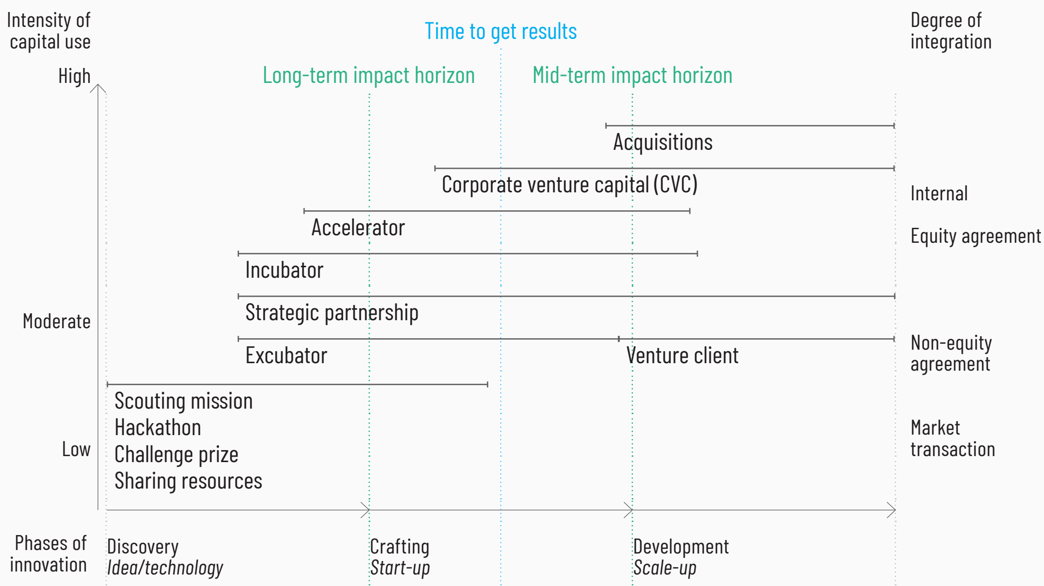


Table 3.2 **Potential private investors for sustainable chemistry start-ups (adapted from OECD 2012 and Root 2017)**

Investor	Description	Typical funding instrument
Business angels/angel investor networks	Individuals or networks with disposable income invest in start-ups. Usually they invest cash, provide time for coaching/mentoring, and make business introductions.	Equity and mezzanine
Banks	Bank loans are one of the most common tools for accessing finance. Banks request collateral or guarantees in exchange for loans.	Debt
Private equity (PE) firms	Private equity firms invest directly in private companies. They tend to focus on more mature start-ups and to invest much larger amounts than do venture capital firms.	Equity
Venture capital (VC) firms	Venture capital refers to investments made in exchange for equity. VC focuses on funding, developing and expanding start-ups which earn the investors return on their capital in a fairly short time.	Equity and mezzanine
Corporate ventures	Corporate ventures are used by large firms to invest in innovative start-ups in order to improve corporate competitiveness with either strategic or financial objectives.	Equity and mezzanine
Impact investors (e.g. foundations or public/semi-public funders such as development finance institutions)	Impact or social investors refers to funds that invest with the intention of creating a positive social or environmental impact. As an eclectic group, they include high net worth individuals (HNWIs), family offices, foundations, banks, pension funds, impact-focused VCs and angels, and development finance institutions (DFIs).	Grant, debt and equity
Crowd funding platforms	Crowd funding is the practice of raising money from a large group of individuals, typically through an online portal.	Grant, debt and equity

Table 3.3 **Examples of investments in sustainable chemistry start-ups by different investors**

Public grants	Individuals or networks with disposable income invest in start-ups. Usually they invest cash, provide time for coaching/mentoring, and make business introductions.
	Enerkem and the City of Edmonton (Canada): Enerkem formed a partnership with the City of Edmonton for the construction of a facility that converts non-recyclable, non-compostable municipal solid waste into liquid biofuels and chemicals. It has since secured several strategic partnerships to co-develop additional plants. Enerkem Alberta Biofuels, a subsidiary of Enerkem Inc., has received a Canadian dollars 3.5 million grant from the Government of Canada through the Western Innovation (WINN) Initiative.
Public investors	The Brabant Development Agency Capital (BOM Venture Capital) Fund (Netherlands), created by the Dutch Government and the Province of Brabant, finances companies and start-ups by providing equity capital and subordinated loans of up to euros 2.5 million. Another example is Innofund (China), an equity fund developed by the Chinese government for which sustainable chemistry start-ups are eligible. The European Investment Bank supports start-ups, including those active in sustainable chemistry, through the European Investment Fund (EFSI), e.g. under the Early Stage Window of EFSI Equity (InnovFin Equity).
Private equity	Capricorn (Belgium), a private venture capital firm with its own sustainable chemistry fund (CSCF), achieved its first milestone capital, closing at euros 50 million in December 2016. The portfolio included three start-ups from Belgium, Germany and the United States.
Mezzanine funding	The Green Centre (Canada) helps commercialize academic and entrepreneurial discoveries. Formed in 2009, it was funded by the Government of Ontario, the Government of Canada and various industry partners, among other technical support. It provides 8,500 square feet of state-of-the-art laboratory facilities for innovation and the advancement of chemistry technologies.
Impact investors (e.g. foundations or public/semi-public funders such as development finance institutions)	Impact or social investors refers to funds that invest with the intention of creating a positive social or environmental impact. As an eclectic group, they include high net worth individuals (HNWIs), family offices, foundations, banks, pension funds, impact-focused VCs and angels, and development finance institutions (DFIs).
Crowd funding platforms	Crowd funding is the practice of raising money from a large group of individuals, typically through an online portal.

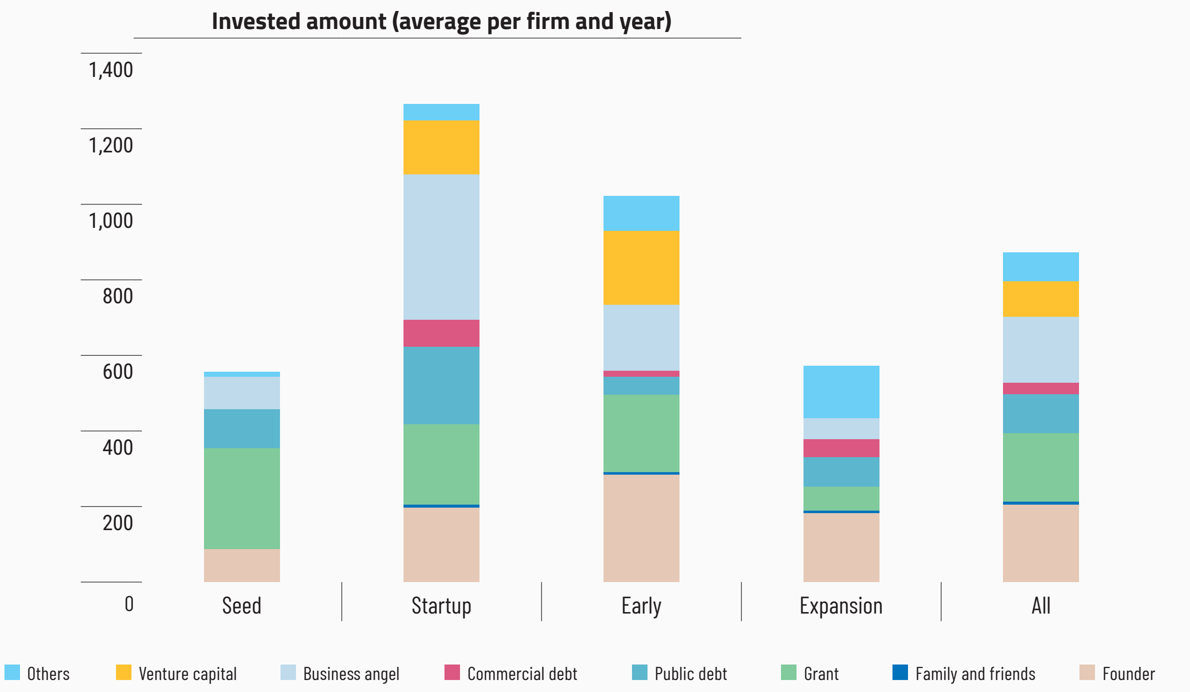
need to make at some point is how to raise money (and whom to ask for it) (Root 2017).

Four main types of funding instruments are available for start-ups: grants, debt financing (loans), equity financing, and mezzanine. A grant typically does not obligate the recipient to repay the funds. Debt financing means accepting capital with the promise of repaying the principal with interest. Equity financing means an investor puts money into a start-up in exchange for a percentage of the company's shares. Mezzanine is a mix of debt and equity financing features (Wilson 2015; Root 2017). Potential private investors in sustainable chemistry start-ups are shown in Table 3.2, which emphasizes that investors use different funding instruments.

Research indicates that some investors may be more appropriate partners for start-ups in earlier development stages, and others in later stages of a firm's development (Söderblom and Samuelsson 2014; Wilson 2015). One of the main reasons for this is that investors have different strategic motives for providing seed money (Root 2017). For example, a publicly funded development finance institution usually invests with the intention of creating a positive social or environmental impact while a corporate venture invests with a view to gaining competitive advantage over other market players. The phenomenon of different investors investing at different development stages is illustrated in Figure 3.6.

Real-world examples of investments in sustainable chemistry start-ups demonstrate that different funding instruments are used by start-ups, and that start-ups have taken different decisions on whom to partner with in order to access finance (Table 3.3). Several public and private stakeholders have established different types of funding opportunities for sustainable chemistry start-ups, including national grants, public investment agencies and equity-based Sustainable Chemistry Funds, as well as cooperative approaches involving public and private partners.

Figure 3.6 **Start-up development stages and typical investors along the innovation chain (Swedish krona thousand) (adapted from Söderblom and Samuelsson 2014, p. 10)**



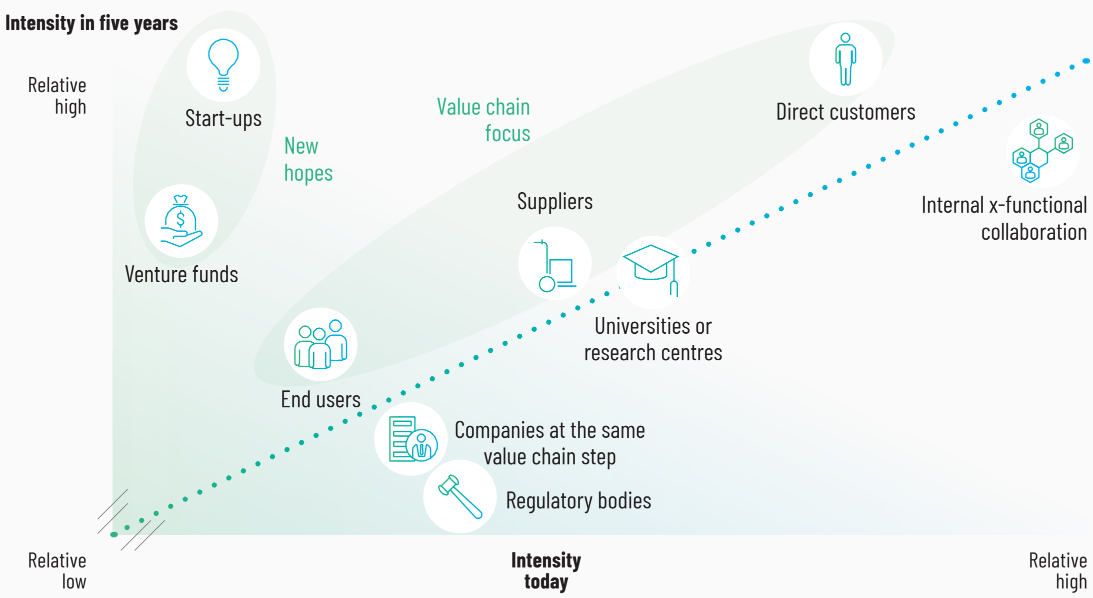
Average invested amount in each phase. The mean in thousand Swedish krona for the respective sources for all firms in the particular phase is reported.

Ⓒ Enerkem, manufacturing of biofuels and renewable chemical products from non-recyclable waste

Chemical companies' engagement in start-ups

While many large chemical companies have research departments, industry leaders increasingly recognize the potential of start-ups. In a recent survey, representatives of large companies responded that in the future they expect "a much higher intensity of collaboration with start-ups than today"; by 2022 they foresee collaboration with start-ups and venture funds surpassing in intensity collaborative approaches with suppliers, universities or end users (WEF 2018).

Figure 3.7 Chemical industry leaders' view of the evolution of the intensity of collaboration with other stakeholders (adapted from WEF 2018)



In taking a strategic approach to identifying and/or supporting start-ups, and to obtaining a growing portfolio of associated start-ups, a number of large corporations have special programmes and instruments dedicated to different sub-goals associated with ultimately gaining competitive advantage (Table 3.4). These can be distinguished as corporate incubator, corporate accelerator, corporate venture capital and corporate strategic partnerships. A Boston Consulting Group (BCG) research study (Brigl *et al.* 2016) found, however, that the chemical industry mainly used corporate venture capital to support start-ups although there are more recent examples of accelerators and incubators. Examples of such ventures led by the chemical industry include BASF Venture Capital, Dow Venture Capital, DuPont Ventures, Solvay Ventures (and Aster Capital along with Alstom and Schneider Electric) and Evonik Venture Capital (Faulkner and Berenshteyn 2013).

3.4 Creating an enabling framework to support sustainable chemistry innovation

Promoting open and collaborative innovation

The open innovation paradigm envisages that companies can no longer afford to innovate by carrying out R&D activities single-handedly (Şimşek and Yildirim 2016). Instead, they are engaging research and knowledge institutions,

Table 3.4 The corporate approach to start-up development (Brigl *et al.* 2014, p. 6)

	Business incubation			
	Corporate incubator	Corporate accelerator	Corporate venture capital	Corporate strategic partnerships
Objective	› Support start-ups with an array of business support resources and services, orchestrated by incubator	› Support start-ups with a structured programme using fixed curricula	› Support existing companies with capital in exchange for equity shares	› Partner with existing companies to drive joint value creation
Benefits to start-up partner	› Office space, hardware	› Office space, hardware › Skilled mentorship and coaching › Start-up network › Technical support › Potential funding support	› Financial support › In many cases, close cooperation with corporate unit as equal partner › Mentorship (in some cases)	› Extend market potential › Close missing IP gap › Limit investments in non-core corporate capabilities › Create competitive advantage
Benefits to company	› Outsourced R&D function	› Wider search field for corporate development and growth options › "First pick" potential in case of promising start- up business	› Equity share in company with strong growth and profit potential › Portfolio extension, especially in advanced technologies and products	› Extend market potential › Close missing IP gap › Save investments in non-core corporate capabilities › Create competitive advantage
Investment	› Up to 25 per cent of equity	› Partly without equity; in some cases up to 5 per cent	› 20 per cent or less	› Possible equity exchange, depending on partnership format
Start-up stage	› Early stage, without existing business	› Start-ups technically ready to "spread wings"	› Small existing companies with high growth potential	› Innovative companies, but not necessarily new players
Time frame	› 12-36 months	› Typically 3 months	› 5-7 years	› Depends on product cycle

Box 3.4 **Open collaborations in sustainable chemistry innovation**

The Eco-Efficient Products and Process Laboratory (E2P2L) is a unique international research entity dedicated to renewable and sustainable chemistry. Based in Shanghai, China, its purpose is to develop innovative eco-efficient products and environmentally benign processes capable of reducing dependence on oil and other fossil resources. E2P2L was set up in November 2011 by the French National Scientific Centre (CNRS), the Belgian chemical company Solvay, the Ecole Normale Supérieure de Lyon in France, and the East China Normal University. In 2013 the Lille University of Science and Technology in France and the University of Fudan in Shanghai joined the consortium. Another example is the GC3, a multi-stakeholder collaborative that drives the commercial adoption of green chemistry by catalysing and guiding action across all industries, sectors and supply chains (GC3 n.d.b).

as well as chemical suppliers and users, financial institutions, engineering companies and digital solution providers, in research and innovation (Huizingh 2011). These efforts can also include collaboration with competitors in seeking lower operational costs and lower risks (Şimşek and Yildirim 2016). Finally, sustainable innovations need scaling up and sharing across sectors if they are to have the potential to shift the sector as a whole.

As shown in Figure 3.8, novel forms of collaboration are being created between different internal entities of chemical companies, as well as with external partners, customers and consumers, regulators and other civil sector communities. Partnerships are often driven not only by science and technology, but also by SDG-related issues, and are implemented with cross-sectoral, global and diverse markets in mind (WEF 2018).

To manifest greater collaboration and partnership among actors, a number of specific concepts and models may be introduced. For example, science and technology parks present opportunities to innovate in open systems where technology developers and diffusers work at one location to translate innovations from universities and research institutes into markets (Şimşek and Yildirim 2016). Newly established research centres, technology promotion offices and

Figure 3.8 **New collaboration approaches in the chemical industry (adapted from WEF 2018)**

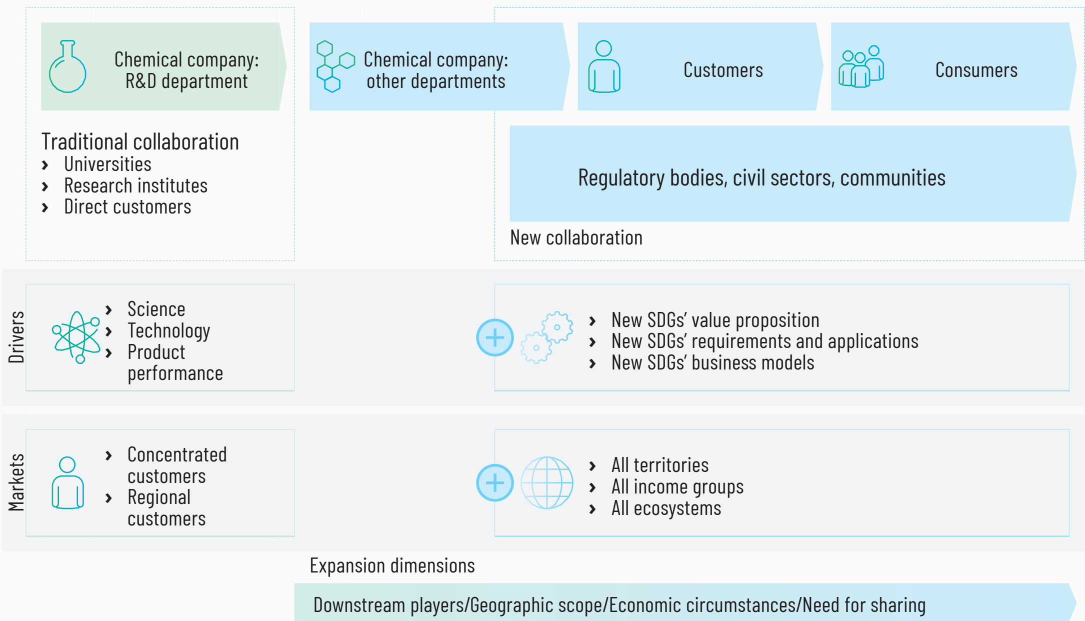
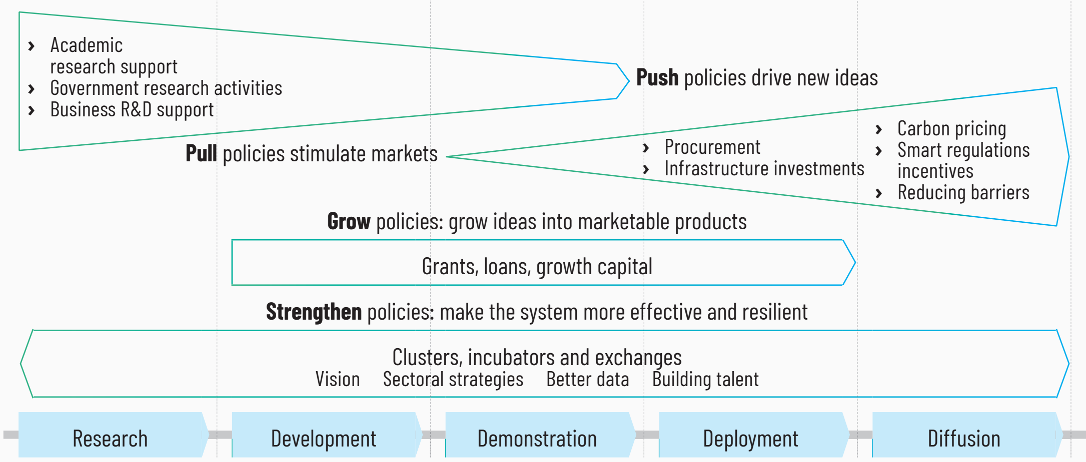


Figure 3.9 Policy interventions that foster technology innovation (adapted from Elgie and Brownlee 2017, p. 15)



joint institutes use a similar approach of co-creating value through increased collaboration between stakeholders (Wissema 2009). Industry is opening up to more collaborative innovation compared with some five years ago, although a large majority of industry stakeholders still face internal collaboration challenges (WEF 2018). Intermediaries play an important role in facilitating such collaboration innovation (WEF 2018).

Enabling policies to promote sustainable chemistry innovation

The national innovation systems approach (OECD 1997) stresses that flows of technology and information among people, enterprises and institutions are key to the innovation process. For stakeholders and policymakers interested in advancing sustainable chemistry innovation, an understanding of the national innovation system can help identify leverage points to identify policy interventions.

Enabling policies and financing by governments are an important dimension of the innovation system. They are factors that can be used to correct inefficiency and distortions in innovations. Elgie and Brownlee (2017) divide potential policy approaches or interventions related to innovation into four categories: 1) push policies driving new ideas; 2) pull policies helping to stimulate market demand; 3) grow policies helping to grow ideas into marketable products; and 4) strengthen policies that cut across the clean innovation system, making it more effective and resilient.

Table 3.5 Examples of push and pull policies to advance sustainable chemistry innovation

Type of policy/intervention	Example
Push policies (driving new ideas and innovation)	› Tax incentives for start-up initiatives › Co-financing or subsidization of science and technology parks (STPs) which include sustainable chemistry components › Sllocating a specified percentage of gross domestic product to R&D and venture funds for start-ups › Increasing the quality of physical infrastructure (academic and research institutions, innovation and technology hubs, makerspaces and internet infrastructure) › Sdopting open and inclusive principles for innovation, with institutions mandated to stimulate open, inclusive, social and collaborative innovation
Pull policies (creating market demand for innovation)	› consumer education and awareness-raising › financial incentives to consumers (e.g. subsidies for sustainable chemistry products) › government procurement to purchase eco-labelled products

While these are general categorizations, this framing illustrates how public interventions may be structured to shape different elements of the innovation system in a direction which supports sustainable chemistry innovation. From the point of view of effectiveness, in certain cases market-based policy instruments (e.g. taxes and tradable permits) tend to induce more innovation than direct regulation. Other characteristics of policy instruments that play a role include stringency, predictability, flexibility, depth and incidence (OECD 2011).

Exploring opportunities for green bonds

Financial instruments and tools can play a role in driving the transition towards sustainable chemistry innovation. Green bonds are an example. These bonds can be defined as "a debt security that is issued to raise capital specifically to support climate related or environmental projects" (International Bank for Reconstruction and Development and World Bank 2017). An important dimension of setting up a green bond is defining criteria, which include green or sustainable chemistry considerations (Ernst & Young [EY] 2016). Green bonds designed to encourage sustainability come with tax incentives such as tax exemption and tax credits. This makes them a more attractive investment than a comparable taxable bond. While green bonds are currently focused on climate change, their potential to advance sustainable chemistry investment and innovation could be explored.

3.5 Measures to strengthen sustainable chemistry technology innovation and financing

Accelerating research and innovation through collaborative and enabling action, including through start-up companies, is key to reaping the promise of green and sustainable chemistry to make a contribution to the 2030 Sustainable Development Agenda. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to strengthen sustainable chemistry technology innovation and financing.

- Use green and sustainable chemistry criteria to assess whether innovations in chemistry are compatible with the 2030 Sustainable Development Agenda.
- Strengthen open and collaborative innovation mechanisms involving research organizations, the private sector, governments and civil society.
- Strengthen support mechanisms for sustainable chemistry start-ups in universities, research institutes, the private sector and all levels of government.
- Strengthen financial instruments for investment in sustainable chemistry innovation, for example through green bonds and venture capital or other multi-stakeholder funding mechanisms.
- Develop guiding policies and criteria for financial resources to support green and sustainable chemistry innovation.
- Review and strengthen innovation policies to ensure that they enable, and do not create, barriers to sustainable chemistry innovation.

4/ Evolving and new business models

Chapter Highlights

New and evolving business models have significant potential to advance sustainability in the chemical industry, if properly applied.

Business models of relevance include service-oriented models (e.g. Chemical Leasing) and coordination benefits models (e.g. chemical parks).

Business models that decentralize production (e.g. 3-D printing) and distribution (e.g. e-commerce) are on the rise, creating opportunities but also raising concerns.

Social entrepreneurship business models are relevant for chemicals and waste, and are emerging around the world.

A business model defines how an organization creates, delivers and captures value in economic, social, cultural or other contexts. Business models are constantly evolving. While they may create opportunities, they can also create potential concerns from a chemicals and waste management perspective. This chapter discusses several evolving and new business models which are considered relevant from a chemical and waste management perspective. They range from service-oriented models, to social enterprises, to models in which production and sales are decentralized.

4.1 Business models in a fast-changing world

In a fast-changing world, new business models with direct implications for the chemical industry are evolving rapidly – providing opportunities to advance sustainability by increasing resource efficiency, and by reducing the use of hazardous chemicals and chemical pollution. Business model innovations for sustainability may be defined as creating "significant positive and/or significantly reduced negative impacts for the environment and/or society, through changes in the way the organization and its value-network create, deliver value and capture value or change their value propositions" (Bocken *et al.* 2014). Business models that have a strong focus on sustainability and circularity include green product- and process-based models, waste regeneration systems, efficiency optimization, management services, and industrial symbiosis models (Beltramello, Haie-Fayle and Pilat 2013). Other emerging business models, such as consumer-centric models and social enterprises, are directly driven by sustainability considerations but are equally relevant to the sound management of chemicals and waste.

4.2 Service-based systems, including Chemical Leasing

Service-based business models, or "product-service systems" (PSS), are an alternative to the traditional sales concept of industrial production. PSS can be broadly defined as "a combination of products and services in a system that provides functionality for consumers and reduces environmental impact" (Hänsch Beuren, Gomes Ferreira and Cauchick Miguel 2013). This means goods continue to be owned by the provider(s).

What a PSS customer actually purchases is the functionality or performance of the goods in the form of a service. A business that offers a service does not seek to maximize sales of a chemical product, but to provide the service in a cost-effective and sustainable manner. Research suggests that service-based business models incentivize industry to change product design; advance life cycle thinking and stewardship; and reduce environmental footprints throughout a product's life cycle (Agrawal and Bellos 2015).

Chemical management services: win-win opportunities

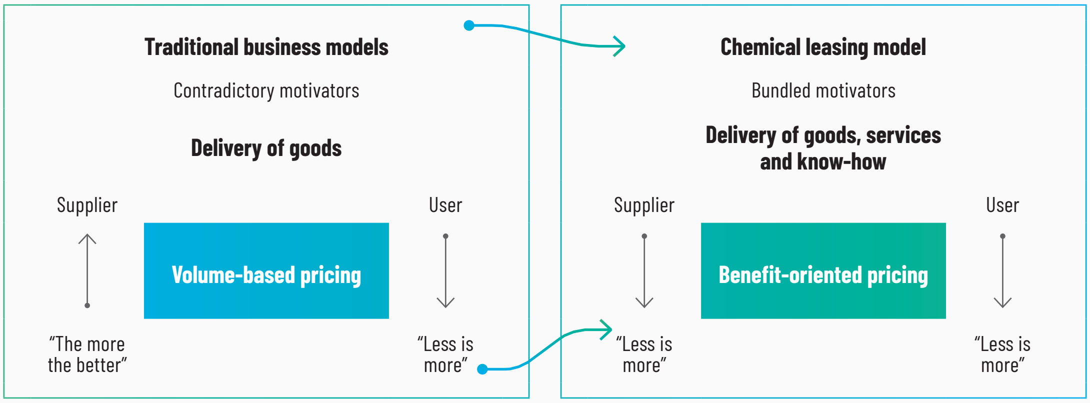
In the chemicals sector PSS are referred to as "chemical management services" (CMS). CMS generally involve a strategic, long-term contract between the service provider and the client. The service provider is compensated based on the quality and quantity of the services provided, rather than on the volume of chemicals sold. Proponents of CMS note that the service provider and customer have the same objective: to reduce the overall life cycle costs of chemicals management (United Kingdom Chemicals Stakeholder Forum 2013). CMS services may encompass (and be provided at) all stages of the chemical life cycle, including production, transport and storage. They can exist in the automotive, air transport, electronics, heavy equipment, food and pharmaceutical, and steel industries, among others. Through technological solutions (e.g. material substitution, pollution prevention, and end-of-life management practices) CMS can help reduce the risks associated with the production and use of chemicals. They can also stimulate sustainable production and a decrease in product consumption levels (Askar 2006).

The market for chemical management services is growing

The CMS supplier community and market have grown significantly in recent years. Annual growth in revenue for CMS providers exceeded 7.28 per cent per year between 2011 and 2016, from around US dollars 2,192 million to US dollars 3,115 million. Revenue growth in 2016 is estimated to have been at the lower end of the 5-10 per cent range, but is expected to increase to 9-14 per cent in 2017-2022. The profitability outlook for 2017-2022 is projected to improve slightly. Companies using CMS include Haas TCM, PPG Industries, KMG Chemicals, Henkel, ChemicoMays, BP, Quaker Chemical, EWIE Co, Intertek and Chemcept (Technical Progress 2018).

© UNIDO, 2018 Global Chemical Leasing award ceremony, 6 November in Vienna

Figure 4.1 Traditional business models vs. Chemical Leasing (adapted from Joas, Abraham and Joas 2018, p. 398)



Republished with permission of Springer Nature; permission conveyed through Copyright Clearance Center, Inc.

Chemical Leasing refers to a business model whereby suppliers sell services (e.g. the number of cars painted) rather than chemicals, creating incentives to minimize the use of chemicals and maximize resource efficiency.

Chemical Leasing: a successful application of chemical management services

Chemical Leasing is a type of CMS whereby "the functions performed by the chemical serve as the unit of payment and chemical suppliers and users work together to optimize chemical use in fulfilling the function" (Joas, Abraham and Joas 2018). Responsibility for the application, handling, storage and disposal of chemicals is thus shifted from the user to the chemical supplier. The supplier, in turn, takes over management of the entire life cycle. Figure 4.1 contrasts traditional business models and the Chemical Leasing model.

Chemical Leasing can be used whenever chemicals are needed to provide a particular function or service. Examples include industrial cleaning and degreasing of parts in the metal processing industry; bonding of boxes in the packaging industry; cleaning of bottles, pipes and vessels in the beverage industry; lubrication of conveyor belts in the beverage industry;

Box 4.1 Chemical Leasing in a middle-income country: wastewater treatment in Colombia

A Chemical Leasing project was implemented in Colombia's petroleum industry through a partnership between Ecopetrol and Nalco, a chemicals provider specializing in water treatment. The aim of this project was to treat wastewater from oil production processes in environmentally sound and cost-effective ways. Following project implementation, there was a 20 per cent reduction in chemicals consumption while water treatment costs were reduced by 80 per cent (US dollars 2.2 million) over 10 months (Moser and Jakl 2014). The unit of payment shifted from dollars per kilogram treatment agent to a unit price (per kilogram barrel of fluid) for the treatment service. This project won the first Global Chemical Leasing Award gold medal in 2010 (Jakl 2011).

© UNIDO, Chemical Leasing Pilot Project in Colombia application of agrochemicals; corrosion and surface protection in the automotive and electric appliances industry; and cleaning in the hospitality sector (Joas, Abraham and Joas 2018).

The Chemical Leasing business model has been successfully implemented for almost two decades in a number of countries (Jakl and Schwager 2008; UNIDO 2016; OECD 2017). At the global level, the UNIDO Global Chemical Leasing Programme has promoted this business model since 2004 (UNIDO 2019). An example of a successful Chemical Leasing approach in a middle-income country is presented in Box 4.1. The 2016 Declaration of Intent on Chemical Leasing has been signed by Austria, El Salvador, Germany, Serbia, Sri Lanka and Switzerland. Additional countries may consider joining (Chemical Leasing 2016).

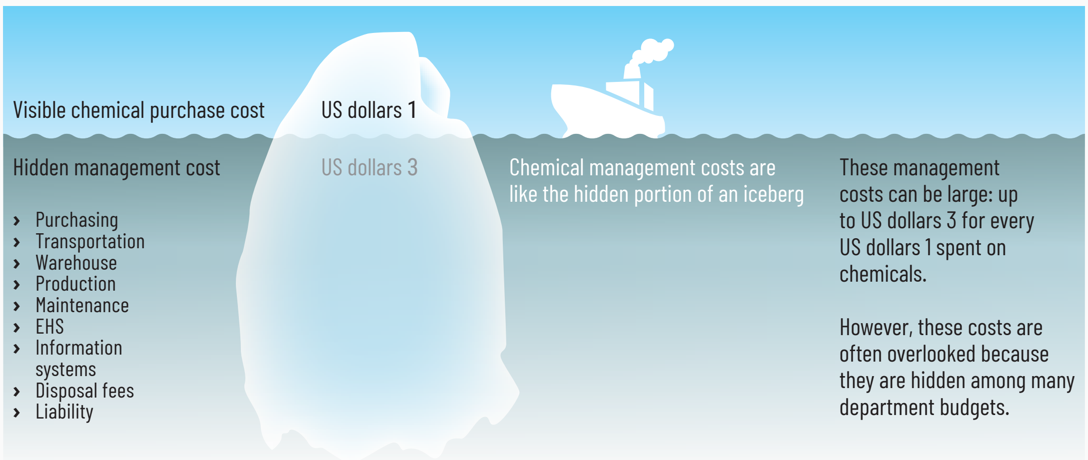
Economic perspectives on chemicals management services

The economic advantages of Chemical Leasing have been analyzed. A recent study (OECD 2017) reported that the benefits of increasing the user's competitiveness include direct cost savings (reduction of chemical quantities if processes are further optimized); indirect cost savings (through energy and waste management); access to better knowledge, with improvement of processes and reduction of risks; and reliable, long-term business relationships. In addition, the benefits of increasing the supplier's competitiveness include higher profits (monetary reward for supply of expertise and services); reduced raw materials costs; reliable, long-term business relationships; access to knowledge about the application of chemicals; and first-hand experience concerning areas for improvement/innovation of substances.

One economic incentive for customers to switch to CMS can be the reduction of the often hidden costs of the management, use and purchase of chemicals (Figure 4.2). Implementing a CMS programme may result in significant cost savings; further incentives include outsourcing of functions that do not represent a core competency of the company, while manufacturing processes and data management can also be strengthened (Chemical Strategies Partnership n.d.a).

Research shows that Chemical Leasing has improved the economic and environmental performance of companies across the chemicals supply chain and provided access to new markets (Moser and Jakl 2014; Joas, Abraham and Joas 2018). In Austria alone, some 4,000 companies were identified as having the potential to benefit from Chemical Leasing, potentially reducing annual use of chemicals by one-third and costs by 15 per cent (OECD 2013). Nevertheless, the uptake of Chemical Leasing has not been as rapid as it could be. More work is needed to

Figure 4.2 Visible and hidden chemicals management costs (based on Bierma and Waterstraat 1997, p. 3; adapted from CSP n.d. b, p. 6)



understand and overcome the obstacles which hinder the uptake of this approach.

4.3 Coordination benefit models: eco-industrial parks and chemical parks

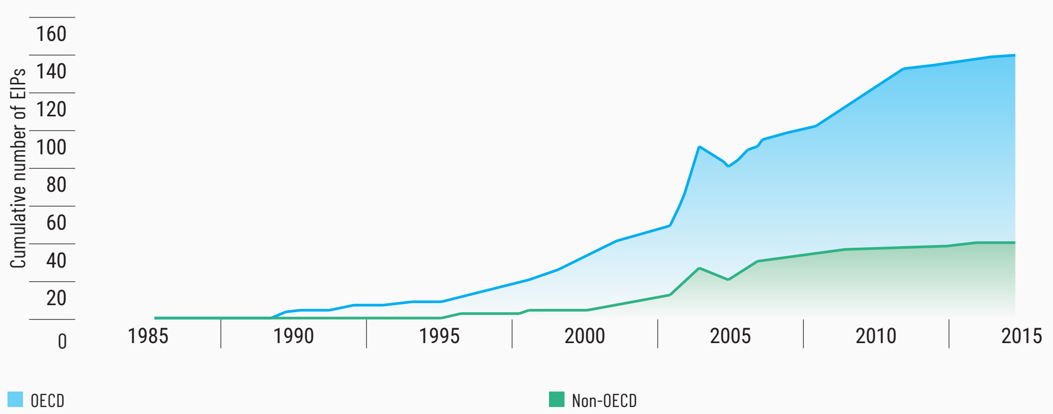
Coordination benefit models are business models based on the coordination of nearby agents, where better economic and environmental benefits can be obtained than if there were no coordination. In the context of coordination between companies located near one another, a coordination benefit model can be referred to as "industrial symbiosis" (Bilsen *et al.* 2013). From a chemicals management perspective, both eco-industrial and chemical parks are of interest. While eco-industrial parks may host a wide range of companies, including chemical companies, chemical parks specifically host chemical companies.

Eco-industrial parks

Chemical companies may be part of eco-industrial parks (EIPs) in which businesses cooperate with each other and with the local community to reduce waste and pollution and efficiently share resources (e.g. information, materials, water, energy, infrastructure and natural resources). They may be planned from scratch or evolved over time. The well-researched Kalundborg Eco-Industrial Park in Denmark is an example of the latter. Companies in the region collaborate in using each other's by-products and otherwise share resources (Chertow and Park 2016). The number of EIPs is increasing (UNIDO, World Bank Group and German Corporation for International Cooperation [GIZ] 2017). Around 250 existed globally in 2018, compared with only 50 in 2000 (World Bank 2018). While the EIP concept mainly originated in Northern Europe, an increasing focus by international development organizations has led to the scaling up of these parks in developing countries (Kechichian and Jeong 2016).

Evidence of the economic benefits of eco-industrial parks is well-documented. Firms in Ulsan Mipo and Onsan, part of the Republic of Korea's Eco-Industrial Park Initiative, have invested US dollars 520 million in energy efficiency, industrial symbiosis, waste management and other environmentally friendly improvements. That investment has yielded US dollars 554 million in savings, while the firms have generated US dollars 91.5 billion in revenues (UNIDO, World Bank Group and GIZ 2017; World Bank 2018). The initiative is part of the country's Eco-Industrial Park Program, led by the Korea Industrial Complex Corporation (KICOX), which has resulted in 56 new patents, savings of 6.48 million tonnes of CO_2 equivalent, and collective financial benefits of

Figure 4.3 **Global growth of eco-industrial parks (EIPs) (adapted from Kechichian and Jeong 2016, p. 15)**



US dollars 1,680 million (World Business Council for Sustainable Development [WBCSD] 2018).

Ownership and funding of eco-industrial parks

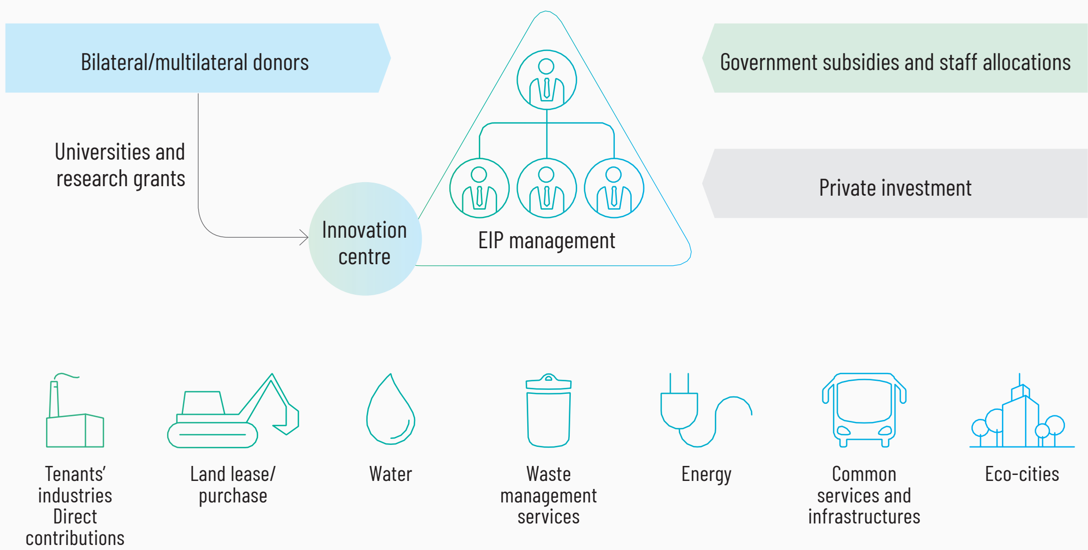
In many cases the land where eco-industrial parks are located is owned by the government, although it may be privately owned. At the development stage the most common financing options are public investment or a public-private partnership. Some parks may also attract foreign investment (Erkman and Van Hezik 2016). A park can request external funding when it is created and during the first years of operation, but it should be economically sustainable in the long run. Private investment, government subsidies and multi/bilateral donor support are among the main external funding sources. Companies are likely to become interested in becoming tenants if they perceive the added value of a park's services (UNIDO 2017). Figure 4.4 shows sources of revenue for eco-industrial parks.

What are chemical parks and what are their benefits?

A chemical park is a business model that brings together raw material suppliers, chemical manufacturers, producers of specialty chemicals, service providers and other companies at one site (American Institute of Chemical Engineers 2011). It can be defined as a "chemical manufacturing complex which possesses controlled entrance and exit points and accommodates several separately owned chemical manufacturing companies" (Dambmann and Allford 2003). These sites, managed professionally, provide a range of services, allowing investors and businesses to concentrate on their core fields. The concept, which originated in the 1990s in Germany, has expanded to other regions and countries, particularly China. The main drivers of chemical parks in China are restructuring and improvement of technological standards in the country's chemical industry, and the promotion of regional economic development through making investment more attractive to foreign and domestic investors. Chemical parks in China are managed at both provincial and national levels (Hauthal and Salonen n.d.).

Chemical parks can have numerous benefits for tenants from both economic and environmental perspectives. A study carried out at the Rizhao Economic and Technology Development Area in China found that economic benefits resulting from sound environmental standards, tax preferences, material substitution and financial subsidies were critical drivers for stakeholder participation in industrial symbiosis (Yu, Han and Cui 2015). Kalundborg Park in Denmark, a pioneering site for chemical an industrial park,

Figure 4.4 Eco-industrial parks' sources of revenue (adapted from UNIDO 2017, p. 49)



Box 4.2 The Shanghai Chemical Industry Park (Zeng and Bathelt 2011)

The Shanghai Chemical Industry Park, in operation since 2004, is the site of chemical production by the petroleum industry. It is about 29.4 km^2 in size and has direct access to the Pacific Ocean. The park is a fully developed industrial area, equipped with infrastructure including streets, internal pipelines, public utilities and environmental protection facilities. All of these have been provided by the Shanghai Chemical Industry Park Development Corporation, which operates and manages the park. In 2006 the park hosted 14 chemical firms with a labour force of 3,250 and total sales of 29.0 billion Yuan (around US dollars 3.6 billion). New investments were expected to lead to a total chemical labour force of 20,000 in the region.

was developed because there was a need for rational consumption of steam by the Statoil refinery. In exchange for steam, the refinery sends its effluent cooling water to a coal-fired power plant as boiler feed (Planète Énergies 2016). Box 4.2 describes the Shanghai Chemical Industry Park.

Challenges and policy opportunities related to chemical industrial parks

A number of challenges exist in establishing chemical parks and mobilizing investors and businesses. Apart from difficulties with the mobilization of initial investments, companies may, for example, not be convinced they will receive a reasonable return when they invest in related upgrades, renovations, more efficient processes, or changes in business practices. They may also be concerned about information sharing with potential competitors (LeBlanc *et al.* 2016). Another challenge for a chemical park operator is to attract new companies. Other barriers relate to technological development and capacity building. However, promoting cooperation among stakeholders though active involvement by policymakers can help overcome these barriers (Zhu *et al.* 2014).

4.4 Customer-centric business models

The development of customer-centric business models is an important dimension of Industry 4.0 (or the Fourth Industrial Revolution) (Renjen 2018). These models involve a better understanding of customer needs and wants, as well as ensuring that the right strategies, processes and marketing initiatives are in place to satisfy them (Kroner 2014). A customer-centric model is built around a deep understanding of customers, what they value, and the contribution each makes to a company's profitability. This includes delivering a positive and seamless customer experience at every touch point across the customer life cycle, maintaining active dialogue with customers, and fostering a culture that puts the customer at the heart of the decision-making process (EY 2013). It may also involve more direct marketing and sales operations to reach consumers faster and more efficiently.

4.4.1 Additive manufacturing/3-D printing

The rise of additive manufacturing/3-D printing

The development of advanced manufacturing technologies, and growing consumer demand for more customized products and services, are bringing about significant changes in the scale and distribution of manufacturing (Ford and Despeisse 2016). 3-D printing, also known as additive manufacturing, is a consumer-centric business model with the potential to revolutionize production processes. It has important implications for the chemical industry. 3-D printing replaces traditional manufacturing, in which products are manufactured at a company's main production facility and shipped elsewhere. An additively manufactured product is printed layer by layer, with each cross section stacked on top of the one below it. This is done without using large, high-throughput machinery, and at

hundreds or thousands of remote locations, with near-zero waste (Phansey 2014).

By "democratizing" manufacturing, 3-D printing allows small fabrication businesses to reduce labour costs and offer manufacturing services close to the point of need. Service-oriented businesses are evolving which offer libraries and exchanges for 3-D printable digital blueprints; services to transmit these blueprints; and services for networking of 3-D printers (Duffy 2016). 3-D printing avoids the need to invest in producing moulds, which requires large product orders to achieve scale. This is of special significance for small and medium-sized manufacturing firms (Wayne 2017).

In light of these opportunities, the global additive manufacturing market is expected to grow to more than US dollars 6 billion by 2022, with a compound annual growth rate of more than 13 per cent between 2016 and 2022 (Market Research Engine 2017). Apart from providing more customer-centric solutions, 3-D printing provides significant economic and environmental benefits. It is estimated that it will reduce costs by US dollars 170-593 billion, primary energy supply by 2.54-9.30 exajoules, and CO_2 emissions by 130.5-525.5 megatonnes by 2025 (Gebler, Schoot Uiterkamp and Visser 2014).

3-D printing technology has significant potential for developing countries, as the cost of printers is falling below US dollars 500 (Ibrahim *et al.* 2015). 3-D printing has the potential to contribute to economic empowerment and improve the livelihood of communities in developing countries by providing opportunities to design and create tools that support and improve people's daily lives (Ishengoma and Mtaho 2014). A growing number of non-profits are promoting and supporting the use of 3-D printing technology in developing countries (Molitch-Hou 2014).

What does 3-D printing mean for chemicals and waste management?

Chemical companies are already developing a range of plastics and resins, as well as metal powders and ceramic materials, for printing prototypes of products, industry parts and semi-finished goods. 3-D printing, as a consumer-centric business model, provides significant opportunities for the chemical industry through, for example, developing innovative feedstocks, printing lab equipment, and maintaining plant assets (Guertzgen 2017). It also provides opportunities to use waste materials such as plastics as raw material for 3-D printing (Walker 2017). Moreover, 3-D printing can enhance design flexibility for chemical equipment, for example with unique designs for modular distillation columns (Mardani *et al.* 2016) and packing for rotating packed beds (Gładyszewski and Skiborowski 2018).

3-D printing can improve efficiency and reduce the time required to manufacture individual batches. For example, a maker of invisible braces has used 3-D printing to increase batch size and reduce the time required to run each batch. The company also requires less space compared with its traditional manufacturing method (Pullen 2014). In addition, plastic waste can be turned into 3-D printing filament, so that 3-D printing becomes a viable means of consuming waste plastics (Kreiger *et al.* 2014; Mohammed *et al.* 2017).

Researchers have designed a 3-D printer to synthesize pharmaceuticals and other chemicals from simple, widely available starting compounds fed into a series of water bottle-sized reactors. This technology could one day enable consumers to 3-D print their own drugs (Service 2018). The technology also enables the manufacture of medications that rapidly disintegrate with a sip of liquid even at high doses, which could help people who have difficulty swallowing pills (Crawford 2015).

Potential health and environment concerns

Despite its significant potential, 3-D printing may also pose risks. Concerns have been expressed, for example, about material use, exposure and emissions (European Agency for Safety and Health at Work 2017). While in general additive manufacturing is considered environmentally preferable to conventional manufacturing, because of its potential for local production and nearly zero-waste manufacturing, research indicates that environmental performance depends on patterns of use, the configuration of the 3-D printer and the materials used (Yale School of Forestry & Environmental Studies 2017). 3-D printing can therefore have varying environmental impacts; for example, the use of polylactic acid (PLA) bioplastic consumes less energy than the use of acrylonitrile butadiene styrene (ABS) plastic (Faludi *et al.* 2015).

Many kinds of 3-D printing machines exist, but not all of them can be operated waste-free. An inkjet 3-D printer wastes, for example, 40-45 per cent of its ink (the portion that is not recyclable) (Faludi 2013). Also of concern is that 3-D printers often use non-environmentally friendly ABS plastics, nylons and other non-recyclable materials and post-processing chemicals that can create toxic fumes. Moreover, it has been shown that these printers can emit ultrafine particles or volatile organic compounds (VOCs). Caution should therefore be used when operating printers and filament combinations in poorly ventilated spaces, or without the aid of combined gas and particle filtration systems (Azimi *et al.* 2016). In addition, strategies for safe disposal of 3-D printed parts and printer waste materials are needed (Oskui *et al.* 2016). There are also concerns that 3-D printing could lead to renewed materialism, with consumers driven to print more, encouraging a culture of consumption and disposal (March 2015).

4.4.2 e-commerce: selling chemicals online

Business-to-business e-commerce websites

Chemical distribution is evolving rapidly, with a growing number of companies and distributers selling chemicals online. In addition, e-commerce is a new way for small and medium-sized chemical distributors to reach existing and potential customers (Independent Chemical Information Service [ICIS] News 2016). Amazon Business, for example, is a business-to-business (B2B) platform that allows registered businesses to shop for office, janitorial and industrial goods online and obtain volume discounts. One chemical company engaged in e-commerce is BASF, which in mid-2015 opened its first e-commerce store in China using the Alibaba B2B marketplace platform. Its goal was to make the company's products and services more accessible to small and medium-sized enterprises (SMEs) (Ling and Pflug 2015). BASF later announced it would establish a flagship online store, along with other major chemical companies such as Covestro, on Alibaba's B2B platform, 1688.com (ICIS Chemical Business 2018). Specialty chemical companies have launched their online stores on the same platform to provide an easily accessible procurement process (Evonik 2017; Solvay 2018).

E-commerce platforms selling to consumers

Online shopping platforms selling to consumers, such as Alibaba, Ebay and Amazon, are growing rapidly. Consequently, an increasing number of hazardous chemicals may find their way onto markets. Some of the major e-commerce

platforms have hazardous chemical policies. Alibaba has a "Flammable, Explosive and Hazardous Chemicals" policy which prohibits the posting of explosives, radioactive or poisonous chemicals, ozone-depleting substances and other harmful substances. Purchasing such materials could lead to delisting of the poster's account (Alibaba 2018). Under Amazon's "Hazardous and Dangerous Items" policy, users are prohibited from listing items for sale that contain bisphenol A, carbon tetrachloride and red phosphorus, explosive substances, products contaminated with radiation, mercury products and refrigerants, among others (Amazon 2018). Ebay has a "Hazardous, restricted or regulated materials policy" which lists items that cannot be advertised on its website, the violation of which could lead to removal of the listing and suspension of accounts (Ebay 2018).

Challenges

Despite these policies, little is known about the extent to which e-commerce platforms have chemical policies and, if so, whether these policies are compatible with regulatory requirements. There are also questions about which jurisdictions guide (or should guide) the chemical policies of e-commerce platforms, and how the selling companies can effectively monitor compliance or violations. To illustrate the challenges, under the European Chemicals Agency's (ECHA) enforcement scheme 1,314 internet advertisements were checked for hazardous chemical mixtures, of which 82 per cent were found to be non-compliant with the EU's Classification, Labelling and Packaging (CLP) regulation (Stringer 2018). If a company sells chemicals online in several regions, it is important for the company to know and follow all the rules and regulations for each region, as chemical products and the selling of them are subject to different rules in different countries (Clarity 2015).

4.5 Social entrepreneurship business models

Social enterprise: a model for change

The purpose of a social enterprise combines revenue growth and profit-making with respect and support for its environment and stakeholder network (Agarwal *et al.* 2018). Social enterprises lie at a point of convergence between the non-profit and for-profit spheres, combining the social orientation and objectives of NGOs with the market-driven practices of businesses. A social enterprise does not do social good to improve its image or regard this as a means to increase sales. Rather, it pursues social objectives and uses business approaches to attain these objectives (Panum and Hansen 2014). A social enterprise business model is essentially driven by a social mission, generates positive externalities for society, and recognizes the centrality of the entrepreneurial business function (Bocken *et al.* 2014).

Social enterprises create economic value as a tool to achieve social goals (Perrini and Vurro 2006). Profit is seen as a tool for advancing sustainability. In this way, enterprises move away from grant dependency to become self-sufficient through the creation of income streams (Panum and Hansen 2014). Social Enterprise UK, in its State of Social Enterprise Survey 2015 (Villeneuve-Smith and Temple 2015), found that the social enterprise movement was growing rapidly, with a greater proportion (40 per cent) of social enterprises increasing their turnover as compared to mainstream SMEs. This growth is driven by the increasing power of the individual (especially millennials), a shift to greater trust of businesses, and technological change and advancement (Agarwal *et al.* 2018).

Social enterprises address a range of social issues. These include social and environmental issues with direct or indirect links to chemicals and waste management. A social enterprise addressing the problem of plastic waste in Kenya through recycling is described in Box 4.3.

How do we know whether an enterprise contributes social and environmental value?

Box 4.3 **Ocean Sole: a social enterprise in Kenya (Panum and Hansen 2014)**

Ocean Sole is a social enterprise operating in Kenya. The founder, Julie Church, was appalled by the vast amount of plastic flip-flops washed up on shore in northern coastal Kenya, disturbing marine life. This gave her the idea of collecting the flip-flops and recycling them into crafts, facilitating the employment of local unemployed women as a workforce. Ocean Sole started with the proposition of creating environmental and social value through the collection and recycling of flip-flops and through environmental awareness-raising in local communities, as well as among the eventual consumers. Embedded in this value proposition is education of the public, together with nudging its behaviour towards using recycled products.


© Ocean Sole Africa, one of Ocean Sole's products

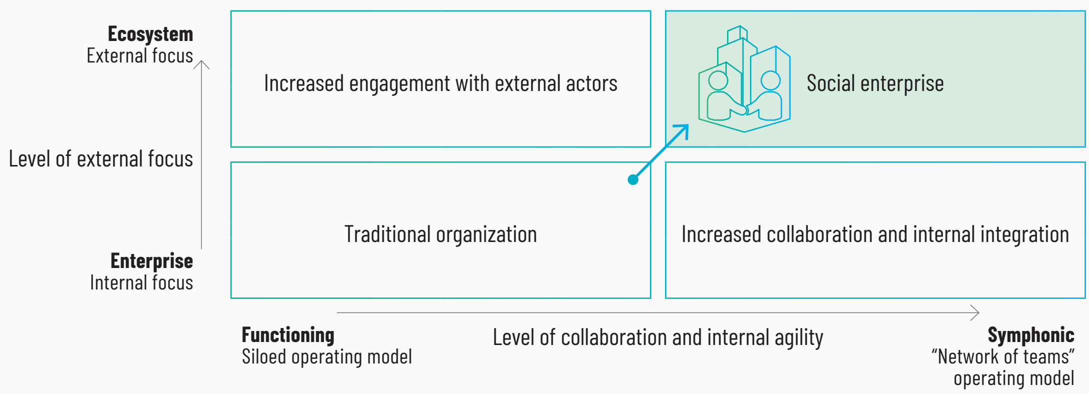
ocean sole africa

The business model of Ocean Sole is effectuated through three main phases: collection of the flip-flops, recycling, and sale. The process is as follows:

The crafts are sold in shops in and around Nairobi, in retailer outlets in Kenya, and internationally.

The Social Enterprise Mark is an example of an international social enterprise accreditation scheme that enables social enterprises to demonstrate they are making a difference. It independently guarantees that a business's central aim is to use its income and profits to maximize positive social and/or environmental impacts, and that this takes precedence over maximizing personal profits for owners and shareholders (Social Enterprise Mark CIC 2018). Figure 4.5 shows the evolution of the social enterprise.

Figure 4.5 **Evolution of a social enterprise (adapted from Agarwal *et al.* 2018, p. 3)**



Social enterprises may fill gaps in governance

Social enterprises have the potential to support and build on government initiatives (Ding 2017). They may also fill gaps when governmental action is lacking. They can have significant impacts in countries with low levels of state capacity to address social problems. From a government perspective, collaborating with social enterprises can result in short- and long-term gains for public budgets through reduced public expenditure and increased tax revenue (OECD and EC 2013). If such benefits are identified, enabling government institutions, resources and policies may be used to scale up social enterprises, including through partnerships with local governments (Shockley and Frank 2011).

Social enterprises' contributions to chemicals and waste management

Social enterprises that address chemicals and waste management issues, directly or indirectly, are emerging in many countries. For example:

- A Melbourne, Australia, social enterprise called *Green Collect* gathers hard-to-recycle waste and employs socially disadvantaged people to refashion it into useful items to sell back to the companies that threw it out (Smith 2016).

- *Wecyclers*, a waste management social enterprise in Lagos, Nigeria, encourages households to collect and turn in waste. They receive "Wecyclers points" that can be used to buy household goods and services. Wecyclers sorts and aggregates the collected materials and sells them to local recycling processors (Okeugo 2015).

- *TackleTox* is a social enterprise that displays, on a map, information about toxic chemical substances emitted by corporations. It currently provides toxic scores for over 28,000 facilities in both the Republic of Korea and the United States (Yoon 2018).

- *Fairphone* is a social enterprise that aims to make smartphones in a modular way, so they can be easily repaired and upgraded over a longer period of use. It also avoids using minerals mined in conditions of armed conflict and human rights abuses (Keizer *et al.* 2016). Fairphone works with its partners to set up projects in Ghana to improve local waste collection efforts and transport discarded phones to Europe for safe recycling. Fairphone's Take Back Program helps ensure that old mobile phones are reused or properly recycled (Fairphone 2016).

- Code Enterprise LLP is India's first cigarette waste management and recycling firm. It operates in 20 states and has already recycled 4 tonnes of cigarette butts into useful products. A chemical process is used to recycle discarded cigarette butts into clean cellulose acetate, the polymer used in the butts. By-products can also be used for plantations and nurseries. The recycled polymer material is used to make cushions, garlands, small stuffed toys, accessories and key chains (Roy 2018).

Challenges and opportunities

When they start a social enterprise, most entrepreneurs face challenges in securing funding and investment capital. Locating the right manufacturer or supplier is another challenge for product-based social enterprises (Muhammed 2018). Still another challenge is mission drift, as a result of which enterprises abandon their social concerns in favour of profit-seeking activities. This can cause internal conflict and lack of support from stakeholders. It is therefore important for companies to avoid or rebalance mission drift (Ramus and Vaccaro 2017).

Governments in a number of countries use policy tools such as fiscal incentives, grants, awareness campaigns and incubation to encourage social enterprises (Sanchez 2016). For example, in the United Kingdom social investment tax relief (SITR) has been introduced. SITR encourages individuals to support social enterprises and receive a tax deduction equal to 30 per cent of their investment (Government of the United Kingdom 2016). In India, the Maharashtra State Social Venture Fund aims to invest in profitable and scalable business ventures with the potential to provide social benefits to the people of Maharashtra (SIDBI Venture Capital n.d.).

4.6 Potential measures to advance the sustainability of business models

New and evolving business models, such as service-oriented models (Chemical Leasing) and models for benefit coordination (e.g. chemical parks), as well as social enterprises, can create opportunities to advance the chemicals and waste management agenda. Other models (e.g. 3-D printing and e-commerce) are also evolving rapidly and will benefit from careful scrutiny. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to advance the sustainability of business models:

- Promote service-oriented chemicals management approaches, such as Chemical Leasing, to enhance resource efficiency and decrease use of hazardous chemicals.
- Use chemical parks as a model for sharing services, learning and information among companies, including SMEs.
- Explore the role and stimulate the establishment of social enterprises to support the sound management of chemicals and waste at all levels
- Review the chemistry dimension of 3-D printing/additive manufacturing and take measures to reap its full potential by managing potential risk early on.
- Take measures to ensure that the distribution of chemicals through e-commerce meets high standards of chemical hazard communication, and is fully compliant with relevant legislation.

5/ Fiscal incentives to advance sound chemicals management and sustainable chemistry

Chapter Highlights

The use of market-based instruments to manage hazardous chemicals and waste is limited, but increasing.

Market-based instruments can effectively complement command and control regulatory measures, such as bans or restrictions.

Market-based instruments create incentives for cost-effective substitution and can spur innovation.

Reforming subsidy programmes that provide perverse incentives is often a challenge.

Careful design, evaluation and flexibility are needed to adjust instruments to market reactions.

Political economy considerations are important when implementing market-based instruments

Fiscal incentives are government policies that change the relative price of a given activity or input, either encouraging or discouraging its use. This chapter takes stock of the extent of, and lessons learned from, the use of fiscal incentives for chemicals management. It discusses the effectiveness, benefits and challenges of market-based instruments, within the broader array of possible policy instruments in the context of chemicals and waste management.

5.1 Market-based instruments as an important complement to bans and use restrictions

Many market-based instruments can be used to create fiscal incentives for sound chemicals management

A wide range of market-based instruments are used in chemicals management (Table 5.1). They stimulate behavioural change by providing price signals to chemical producers and manufacturers, downstream users, consumers and waste management agents, among others. Incentives can be created by removing existing price distortions that generate perverse incentives for overuse, or by implementing new market-based instruments such as taxes, charges, deposit-refund systems, subsidies and tradable permits. The level of taxes and charges should ideally

Table 5.1 Types of market-based instruments and examples of their application to chemicals management (based on Stavins 2001; Sterner and Coria 2011; OECD n.d.)

Policy instrument	Description	Example of application
Tax	By increasing the price of using a chemical, a tax incentivizes decreased use. Typically levied by the state, with its proceeds going to the general budget. The level should reflect the damages caused by production, use and/or disposal of the chemical, which in the absence of the tax would not be reflected in the market price.	Pesticides; inorganic fertilizers; chlorinated solvents; batteries
Charge/fee	Similar to a tax, but revenues are typically earmarked. The level of a fee should reflect the cost of providing a specific service, such as processing hazardous waste.	Hazardous waste; pesticide or chemical containers; tyres; batteries
Subsidy	A subsidy is the mirror image of a tax. It can provide incentives to increase the use of alternative chemicals that are less hazardous. In particular, authorities may want to subsidize learning and technology development.	Subsidies for organic farming; lead paint removal
Subsidy removal	In many cases subsidies are used without giving sufficient attention to their distribution, potentially resulting in unsound practices from a health or environmental perspective. Hence, subsidy removal is considered a policy instrument in its own right.	Removal of subsidies for use of chemical fertilizers or pesticides
Deposit-refund	A surcharge is paid when potentially polluting products are purchased. A refund is received when the product is returned to an approved centre, whether for recycling or for disposal.	Pesticide or chemical containers; batteries; tyres
Tradable permits	An overall level of "allowable" pollution is established and allocated among firms in the form of permits. These permits can be traded on a market at market prices.	Lead in gasoline (trade among refineries); ozone-depleting substances (trade among producers and importers)

be set so that all externalities (i.e. the full cost to society from production, consumption and disposal of targeted chemicals of concern, or products that include such chemicals) is reflected in their price (Sterner and Coria 2011).

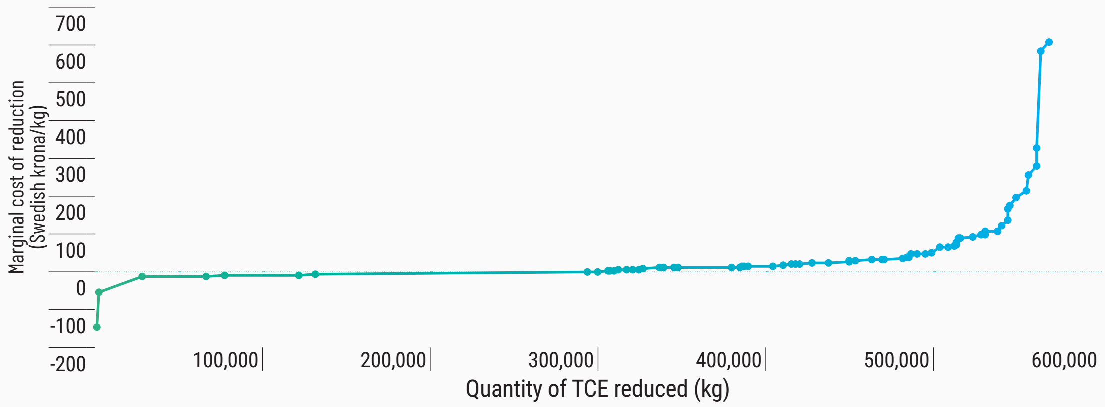
Market-based instruments can create incentives for cost-effective substitution and spur innovation

The two main arguments in favour of fiscal incentives are that they can be more cost-effective, and better at promoting innovation, than bans, use restrictions or technology standards. These command and control policies (commonly used

Box 5.1 Shifting taxes from labour to resource use and pollution (Groothuis 2016)

Achieving sustainability is affected by a number of factors They include efficient use of resources, closing material loops, reducing (toxic) waste, reclaiming waste as raw material, and designing materials and chemicals that fit these purposes. An independent Dutch think tank researched a possible shift of taxation of labour to pollution, use of resources and consumption. In the Ex'tax Policy Toolkit they presented a suite of tax base options through which such a shift can be designed, covering topics such as building materials, food production, metals and minerals, and waste. Key findings of the research were that a shift in taxation would result in increased GDP, create jobs, and cut emissions and pollution. This shift incentivizes sustainable business models and innovation, including in the chemical sector, given an increase of the cost of water, harmful emissions, metals and minerals through systematic application of the polluter pays principle. Moreover, reductions in labour costs, combined with increased resource and pollution costs, are expected to support labour-intensive R&D efforts, repair, maintenance and collection of waste, thus stimulating ecological product design.

Figure 5.1 Marginal cost of reducing the use of trichloroethylene (TCE) in metal degreasing (adapted from Slunge and Sterner 2001, p. 292)



The marginal cost of reducing the use of TCE (or replacing its use altogether) in metal degreasing were reported by 65 companies in Sweden. For most companies the marginal costs were relatively low, but some reported that it would be very costly to reduce TCE use.

in chemical risk management) typically allow very little flexibility in regard to the means of achieving specific targets (Stavins 2001). Instead, all firms must meet the same target no matter how costly the change. However, the cost of complying with a ban or use restriction often differs between companies. This may be due to differences in, for example, production processes and sunk costs from technology investments. Figure 5.1 provides an example of differences in the marginal costs of reducing the use of trichloroethylene (TCE) in metal degreasing.

Companies have an incentive to substitute the targeted chemical as long as the marginal cost of substitution is lower than the cost of using the targeted chemical. By allowing firms with different substitution costs to reduce use on different time scales, market-based instruments can incentivize a cost-effective reduction in the use of the targeted chemical. Moreover, by increasing the cost of using a specific chemical, taxes and charges can spur innovation and the search for new alternatives. Innovation can be further incentivized if tax proceeds are invested back into the search for cleaner, less harmful substances.

Market-based instruments complement rather than replace bans and use restrictions

While market-based instruments have some merits, there are many situations in which their use is less appropriate. For example, when the health and environmental costs of exposure to a hazardous chemical are very high, the effects are location-specific or threshold effects are likely. In such situations bans and use restrictions are more appropriate (Weitzman 1974). In practice, many context-specific factors (e.g. information constraints, administrative costs, distributional effects and political economy pressures) determine which policy instruments are most effective and feasible to implement. Policy instrument design therefore needs to be context-specific.

In many cases it can be beneficial to combine market-based instruments with restrictions on exposure to hazardous chemicals. Introducing a tax or charge which creates incentives for substitution and innovation can make it easier to implement tougher use restrictions or even bans at a later stage. Transparency, and access to information on the use of chemicals and its associated effects, are often prerequisites for effective design and implementation of market-based instruments.

Box 5.2 Risk-based pesticide taxation in Norway and Denmark

In Norway a new taxation scheme for pesticides (plant protection products) was introduced in 1999. Pesticides were classified in different risk groups, with higher taxation for higher risk categories. Figure 5.2 indicates that a shift towards using pesticides that were relatively less hazardous resulted. A difficulty with classifying pesticides into distinct risk categories is that those with similar levels of environmental and health risks may show big differences in their tax rates if they are at the bottom or top of their respective risk categories. An alternative pesticide taxation scheme was introduced in Denmark in 2013. Under this scheme, the tax level for each approved pesticide was calculated based on its human health risks and environmental characteristics. Instead of distinct risk categories, the tax level was based on an environmental load index ranging from 0 to 40. There was considerable difference in the tax levels, which ranged from euros 0.57 to euros 25.5 per hectare. The new pesticide taxation scheme was projected to play a major role in achieving the government's objective of reducing the total quantity of pesticides applied by 40 per cent between 2013 and 2015 (Böcker and Finger 2016). Preliminary evaluations indicate that this objective was met (Ørum, Kudsk and Jensen 2017). Pesticide taxation in Norway and Denmark is combined with tax exonerations for farmers who fulfil specific requirements regarding pesticide management and observe other use restrictions.

5.2 Experience with using market-based instruments in key industry sectors

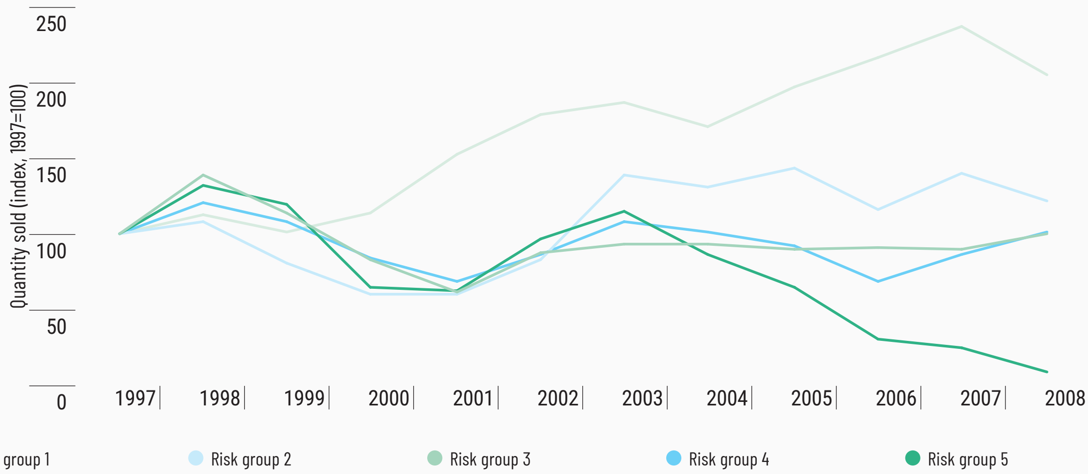
Use of fiscal incentives to manage hazardous chemicals: limited but increasing

Compared with other policy areas, the use of market-based instruments in chemicals management is relatively limited. Market-based instruments are mainly used in high-income countries, but a number of low- and middle-income countries have also begun to use them, particularly in relation to hazardous waste management and reducing the use of plastic bags. In many cases where market-based instruments have been used for chemicals management, formal evaluations of their effectiveness are lacking. The cases presented below illustrate some applications, as well as problems that policymakers face in designing policy instruments.

Taxing pesticides to reduce environmental and health risks

Several countries, including Denmark, France, Norway and Mexico, have begun to use differentiated taxation of pesticides (mainly plant protection products) to incentivize farmers to reduce the use of hazardous pesticides (Box 5.2 and Figure 5.2). Factors taken into account in determining the taxes include, for example, hazard properties, health risks, environmental

Figure 5.2 Effects of differentiated taxation on quantities of pesticides sold in Norway, 1997-2008 (adapted from Kjäll 2012)



Under the taxation scheme for pesticides (plant protection products) introduced in Norway in 1999, pesticides were divided into five risk groups with higher taxation for higher-risk groups. A shift towards using more of the relatively less hazardous pesticides took place.

load or environmental harm, depending on the country. Recent evaluations have found evidence that taxation which is linked to hazards and risks can be effective in reducing pesticides' environmental and health effects. In contrast, non-differentiated taxation of pesticides (e.g. through ad valorem or per unit taxes) can have unintended consequences, as quantity reductions may be achieved through substitution with more toxic products (Finger *et al.* 2017). Closer proportionality of taxes to reduce environment and health risks may also increase the chance that a tax is perceived as fair. Such taxation may not only enhance the economic desirability of taxes, but also increase their political legitimacy (Söderholm and Christiernsson 2008).

Reforming subsidy programmes which create perverse incentives is often difficult in practice

Many countries provide substantial subsidization of agrochemicals in order to promote agricultural production and increase food security. However, these subsidies can have severe negative environmental effects and they imply a high fiscal burden. The nature of the environmental effects

Box 5.3 The fertilizer subsidy programme in India

To incentivize agricultural production, the central government in India subsidizes the use of chemical fertilizers. This has played an important role in increasing grain production. However, the cost to the government of keeping fertilizer prices below the market price has increased dramatically since the subsidy programme was introduced in the late 1970s. In 2015 the cost of fertilizer subsidization was estimated at approximately US dollars 12 billion.

There is limited evidence concerning this programme's environmental effects. It can be shown that the programme has led to imbalanced use of nutrients by farmers through keeping the price of urea (an inexpensive form of nitrogen fertilizer) at a very low level. Excessive and imbalanced use of nutrients has contributed to soil degradation and water pollution (Gulati and Banerjee 2015). A key challenge in reforming the programme is that many farmers are financially dependent on these subsidies (Praveen *et al.* 2017).

Box 5.4 **Chemical taxes on consumer products in Denmark and Sweden**

Responding to growing concerns about risks from cumulative exposure to hazardous chemicals in consumer goods, in 2000 Denmark introduced a tax on products containing PVC and phthalates. The rate was approximately euros 0.3 per kilogram of PVC and euros 0.9 per kilogram of phthalate, with some variation depending on the product. As part of broader tax reform, the Danish government decided to abolish this tax in 2019. The effects of the tax are uncertain (Stringer 2017). An early assessment pointed to a 15 per cent decrease in the use of phthalates between 2002 and 2004 (Government of Denmark 2006). The rate has not changed or been adjusted for inflation since the tax came into effect. European regulations on phthalates have since been introduced.

Sweden introduced a tax on certain chemicals in electrical and electronic products in 2017. Producers and importers of these products pay an excise duty of around euros 0.8 per kilogram for kitchen appliances and euros 0.12 per kilogram for other electronic products. There is a maximum amount of euros 32. per item. If producers and importers can prove that electronic products do not contain additive compounds of bromine, chlorine or phosphorus, they can obtain a 50 per cent tax deduction. If they can also show that the products do not contain reactive added bromine or chlorine compounds, a deduction of 75 per cent is allowed. Since the tax recently came into force, it has not yet been evaluated. However, it has been criticized by industry for not being based on comprehensive risk assessment and for being administratively burdensome.

depends on how the subsidy programme is designed and on site-specific agroenvironmental conditions. This makes it difficult to carry out a general environmental assessment of the benefits of agricultural subsidization.

Reducing or removing subsidies is often difficult, as they tend to encourage lobbying by beneficiaries in order to protect and prolong the subsidies. Box 5.3 describes the fertilizer subsidy programme in India.

Market-based instruments can be used at different stages in the chemical life cycle

Market-based instruments are applied at different stages of the chemical life cycle. For example, in the United States chemical producers and manufacturers took part in schemes with tradable permits to incentivize refineries to phase out lead in gasoline in 1982-1987, and in the phase-out of ozone-depleting substances in the early 1990s (Harrington, Morgenstern

Box 5.5 **Different effects of charges on plastic bags in Ireland and South Africa**

Charges have been used in several countries to reduce demand for plastic bags. The primary purpose has been to reduce plastic littering. The effects of these charges are mixed. A charge of euros 0.15 per bag, introduced in Ireland in 2002, led to a 90 per cent reduction in use and reduced littering (Convery, McDonnell and Ferreira 2007). Similarly, in South Africa the charge of around euros 0.05 (rand 0.46) introduced in 2003 led to an estimated 90 per cent reduction in demand for plastic carrier bags. However, after pressure from manufacturers the charge was lowered after only three months and demand for the bags increased again (Dikgang, Leiman and Visser 2010). In Ireland, besides the effect of the charge on demand, extensive stakeholder consultations and information campaigns conducted in relation to the plastic bag charge contributed to the effectiveness of the policy instrument. In South Africa the revised charge was too low to affect demand. Since 2015, large retailers in England have been required by law to charge 5 pence (around euros 0.06) for single-use plastic carrier bags. The seven main retailers issued around 83 per cent fewer bags (over 6 billion bags fewer) in 2016-2017 compared to the calendar year 2014. This is equivalent to each person in England using around 25 bags in 2016-2017, compared to around 140 bags per year before the charge (United Kingdom Department for Environment, Food & Rural Affairs 2018).

and Sterner 2004). The Norwegian tax on trichloroethylene and perchloroethylene from 2000 is an example of chemicals used in the metal manufacturing industry and dry-cleaning facilities being targeted (Slunge and Sterner 2001). Taxes on phthalates, polyvinyl chloride (PVC) and flame retardants introduced in Denmark and Sweden are examples of taxes targeting consumer products where it is the importer or product seller who pays the tax (Box 5.4) Taxes and/or fees on plastic bags used in Ireland, South Africa, the United Kingdom, the United States and a number of other countries are examples of those paid by consumers (Box 5.5). In Canada, Loblaw Companies Limited has estimated that its voluntary 5 cent fee on plastic bags prevented the use of 11 billion bags in Canada subsequent to its launch in 2007. Proceeds are donated to an environmental organization (Loblaw Companies Limited 2017, p. 11).

Charges and refunds used to finance hazardous waste management

Charges and deposit refund systems are frequently applied in the management of hazardous wastes such as batteries, end-of-life vehicles, and waste electric and electronic equipment. These instruments can both incentivize reduced use of, for example, batteries containing hazardous chemicals, and finance systems for the collection and processing of hazardous waste. Box 5.6 describes how a charge on waste electric and electronic equipment (WEEE) is used to finance hazardous waste management in China.

In many countries the establishment of extended producer responsibility (EPR) systems has shifted the cost of waste management from authorities to producers and greatly increased the rate of recycling of different waste categories. A provincial EPR programme for tyres across Canada, for example, increased the rate of collection to ~90 per cent, and largely eliminated the stockpiling and burning of end-of-life tyres countrywide (Canadian Association of Tire Recycling Agencies 2018). However, little effect has been seen on product design. Costs to producers are often not directly connected with their own products, while insufficient collection further lowers the incentive for eco-design (Kalimo *et al.* 2015; Turner and Nugent 2016; Zeng *et al.* 2017).

Box 5.6 **The waste electric and electronic equipment (WEEE) recycling fund in China**

Several areas in China have been severely polluted due to crude methods of WEEE recycling in an uncontrolled informal sector. To help create a regulated formal sector for safe WEEE recycling, the WEEE Processing Fund Collection and Subsidy Management Approach was introduced in 2012. Producers and importers pay a charge based on annual sales and product type. Revenues are placed in a government fund which is used to support formal dismantling companies (Gu *et al*. 2017). The fund system effectively reduced the informal sector for the original five product groups and established a formal sector consisting of more than 100 licensed enterprises (Zeng *et al.* 2017). However, the fund is financially imbalanced, as subsidies to the formal enterprises are five to 10 times higher than the fee charged to producers and importers of electric and electronic products (Gu *et al*. 2017; Zeng *et al*. 2017).

5. 3 Context-specific design of market-based instruments is critical for their effectiveness

Careful design, evaluation and flexibility are important in order to adjust to market reactions

Optimally, a "green tax" should be set such that the marginal damage is equal to the marginal benefit of using the chemical. From the point of view of economic efficiency, it is desirable to target policy instruments to specific environmental or health damage as closely as possible. The risk of restricting the use of chemicals that do not cause negative health and environmental effects is thereby reduced. The design of a particular policy instrument also needs to carefully consider technical and political complications associated with the distribution of the regulatory costs and benefits that result from targeting actors at different stages of the chemical life cycle (Söderholm 2009; Coria 2018).

Good knowledge of context-specific factors such as price elasticities, market structure, availability of substitutes, and exposure characteristics for regulated hazardous chemical facilitates the choice and design of policy instruments. However, in many cases there is a lack of data, and assessments based on existing data are often surrounded by considerable uncertainties. There is a need for careful data collection, monitoring and evaluation of the performance of different policy instruments for chemicals management. Flexibility to adjust tax levels after observing market reactions is also necessary.

Balancing the benefits of a targeted approach against its transaction costs is a key dilemma in policy instrument design (Vatn 1998). It may be difficult or impossible to acquire the needed information on the production of the chemical itself, so that those planning such an approach would typically move up the life cycle, for example taxing use of the chemical as an input to the production of other goods and services. However, in some cases information on the production of other goods and services is hidden or private and the regulator is forced to use taxes and similar instruments based on final disposal of the chemical. This is the case for non-point pollution, where the regulator can only observe final pollution levels in the aggregate.

Political economy considerations are important when implementing market-based instruments

The introduction of market-based instruments for chemicals management often faces resistance from interest groups which will pay higher taxes or will no longer benefit from a subsidy. Consultation and monitoring of stakeholders' reactions to a newly created incentive are important in order to help avoid undesired side effects and ensure that incentives operate at the right level. How information on policy change is communicated (and how revenues are used) are often critical to successful implementation.

5.4 Potential measures to scale up the use of fiscal incentives

The use of market-based instruments has the potential to effectively complement regulatory approaches to advance the sound management of chemicals and waste. Further international research and knowledge sharing could help to reap the full potential of these instruments. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to scale up the use of fiscal incentives to advance sound chemicals management and sustainable chemistry:

- Expand the use of differential taxation of hazardous chemicals, based on lessons learned from recent hazard- and risk-based taxation.

- Evaluate and address the effects of subsidies and other policies that can generate perverse incentives which increase use of hazardous chemicals in agriculture and other sectors.

- Use charges to speed up the phasing out of substances of very high concern.

- Evaluate the use of market-based instruments for groups of chemicals, based on the precautionary principle applied to the identified hazards of the active ingredients in similar chemicals (e.g. taxes on flame retardants and phthalates).

- Use legal requirements for Extended Producer Responsibility, environmental liability and access to information in order to incentivize sound chemicals management, in line with the polluter pays principle.

- Establish a policy learning process through systematic monitoring and evaluation of the effectiveness of policy instruments for chemicals management in different sectors and contexts.

6/ Sustainable supply chain management for chemicals and waste in the life cycle

Chapter Highlights

A number of retailers, product manufacturers and companies in the chemical industry have taken measures to include sustainability in their procurement processes.

Identifying and sharing information on chemicals in products, and their human and health impacts in the life cycle, are important but challenging.

Industry action to advance the flow of information in the supply chain on chemicals, and products that contain chemicals, is gaining momentum, although gaps remain.

The recycling sector, which has a key role to play in advancing non-toxic material flows and circularity, needs to have appropriate knowledge about the chemicals in its supply chain.

Sustainable supply chain management is essential in ensuring that procurement decisions comply with sustainability criteria and create a force driving upstream suppliers.

While the generation of relevant data and knowledge is valuable, green and sustainable chemistry principles can already be applied in the design of new products.

The complexity of global value and supply chains and the increasing trade in chemicals and products (discussed in Part I) create both the need and opportunities for key actors in the supply chain to understand and take action with respect to chemicals and products throughout the product life cycle. This chapter focuses on sustainable supply chain management. It provides both a conceptual discussion and examples from key actors in the value chain, in order to enhance the flow of information and sustainability considerations within the supply chain.

6.1 Drivers for sustainable supply chain management

From supply chain risk management to sustainable supply chain management

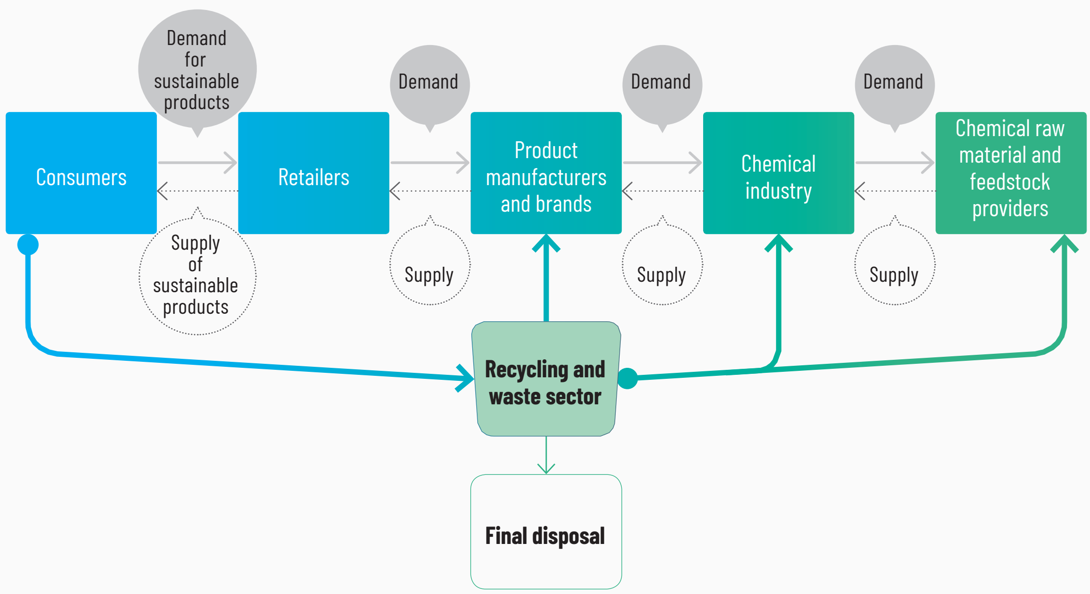
Companies have traditionally focused on managing technological and economic risks that occur along their supply chains though supply chain risk management (SCRM) strategies. Supply chain risk may be defined as "the likelihood and impact of unexpected macro and/or micro level events or conditions that adversely influence any part of a supply chain leading to operational, tactical, or strategic level failures or irregularities" (Ho *et al.* 2015). However, the image of a company – large- or small-scale - is not only related to its economic performance, but also to its environmental and social behaviour and impacts. These may include impacts caused by its suppliers and sub-suppliers in the supply chain (Leppelt *et al*. 2013). Certain companies in the pharmaceutical sector, for example, have been held responsible for the environmental conduct of some of their suppliers (Fick *et al*. 2009).

It makes business sense for companies to know as much as possible about the chemicals in their products and supply chains. There are costs companies may eventually have to pay for not knowing about, or not acting on, harmful chemicals in their products and supply chains, whereas they could reap benefits through managing chemicals safely. Nevertheless, most product sectors do not have sufficient information systems in place to ensure reliable information exchange on chemical content, and active strategies are required to facilitate that exchange (Rossi 2014).

Forward-looking industries are not only addressing environmental and social sustainability issues related to their production processes and products; they have also begun to identify and address potential risks associated with their upstream supply chains (Foerstl, Reuter and Blome 2010; Boström *et al*. 2015). These sustainability considerations along the supply chain are driven by the objectives of lowering reputational risks, enhancing operational performance, and ultimately enhancing competitiveness. Companies can derive numerous business benefits from sustainable supply chains, including product differentiation; increased market share and growth in consumer support; reduced compliance and supply chain management costs; and better labour productivity (EY 2016).

An important aspect of sustainable supply chain management is companies' understanding of the sustainability priorities of stakeholders, including downstream customers. Understanding these stakeholder concerns may, in turn, be translated into signals to their own suppliers and sub-suppliers (Foerstl *et al.* 2015). Figure 6.1

Figure 6.1 **Interface of demand and supply in driving the sustainability of chemicals in the supply chain**



Consumers and retailers play important roles in driving demand for safer chemicals and products. At the same time, green and sustainable chemistry innovations can drive the development of safer chemicals and products "downstream" in the value and supply chains. Both "pull" and "push" approaches are important and can complement each other.

represents the interface of demand and supply for sustainable products throughout the supply chain, from consumer retailers and retailer demand to the chemical industry and the suppliers of its feedstocks.

The role of retailers in influencing upstream supply and procurement

Retailers are in a critical position to drive the sustainability activities of different entities along the supply chain (Sebastiani *et al.* 2015). They are closest to consumers in the supply chain. They also have both financial and reputational incentives to implement management programmes that recognize potential concerns, as well as to reduce or eliminate specific chemicals from products in their supply chain. Consumers in both developed and developing countries consider ingredient transparency to be one of the biggest issues companies face (Retail Industry Leaders Association [RILA] n.d.). Many retailers have become leaders in incorporating sustainability considerations in their business practices and procurement processes (Lo 2013). They are working individually and collectively to discontinue the use of those chemicals of highest concern and thereby address consumer expectations (Box 6.1). This can be done through, for example, chemical ingredient assessment, supplier chemical assessment, restricted substances lists, and substituting or redesigning to eliminate priority chemicals (RILA n.d.).

The role of downstream product manufacturers and brands

Similarly, proactive product manufacturers engage in voluntary chemicals management practices to stay ahead of compliance regulations and maintain relationships with stakeholders. Many have joined coalitions to collaboratively address sustainable supply chain management, including its chemicals management dimension (Box 6.2). An important component of such chemicals management strategies is enhancing communication about the presence of chemicals in products in the supply chain and assessing potential risk. Increasing preference is being given to suppliers which help companies meet their sustainability goals (EY 2016). Furthermore, certifications and standards that reflect risk-based approaches to sustainability are being advanced, such as the United States Green Building Council (USGBC) initiative on the Integrative Analysis of Building Materials (USGBC 2019).

Companies may also expand their relationships beyond auditing and monitoring, and invest in capacity building and training of suppliers, in order to work towards shared commitments. An example is the amfori Business Environmental Performance (BEPI) Supply Chain Chemical Management module, which supports members in addressing chemical issues in their supply chain within a collaborative framework with common tools and standards. The module

Box 6.1 Examples of chemical sustainability initiatives in the retail sector

In 2013 Walmart, one of the world's largest retailers, announced its sustainable chemistry policy. This policy includes goals for restricting 2,700 harmful chemicals in household products by 2022; increased transparency of ingredients; and encouraging suppliers to certify their products to third-party standards such as the US EPA's Safer Choice (Sustainable Brands 2017; Porter 2018; Sager-Rosenthal 2019).

The large North American retailer Target has also announced a new chemical strategy addressing the company's entire value chain and operations and every product it sells. Target has a policy of commitment to transparency, proactive chemicals management, and innovation across all its owned and national brand consumer products and operations (Target 2017; Porter 2018; Sager-Rosenthal 2019). In Europe the home improvement retailer Kingfisher has published a chemicals policy focusing on transparency, chemicals management and innovation (Kingfisher 2018).

The largest pharmacy chain in the United States, CVS, has updated its list of restricted chemicals for use in baby, beauty and personal care and food products. It will remove parabens, phthalates and formaldehyde donors from more than 600 products (Sturcken 2017).

provides a platform and tools to communicate with producers in all tiers, improve their chemicals management and respond to detox concern (amfori 2019).

Box 6.2 **Downstream sector sustainable supply chain initiatives addressing chemicals of concern**

Responsible Business Alliance
Advancing Sustainability Globally

The Responsible Business Alliance (RBA) is the world's largest industry coalition dedicated to electronics supply chain responsibility. RBA members, which are held accountable to a Common Code of Conduct, use a range of training and assessment tools to support continuous social, ethical and environmental responsibility improvements in their supply chains (RBA 2018).

The Pharmaceutical Supply Chain Initiative (PSCI) was established by the pharmaceutical sector. Its members share a vision of responsible supply chain management, in order to deliver better social, health, safety and environmental outcomes in the communities where they buy. The PSCI created the Pharmaceutical Industry Principles for Responsible Supply Chain Management, which address five areas of responsible business practices and the relevant standards the pharmaceutical supply chain is expected to uphold. It has also developed tools to assess supply chains against the principles, as well as conducting supplier capacity building workshops and events (Mezaros 2017).

The Responsible Beauty Initiative (RBI) was launched by four industry leaders (Clarins, Coty, Groupe Rocher and L'Oréal) and EcoVadis, the leader in supply chain sustainability ratings, as a collaborative effort to strengthen sustainable practices, improve environmental footprints and social impacts, and maximize shared value across their collective supply chain. By using the EcoVadis sustainability ratings tool, RBI members aim to facilitate the social responsibility evaluations of their supplier network and engage suppliers more effectively (EcoVadis 2017). Another example of such an initiative is the Beauty and Personal Care Sustainability Project, which brings together key actors in the value chain (Forum for the Future 2018).

© Jenson/Shutterstock

Box 6.3 **Together for Sustainability: chemical industry collaboration with suppliers to advance sustainability**

TOGETHER FOR SUSTAINABILITY

Together for Sustainability (TfS) is an industry collaboration of 19 major chemical industry players to drive sustainability in the chemical industry supply chain by adopting a harmonized set of assessment and audit processes, and by developing and implementing a global supplier engagement programme. Through training, events and feedback, TfS raises awareness of sustainability topics among suppliers and supports continuous improvement of suppliers' sustainability performance (EcoVadis 2015).

In 2015 the initiative's members conducted a total of around 5,000 sustainability assessments and audits. The audit results are available to all TfS members with the suppliers' consent. BASF, one of the founding members, audited 135 supplier sites and initiated 1,044 sustainability assessments in 2015. If a need for improvement was discovered, suppliers were supported in the development of measures to meet the required standards. If no improvement took place, the business relationship was terminated. In 2015 four suppliers did not meet requirements (BASF 2015).

The role of the chemical industry in sustainable supply chain management

The chemical industry has a major role to play in engaging in collaborative relationships, not only with downstream customers through (extended) producer responsibility but also with its own suppliers. Some chemical companies have developed and implemented green and sustainable supply chain management practices with the integration of environmental concerns at the core, such as circular production processes and supply chain management and the tracking of performance and engagement of suppliers through closer supply chain collaborations (Genovese *et al.* 2017). Box 6.3 provides an example of such an initiative.

6.2 Information flow on chemicals in the supply chain

Strengthening two-way communication about chemicals in the supply chain

Producers and brands downstream of the chemical industry have an interest in obtaining information about the chemicals in the products they produce. Practices to strengthen the knowledge base of a producer include obtaining information on the chemicals present in articles; data on releases during production and from products; and safety information (e.g. from safety data sheets) to be provided to worker safety managers, retailers, consumers and other stakeholders. In addition, traceable information on waste handling and associated recycling processes can prevent the unintended contamination of products made from recycled materials. For example, the Proactive Alliance (a group of industry representatives seeking full material disclosure of chemicals, including retailers and product manufacturers) is exploring the possibility of a global cross-sectoral standard for exchanging data on individual articles. Its aim is for this standard to enable transferring data on substances in articles from one sector to another and to foster simpler compliance declarations. This initiative addresses the challenge that many sectors have material declaration systems, while no standard exists for sharing information between companies in different sectors (Stringer 2018).

Taking a product life cycle perspective helps producers to better understand the supply chain from a sustainability point of view, and to evaluate a holistic approach to address environmental, economic and social impacts. However, effective communication between actors in the supply chain is challenging and may be complex. Both push and pull concepts are relevant to improving flows of relevant data and information in the supply chain. The push dimension refers to chemical industries' responsibility to follow the use of a chemical through the chain leading to its customers, while the pull dimension refers to retailers, product manufacturers and brands pulling information from their upstream suppliers, including from the chemical industry.

Use of information tools to increase transparency on chemicals in the supply chain

There is an increasing range of available tools companies can use to communicate sustainability information along the supply chain. For example, companies may ask suppliers to fill in forms about the chemical content of products (Scruggs 2013). Eco-labelling and social labelling can be used to verify compliance with important aspects of sustainability and to hold suppliers responsible for ensuring sustainability in supply chains. The *Blauer Engel* (Blue Angel), the German government's eco-label, has established standards for environmentally friendly products and services which are decided by an independent jury according to defined environmental and sustainability criteria. Around 12,000 products and services from some 1,500 companies have been awarded the Blue Angel. Another example is the Safer Choice programme (formerly Design for Environment, DfE), administered by the US EPA, whose label covers over 2,000 products and includes requirements for performance, packaging, pH and VOCs (Perlmutter 2015).

At the global level, under SAICM the Chemicals in Product Programme led by UN Environment (see Part II, Ch. 4) brings together SAICM stakeholders to strengthen information flow on the presence of chemicals throughout the supply chain. An assessment of different tools for, and approaches to, managing material information in global supply chains prepared within this framework by UNEP's Chemicals in Products project found that IT-supported information exchange systems providing "full material disclosure" (FMD) were the most advanced solution (UNEP 2015).

Supplier codes of conduct are a way to establish sustainability expectations for the supply chain, which supply management professionals, suppliers and other actors can use to make informed decisions (UNEP 2014). Supply chain information systems and product information systems provide information on restricted chemicals and material declarations. For example, use of the Globally Harmonized System for Classification and Labelling (GHS) promotes the transfer of information to users of chemicals through labelling and safety data sheets (Swedish Chemicals Agency 2016). Other tools include auditing procedures, procurement guidelines and eco-branding (Boström *et al.* 2015).

While the chemical industry needs to implement effective communication and information exchange with its suppliers, it also needs to engage with downstream partners to ensure

Box 6.4 **Strengthening information flows between the chemical industry to downstream customers**

The International Council of Chemical Associations (ICCA) represents chemical manufacturers and producers around the world. ICCA members account for more than 90 per cent of global chemical sales. Increasingly, consumers seek more detailed information from product manufacturers about ingredients in the products they use. The ICCA launched a Value Chain Outreach programme, starting with the electronics sector and later extending it to the automotive and textiles sectors. Through this programme chemical companies aim to improve communication with retailers, product manufacturers and others along the chemical value chain concerning how to safely manage and use chemicals throughout their entire life cycle, from production, transport and use through eventual recycling or disposal. Each part of the value chain shares responsibility (i.e. through product stewardship) for prioritizing health, safety and environmental protection at each stage of the chemicals' life cycle (ICCA 2015; Patel 2016).

that chemical safety information is appropriately communicated and that chemicals are put to their intended use. Box 6.4 provides an example of a chemical industry initiative to strengthen communication with downstream product manufacturers.

The supply chain, and the ability to trace chemicals, become increasingly complex along the value chain. Participants in the value chain maintain records and update them continuously, which must also be carried out by others in the network. As a result, participants in the supply chain potentially incur costs and delays and must address inaccuracies, which could be further complicated due to third party audits. Important information about chemicals in products may be missed out using this approach.

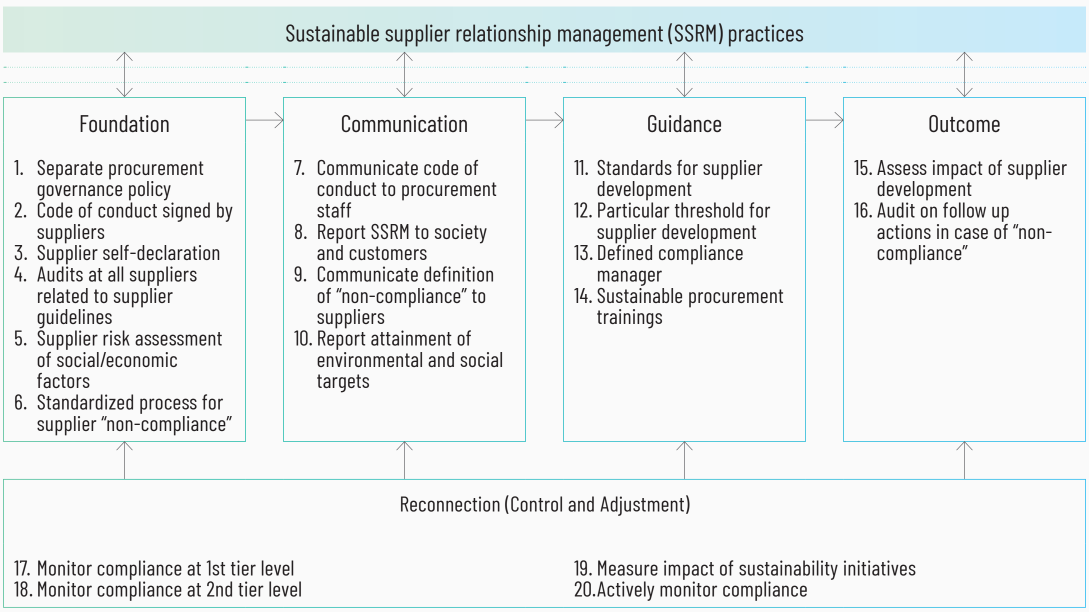
While existing IT solutions such as the International Material Data System (IMDS) or the Sustainability Data Exchange Hub (SustainHUB) are effective, the use of blockchains (lists of cryptographic information about individual business-to-business supply chain transactions) can help decentralize and optimize necessary information flows and bring greater efficiencies to global chemical supply chains (Goodnight 2017). Blockchains could create a new model of trust by establishing transactional relationships between businesses through smart contracts, certifications and compliance (International Business Machines Corporation 2018).

6.3 Collaborative relationships for sustainable supply chain management

Sustainable Supplier Relationship Management

Successfully managing the cross-border and often sector-spanning nature of complex supply chains entails governance challenges. These include addressing geographical distances in the supply chain; information, communication and knowledge exchange related to supply chain complexity and fragmentation; compliance and implementation gaps; challenges in supply chain power relations; and credibility issues (Boström *et al*. 2015; Blome, Foerstl and Schleper 2017).

Figure 6.2 **Sustainable Supplier Relationship Management (SSRM) practices (adapted from Leppelt *et al.* 2013, p. 100)**



Reprinted with permission from Elsevier.

Stakeholders often hold the buying companies responsible for compliance issues in their upstream supply chains. To address sustainability concerns in upstream supply chains, companies need to implement measures that substantially affect supplier conduct, with many firms relying on improving sustainability performance in the supply base through proactive supplier management (Marquis, Toffel and Zhou 2016). There is an overview of measures to manage supply chains and relationships with suppliers, in order to meet sustainability objectives, Figure 6.2 An important aspect of this framework is the fostering of behavioural change in suppliers in a cooperative manner, through "inclusive multi-stakeholder coalitions" rather than through prescriptions by the customer.

Broader governance measures need to support tools

While the tools discussed above are important, in most cases they are not sufficient in themselves to overcome the geographical, informational, communication, compliance, power and legitimacy challenges that are barriers to sustainable global supply chains. Therefore, it is suggested that such tools be used with a wider range of approaches including (Boström *et al.* 2015):

- coalition and institution building on a broader scale (e.g. through developing inclusive multi-stakeholder coalitions);
- ensuring flexibility to adapt global governance arrangements to local social and environmental contexts of production and consumption;
- supplementing effective monitoring and enforcement mechanisms with education and other programmes to build compliance capacity; and
- integrating reflexive learning to improve governance arrangements over time.

6.4 Considering circularity in supply chain management

Resource efficiency considerations include transitioning from a traditional linear flow of materials in a "take-make-use-dispose" economy

Box 6.5 **The Circular Economy Package (EC 2018)**

The Circular Economy Package was adopted in December 2015 by the European Commission. Four objectives were formulated that pinpoint the direction of innovation in circular supply chain management and are relevant to chemicals and waste management (EC 2018):

- Ensure that appropriate information on substances of concern in products is available to all actors in the supply chain and ultimately also becomes available to waste operators. This will contribute to the promotion of non-toxic material cycles, and improve the risk management of chemicals during repair and other forms of reuse and in waste recovery processes.
- Make recycling easier and improve the uptake of secondary raw materials by promoting non-toxic material cycles. In addition, when considering possible chemical restrictions and exemptions to restrictions, more attention needs to be given to their impact on future recycling and reuse.
- Enable a more harmonized interpretation and implementation of end-of-waste rules across the EU to further facilitate the use of recovered material within the EU.
- Ensure a more consistent approach between chemicals and waste classification rules.

In the corresponding EU Action Plan for the Circular Economy, it is stressed that the functioning of value chains needs to be rethought. Value chains, especially for complex composite materials (e.g. plastics) or chemical formulations (e.g. plant protection products), are closely connected with the creation of material cycles, where hazardous chemicals are reduced to a minimum in support of a "non-toxic environment" (Goldenman *et al.* 2017). The new database to be hosted by the European Chemicals Agency (ECHA), created under the amended Waste Framework Directive on the presence of substances of very high concern (SVHC) in articles, is a concrete measure to help achieve this goal (ECHA 2018).

to a more circular flow of materials. In this approach a core principle is the elimination of waste through improved design of products, use of processes that have increased resource efficiency, and increased recyclability of materials (Sheldon 2016). Circular supply chains therefore cover remanufacturing, reuse and recycling processes (Dora, Bhatia and Gallear 2016; Genovese *et al*. 2017). Maintaining the value of materials, products and resources in the economy for as long as possible, and minimizing waste generation, represent an essential contribution to the development of sustainable, low-carbon, resource-efficient and competitive economies (EC 2015). Box 6.5 describes the Circular Economy Package adopted by the European Commission.

End-of-life treatment of chemicals and products is the stage at which improved waste management and recycling strategies are considered. In a circular economy, materials that can be recycled are inserted back into material and product life cycles as "secondary raw materials". One barrier to promoting the use of secondary raw materials is uncertainty about their performance quality and chemical content, including possible contamination. Chemical contamination of articles may prevent recycling, or it may present new, unexpected exposure situations if contaminated recycled materials are used in products when use of these substances was not foreseen (Goldenman *et al.* 2017). In the fashion industry some retailers allow customers to exchange unwanted clothes for a discount, so as to use them as raw material for new products. Due to complex supply chains, companies often do not have an adequate understanding of conditions in far-away factories, including chemical use (Bomgardner 2016). Promotion of uncontaminated material cycles and better tracking of chemicals of concern in products can help address these concerns and facilitate recycling through the uptake of secondary, non-toxic raw materials. Improved tracking of chemicals of concern should also be used to identify contaminated materials in the waste stream and separate them, in order to maintain a high recycling rate while generating uncontaminated secondary raw materials.

Many stakeholders have embraced the circular economy approach. The ICCA, for example, has expressed its commitment to play a key role in the systemic transition to a circular economy as a key component of sustainability, whereby resources and materials are continuously cycled to eliminate waste while creating value for all. According to this view, circular economy initiatives must embrace a holistic view of the economy that considers both environmental and societal impacts of a product or material across its life cycle. Enabling policies are needed that take a holistic view and consider all stages of a product life, including the closure of loops at end-of-life, while being transparent, risk-based and flexible in nature. This will unleash market forces that drive innovations towards a circular economy.

6.5 Integrating life cycle thinking and sustainability into product design

Taking a systems approach in designing products

To address challenges associated with chemicals and their products, it may not be sufficient to base chemical synthesis on functionality criteria only (e.g. water repellency, resistance to high temperatures and economic viability). Sustainable design and supply chain solutions go a step further, considering life cycle impacts, from synthesis (energy, water, other chemical use) to toxicity and environmental effects, during the product life cycle as components of chemical and product design criteria. Chemical and product design, synthesis and manufacturing are therefore important stages for the implementation of broader sustainable supply management strategies, which can be understood as a systemic shift involving both technological and non-technological innovations (Kirchherr, Reike and Hekkert 2017; Homrich *et al.* 2018).

The coordination of product and supply chain design decisions plays a critical role in improving the sustainable supply chain's performance. A product's design determines its future costs, which in turn depend on the supply chain configuration (e.g. the number and locations of supply chain partners, and their capabilities and capacities) (Metta and Badurdeen 2013). Integrating product design in the supply chain is therefore a basis for establishing sustainable competitiveness in increasingly complex customer markets. Moreover, integrating product design in the supply chain increases communication, supply chain visibility and responsiveness, as well as reducing supply chain risk (Khan *et al.* 2016). Box 6.6 describes the Design Thinking approach to advance sustainability.

Green and sustainable chemistry design considerations along the supply chain

Green and sustainable chemistry, as already discussed, encompass the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes (Friege 2017). While the focus of green chemistry is on reducing waste, increasing yield and reducing non-renewable energy and material input (along with environmentally conscious

Box 6.6 The Design Thinking approach to advance sustainability

Design Thinking is a systematic approach to solving complex problems associated with all aspects of life. In contrast to conventional approaches, starting with technical solvability, Design Thinking puts customer needs (as well as user-centred inventions) at the heart of the process. It also requires steady back-coupling between the innovator and the customer. However, Design Thinking is not only about product and service innovation. It is a means of increasing the problem-solving competence of the user, or of the companies using it, for all kinds of product and service innovation. Design Thinking is also increasingly used in revising internal company processes, especially in areas such as finance and accounting, the supply chain, personnel administration and client management, complementing what traditional methods (e.g. Lean Six Sigma) have to offer (Waerder, Stinnes and Erdenberger 2017).

Table 6.1 From traditional to green and biomimetic chemistry technologies (Van Hamelen 2018, p. 6)

TRADITIONAL	GREEN AND BIOMIMETIC
› "Heat, beat, treat": chemical reactions under high temperature, high pressure and chemical treatment › Organic solvents › Fossil feedstock and fossil energy › High purity of feedstock is imperative › Use of the entire periodic system › Resources sourced globally › Controlling risk by taking safety precautions	› Chemical reactions take place at room temperature and pressure › Water as solvent › Low-energy chemical reactions › Local feedstocks, diverse sources › Degradation is part of design: "timed degradation" of "triggered instability" (John Warner), "Nature's disassembly processes" (Janine Benyus) › Functionality is created by the structure, not the material itself › Living systems only utilize 25 elements; carbon, oxygen and sodium make up 96 per cent of atoms in living systems; other elements are used in trace amounts › Controlling risk by adopting the inherent properties of the materials

design of chemical reactions and products), sustainable chemistry has a broader focus, in line with broader sustainable supply chain approaches. Table 6.1 provides an overview of approaches that can help move from traditional to green and biomimetic technologies that enable the transition to circular and sustainable supply chains.

6.6 Measures to strengthen sustainable supply chain management

Sustainable supply chain management plays a key role in ensuring that purchasing and procurement decisions comply with sustainability criteria, and that they create a force that will drive upstream suppliers to participate in the growing markets for sustainable products. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to strengthen sustainable supply chain management:

- Develop sustainable chemistry supply chain policies throughout the supply chain.
- Enhance information sharing among all actors in the supply chain, on chemicals in products and chemicals in products' waste, and harmonize approaches to share such information.
- Develop collaborative approaches to sustainable supply chain management in the private sector that bring together companies in specific sectors, and include other stakeholders.
- Promote emerging good practices and initiatives in sustainable supply chain management for chemicals and waste in countries where these ideas, practices and initiatives are less well-known.
- Take proactive corporate measures to design sustainable products and sustainable solutions, and become market leaders, taking into account green and sustainable chemistry approaches.
- Strengthen legislation on the chemicals and waste interface, in order to provide clear guidance to recyclers that will advance non-toxic materials flow.

7/ Sustainability metrics and reporting: measuring progress, strengthening accountability

Chapter Highlights

A variety of metrics exist to assess the chemicals and waste dimension of companies and producers, including life cycle assessment and chemical footprint indicators.

Reporting by industry is increasing, and self-reporting in the chemical and related industries is complemented by independent external assessments.

Opportunities exist to link, align and/or develop metrics and reporting standards, drawing on existing international initiatives.

Stakeholders can take further steps to increase both transparency and rigour, thereby ensuring that metrics are fit for purpose and audience.

Opportunities exist to develop a common understanding of green/sustainable chemistry metrics.

Metrics and industry sustainability reporting could become important aspects of measuring progress in a beyond 2020 framework.

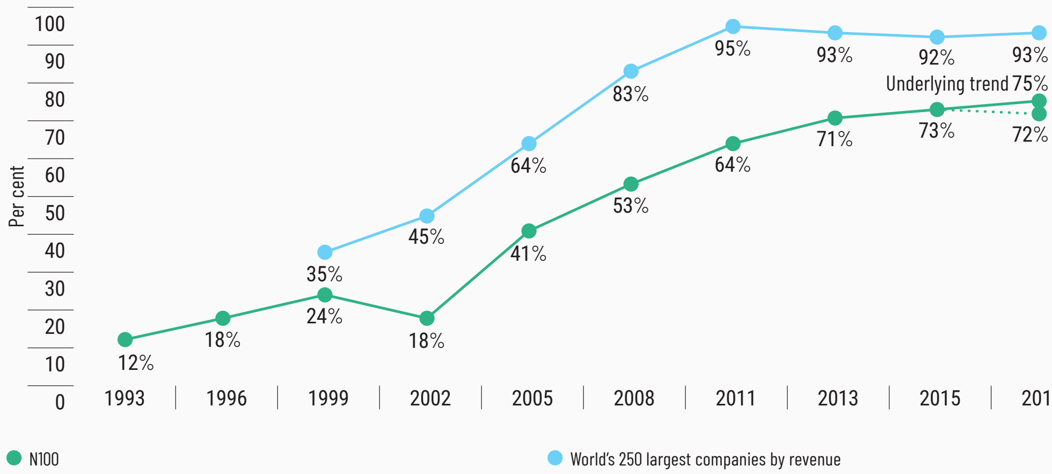
Private sector initiatives and standards, including on chemicals and waste, have been mentioned in various chapters of the GCO-II. This chapter discusses metrics and reporting schemes aimed at providing interested stakeholders with knowledge about the performance of the private sector related to sound management of chemicals and waste. The chapter is not able to cover all relevant initiatives. Nor does it seek to judge the merit of the schemes mentioned. Rather, by drawing attention to the topic, it aims to raise the question of how metrics and reporting schemes could fit into, and be strengthened within, a global approach on chemicals and waste beyond 2020.

7.1 The growing momentum of private sector sustainability metrics and reporting

An increasing number of companies report on their sustainability performance, including that related to chemicals and waste management

Traditional corporate reporting has focused on information that may influence the decisions of those who consult a company's financial statements, such as investors. More recently, momentum has been generated to integrate sustainability aspects into corporate reporting. According to some estimates, the share of the world's 250 largest companies reporting on their sustainability performance increased from 35 per cent in 1999 to 93 per cent in

Figure 7.1 Share of the top 100 companies in 34 countries (N100) and of the world's 250 largest companies providing corporate responsibility reports (per cent), 1993-2017 (adapted from Blasco *et al.* 2017, p. 9)



The survey's findings indicate that corporate responsibility reporting has become standard practice for most large and medium-sized companies across the world. The terms corporate responsibility, corporate social responsibility, and environmental, social and governance are often used interchangeably.

2017 (Blasco *et al.* 2017). The use of metrics to assess companies' environmental, social and governance (ESG) performance, as well as their economic performance, has grown significantly, particularly in the Asia-Pacific region (KPMG *et al.* 2016). While the majority of countries in the world have sustainability reporting policies, such policies are still largely lacking in Africa and West Asia (Global Reporting Initiative [GRI] 2016).

Sustainability reporting is often based on formalized standards and guidance, and the use of the majority of sustainability reporting instruments is mandatory (KPMG *et al.* 2016). However, a growing share of reporting (approximately one-third in 2016) is voluntary (KPMG *et al.* 2016). Materiality in sustainability reporting implies a broader scope, including aspects that may affect the company's "ability to create, preserve or erode economic, environmental and social value for itself, its stakeholders, the environment, and society at large" (GRI n.d.). If actors focus on short-term financial aspects, disclosure may lead to management and investment decisions that are suboptimal from a sustainable development perspective.

Regulations, consumers, and actors in the supply chain drive sustainability reporting

While regulation – and the need for compliance – continue to be major drivers of sustainability reporting (Cockcroft and Persich 2017), there is growing awareness in the corporate sector that strong performance on sustainability issues and transparent reporting are beneficial to business and provide new opportunities to generate revenue. In the long term, companies which voluntarily adopt sustainability policies have been shown to significantly outperform their counterparts in terms of market and accounting performance (Eccles, Ioannou and Serafeim 2014). Companies thus have an intrinsic interest in making their contributions to achieving the SDGs more visible and communicating them, given that these contributions may be overlooked or not adequately attributed. Sustainability reporting may also change perceptions of the chemical industry and increase competitiveness, thereby attracting new talent (WEF 2019).

The general public and consumers are a main driver for these developments. They are increasingly conscious of (and demand information about) the sustainability performance of companies and/or products before making choices. The need to gain the trust of society is thus an important driver for transparency (WBCSD 2014). NGOs seek to provide relevant information and place pressure on companies, naming frontrunners and shaming laggards (Follette *et al.* 2017). Retailers may be particularly sensitive to this driver, consequently exerting pressure on suppliers. Suppliers, in turn, are likely to signal a need for information on sustainability performance further upstream. Equally important, the chemical industry, further upstream, is assessing, auditing and communicating its performance, including that of suppliers, as is done through the Together for Sustainability (TfS) initiative (TfS 2016). Sustainability reporting by various actors along the supply chain thus becomes an important source of information for corporate decision-making.

Financial market actors also use sustainability performance and non-financial information in making investment decisions (Deloitte 2016). This steers companies towards improved sustainability policies and long-term value creation, as exemplified by a recent letter to CEOs from Blackrock, the world's largest asset manager (Fink 2018).

7.2 A snapshot of private sector metrics and reporting on chemicals and waste

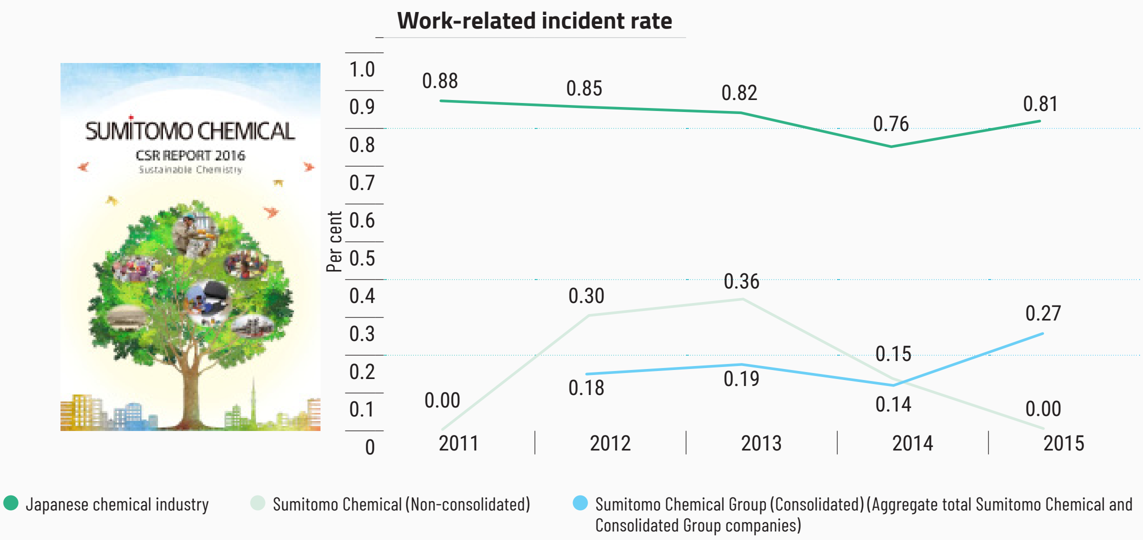
7.2.1 Metrics and reporting developed by industry

The chemical industry

RESPONSIBLE CARE®
OUR COMMITMENT TO SUSTAINABILITY

Industry associations also play a role in communicating sustainability performance. In the context of the Responsible Care® initiative of the International Council of Chemical Associations (ICCA), participating companies collect and report data for a set of environmental, health and safety performance measures. While the number of organizations reporting under Responsible Care® has varied over the years, reporting rates have increased overall. For example, the number of organizations reporting on fatalities in the workforce increased from 25 in 2000 to 42 in 2013 (ICCA 2015). In the United States, a Responsible Care® Management System has been established that includes independent third-party certification and transparent reporting and performance metrics (ICCA 2015). This management system has the potential to serve as the benchmark for

Figure 7.2 Snapshot of Sumitomo's Corporate Social Responsibility Report: work-related incident rate (per cent), 2011-2015 (adapted from Sumitomo Chemical Group 2016, p. 10)



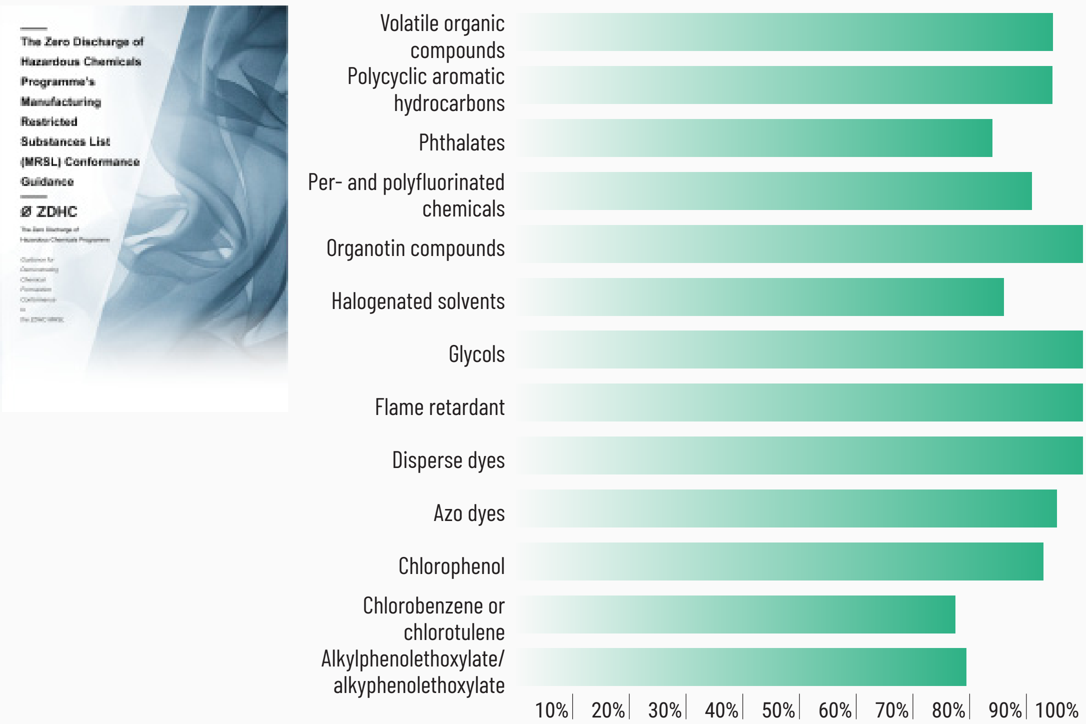
monitoring and assessing implementation in other countries.

Almost all major chemical companies now publish regular reports on ESG performance. For example, the Dow Chemical Company (2017) and the Sumitomo Chemical Group (2016) publish sustainability reports on a regular basis to communicate performance on selected indicators, increasingly mapped against the SDGs. Under Chemie3, a sustainability initiative of the German chemical industry tailored in particular to SMEs, 40 economic, environmental and social indicators have been developed to measure progress towards sustainable development, such as product safety and resource efficiency. Progress against the indicators is reported publicly and on a regular basis (Chemie3 2018). In some cases approaches are developed in collaboration with external partners, as in the case of the Additives Sustainability Footprint of the PVC industry (UN 2018).

Downstream sectors

Efforts to self-assess and report sustainability performance across the supply chain can also be observed among chemical-intensive downstream companies and retailers. One example is the

Figure 7.3 ZDHC and PUMA's rates of compliance with MRSL parameters in wastewater (per cent), 2017 (adapted from PUMA 2018, p. 10)



Box 7.1 Johnson's Greenlist™ Programme (GC3 n.d. a)

S.C. Johnson is a formulator of chemical-intensive products used in millions of households. In 2001 the company, which does not produce the ingredients that go into its products, launched an innovative chemical classification process called Greenlist™ that rates raw materials based on their impact on human health and the environment. The scores are reported alongside performance and cost information in the company's chemical formulary, so that chemists can easily compare these materials. Over time most suppliers have embraced the Greenlist™ protocol. The programme has evolved to the point that suppliers are designing new chemicals based on the Greenlist™ scores.

Zero Discharge of Hazardous Chemicals (ZDHC) initiative, which covers the global textile, leather and footwear sectors (ZDHC 2018). This programme brings together 24 signatory brands, 53 value chain affiliates and 15 associates whose aim is to eliminate the use of priority hazardous chemicals throughout their value chains. The ZDHC Roadmap to Zero Programme includes harmonized approaches in areas such as its manufacturing restricted substances list (MRSL), wastewater quality, audit protocols, and data and disclosure (Figure 7.3). Rates of compliance are made publicly available (ZDHC 2018).

7.2.2 Independent assessment schemes with industry participation

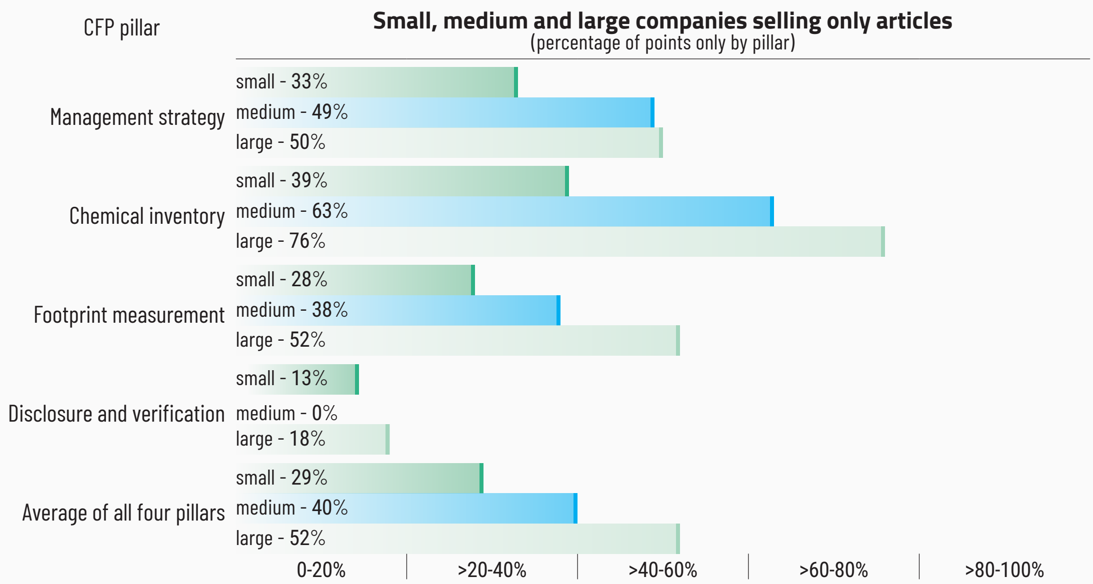
Companies may choose to engage with external bodies to assess and certify their products based on a set of criteria covering selected economic, social and/or environmental topics. This may include product recyclability assessment and certification schemes, such as the Cradle to Cradle Product Standard (Cradle to Cradle Products Innovation Institute 2018) and the textile production and product-specific Bluesign (Bluesign 2018). Environmental Product Declarations are another reporting tool which companies all along the supply chain can use to disclose environmental impacts throughout the life cycle of products, including aspects related to waste management and disposal (International EPD System 2017). In the building sector, the membership-based United States Green Building Council (USGCG) provides third-party certifications of buildings meeting certain sustainability criteria (USGBC 2018).

The Future-Fit Business Benchmark (Future-Fit Foundation 2017) seeks to support both chemical companies and downstream actors in articulating, assessing and transforming how they create long-term value for themselves and society as a whole. This approach is based on the identification of an extra-financial break-even point for business, expressed as a unified set of social and environmental goals drawing, among others, on criteria such as chemical releases and the use of chemicals that are likely to build up in nature and/or are considered harmful according to the SIN (Substitute It Now!) List (International Chemical Secretariat [ChemSec] 2017). Under the Future-Fit scheme, independent assurance by third parties and publication of the scores is optional.

Some of these schemes focus on assessing and communicating performance to downstream users and the general public. The Chemical Footprint Project (CFP), for example, provides a quantitative metric which manufacturers, brands and retailers can use to measure progress in reducing the use of chemicals of high concern. Participation is voluntary and the results are made publicly available (Rossi *et al*. 2017).

A number of broader sustainability reporting initiatives are in place that also cover – to a varying extent – topics relevant for the sound management of chemicals and waste. The Global Reporting Initiative provides widely used Sustainability Reporting Standards which include guidelines and standards that companies and

Figure 7.4 Average percentage of points across four Chemical Footprint Project (CFP) pillars scored by small, medium and large companies selling only articles (adapted from Rossi *et al.* 2017, p. 7)



other organizations can use for sustainability reporting (GRI n.d.). The Sustainability Accounting Standards Board (SASB) provides standards for integrating relevant ESG considerations into reporting. They cover 79 industries in 11 sectors. Likely material sustainability issues for disclosure by the chemical industry identified include, among others, wastewater management; waste and hazardous materials management; employee health and safety; life cycle impacts of products and services; and accident and safety management (SASB 2015; SASB 2018).

7.2.3 Independent external assessment of industry performance

Growing investor interest in corporate sustainability performance has led to the incorporation of more detailed information on chemicals and waste management in external assessment schemes. Under the Dow Jones Sustainability Index, for example, chemical suppliers and downstream companies are requested to provide information on the percentage of products that contain substances regulated as hazardous, are of international concern, or may become regulated in the future, as referenced by ChemSec's SIN List (ChemSec 2017). Various service providers assess performance on environmental, social and governance topics, including chemicals and waste management, to allow investors to assess respective risk profiles (Sustainalytics n.d.).

A number of initiatives provide independent assessments of chemicals and waste management performance directed to consumers and the general public. For example, the Mind the Store initiative in the United States informs consumers by providing an aggregate grade based on criteria such as whether a policy is in place to ensure that suppliers conduct credible hazard assessments for alternatives to chemicals of high concern

Box 7.2 Sustainability information of relevance to the financial sector

The financial sector is important in driving the demand for information on sustainability performance of companies. A number of metrics and reporting schemes exist to inform investment decisions, including the following:

- *ESG (environmental, social and governance) factors*: These are a subset of non-financial performance indicators which include sustainable, ethical and corporate governance issues and ensuring there are systems in place to ensure accountability. The UN-backed Principles for Responsible Investment (n.d.) provide a voluntary ESG framework for companies and funds, on the basis of which investors can make informed investment decisions with respect to sustainability and governance practices (UNEP and World Bank 2017; Financial Times n.d.).
- *Environment-related financial disclosure and transparency*: This allows investors to exclude companies in the chemical industry or among downstream users of chemicals, including formulators and retailers, which are not working towards the implementation of more sustainable practices.
- *Environmental disclosure on stock exchanges*: Stock exchanges have historically played an important role in economic growth and development through enabling effective capital allocation. It is increasingly clear that environmental and social issues have an impact on corporate performance. Therefore, stock exchanges (or the relevant securities regulators) should require disclosure in the same way that financial disclosure is required (Cleary 2015).
- *Environmental and sustainability stock market indices, ratings and associated products*: These are useful to investors as they seek to shift to more sustainable investment (Cleary 2015). It is important that robust methodology be used, which can address relevant green and sustainable criteria within the chemical industry and downstream use sectors.
- *Environmental risk management by financial institutions*: This includes risk management frameworks, such as the Equator Principles, which are adopted by financial institutions to determine, assess and manage environmental and social risk in projects. It is primarily intended to provide a minimum standard for due diligence and monitoring to support responsible risk decision-making. The most recent version of the Equator Principles (currently under review) advises that assessment documentation may include “pollution prevention and waste minimization, pollution controls (liquid effluents and air emissions), and solid and chemical waste management” (Equator Principles 2013).

(Safer Chemicals, Healthy Families 2018a). Others provide consumers with online product and ingredient information to help guide better informed buying decisions for specific applications (GoodGuide 2018). The scientific community also provides information on the sustainability performance of relevant stakeholders, including the chemical industry. For example, one study (Britzelmaier *et al.* 2015) assessed the corporate sustainability management of international chemical companies across four categories: reporting, ecology, environment and economy.

Eco-labelling can be a useful tool to encourage more sustainable production and consumption by helping customers from the public and private sectors identify greener and more sustainable products. Eco-labelling uses specific criteria (e.g. hazard properties) to provide information about the environmental characteristics of a product. Such labels are initiated in some cases by governments and in others by the private sector. In recognizing that environmental concerns may become a market advantage, private companies use eco-labels to increase awareness and influence consumer decisions through their purchasing (Tranchard 2018; International Organization for Standardization 2019). An example of a certification scheme for products and services that also covers chemicals and waste related issues is the *Blauer Engel* (Blue Angel) in Germany.

7.3 Green and sustainable chemistry within metrics and reporting schemes

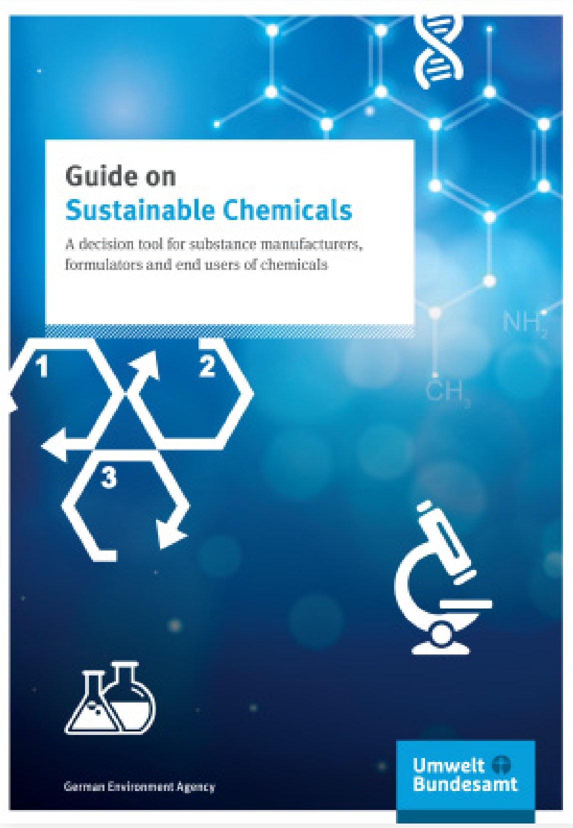
Stakeholders use the green and sustainable chemistry concepts in standards and reporting

In their reporting, various stakeholders use the terms "green chemistry", "green engineering" and "sustainable chemistry". In doing so, some have developed their own metrics to measure performance. For example, Dow has set a goal of increasing sales of sustainable chemistry products, defined sustainable chemistry, and developed a Sustainable Chemistry Index to track progress. The index combines variables such as the recycled content of the product, its social benefit, and risks it may pose at the end of the life cycle (Dow Chemical Company 2015). Sigma-Aldrich has developed a quantitative assessment of a product's performance against the 12 Principles of Green Chemistry in order to optimize the manufacturing process accordingly (Sigma-Aldrich n.d.). S.C. Johnson applies requirements for full disclosure of products' ingredients and green chemicals selection criteria (S.C. Johnson & Son 2018).

Exploring the potential of sustainable chemistry metrics to assess and communicate performance

As highlighted in Part I, Ch. 1, there is currently no common understanding among stakeholders of sustainable chemistry or how to assess information about the sustainability of chemical processes and products. A recent report by the United States Government Accountability Office (2018) highlights the challenges of using different metrics, which incorporate different factors, in order to evaluate the sustainability of processes or products. It finds that this impedes the development and adoption of sustainable chemistry technologies, while there is as yet no common understanding of how to measure progress towards green and sustainable chemistry.

Efforts are under way to advance a common understanding of green and sustainable chemistry. For example, one study (Tickner and Becker 2016) explores how measuring progress towards mainstreaming green chemistry requires the use of relevant metrics at the molecular/process level (e.g. water usage in the process), the product and material level (e.g. the inherent hazard of chemicals or materials in a product), the firm and sector level (e.g. the existence of effective chemicals management strategies), and the societal level (e.g. the production volume of chemicals meeting the Principles of Green Chemistry) in a complementary manner (see also GC3 n.d. b).



The German Environment Agency (UBA) developed a *Guide on Sustainable Chemicals*, a decision tool for substance manufacturers, formulators and end users (UBA 2011). Since 2016 there is a corresponding IT tool, SubSelect (UBA 2016), which can be used to measure the sustainability of Chemical Leasing projects (UBA 2018) and has an ongoing activity on sustainable chemistry case studies. At the international level, UNEP has developed an analysis of submissions of cases from stakeholders that have relevant experience with the issue of sustainable chemistry, in response to a mandate received from the second UN Environment Assembly (UNEA-2). Among other considerations, it looks at the possibility of developing practical guidance on sustainable chemistry (UNEP 2019).

7.4 Strengthening the chemicals and waste dimension of sustainability metrics and reporting

The metrics and reporting landscape is complex and fragmented

The rapid proliferation of sustainability reporting instruments has created a complex and fragmented landscape (KPMG *et al.* 2016). One study found more than 2,500 different metrics for supply chain performance reporting (Ahi and Searcy 2015). While the availability of a large set of metrics may allow companies to report on specific aspects of particular relevance, it also presents challenges in regard to providing meaningful information. Technological advances (e.g. in the context of big data) could help in gathering and analyzing publicly available sustainability reporting data, in order to create useful data points for chemicals management across the value chain.

Sustainability instruments and metrics to assess performance with respect to chemicals and waste vary significantly, for example in terms of who undertakes them, who/what is being evaluated, the scope of the assessment, and the methods used and the audience. Depending on these variables, the results communicated in terms of chemicals management performance, along with the transparency of the scheme, may vary significantly. To ensure credibility, and to avoid the suspicion of "greenwashing", it is important for methods to be transparently documented (Berrone 2016; Stacchezzini, Melloni and Lai 2016). It has been argued that the growing number of footprint indicators, and the absence of consistent methods, may result in incoherence and contradictory results which could also hamper the usefulness of such reporting for policymaking and corporate decision-making and represent a market barrier for green products (Ridoutt *et al*. 2015).

Integrating chemicals and waste into metrics and reporting schemes

A review of existing sustainability metrics and reporting in the chemical industry focuses on "traditional" environmental and social concerns such as job creation, labour rights, carbon footprints and resource efficiency. Specific issues of relevance to chemicals management are often inadequately addressed and not integrated into companies' sustainability strategies (Cockcroft and Persich 2017). Similarly, related and chemical-intensive downstream industries could enhance the consideration of chemicals and waste in their reporting efforts. Opportunities also exist to further and more comprehensively integrate chemicals and waste management issues into existing and widely used reporting schemes like the GRI.

Ensuring that metrics are fit for purpose and audience

In some cases simplified metrics are needed for effective communication of relevant information to the target audience, such as investors or consumers. Footprint indicators aim to do this by providing a single consolidated metric. However, depending on the approach used, footprints could also be used to draw attention to a selected stage of the life cycle while neglecting others, which might give an incomplete picture of the environmental impact. Life cycle assessments may help provide a more comprehensive picture, including of potential trade-offs across different stages of the life cycle, thus providing a more useful basis for decision-making in certain contexts. Meanwhile, increased complexity comes at a cost and the results may be less easily accessible to non-experts (Ridoutt *et al*. 2015).

Existing sustainability metrics and reporting schemes have been criticized for not placing the reported indicators in the environmental, social and economic context as this applies at the relevant level (local, regional, global) (McElroy and Baue 2013; Kropp 2014; Haffar and Searcy 2018). Context-based metrics that give due consideration to relevant thresholds, including where these are not fully understood, may help determine the value of companies' reported

efforts to increase the sustainability performance of their portfolio. As regards chemicals and waste, this could prove a straightforward exercise in some areas but a more complicated one in others, as is also evident from the difficulties of identifying a measurable planetary boundary for chemical pollution (Robèrt, Broman and Basile 2013; Diamond *et al.* 2015). More research may be needed in order to explore the value and feasibility of context-based sustainability metrics.

Taking steps towards coherent metrics and reporting

There may be value in exploring opportunities to align and/or develop harmonized metrics and reporting standards, as appropriate (e.g. at the sectoral level). Such efforts could draw on existing international standards in order to increase efficiency and the comparability of results. Life cycle approaches, for example, could draw on International Organization for Standardizaton (ISO) standards 14040 and 14044, which specify requirements and provide guidelines for life cycle assessment (Ridoutt *et al.* 2015).

Some progress has been made towards the establishment of binding global norms in the area of sustainability reporting. At the UN Conference on Sustainable Development in Johannesburg (UN 2012), several proposals were discussed concerning a potential legally binding instrument on sustainability reporting for certain corporations. This concept was based on the "report or explain" approach that has become law in Denmark and is a requirement for companies listed on some stock exchanges. Although the initiative failed, it had the support of various private businesses, including strategic investors and insurers, and the debate around the various proposals has perhaps opened the door to broader consideration of mandatory environmental and social performance standards (Stec, Paszkiewicz and Antypas 2017).

Proposals have been made to develop a common conceptual framework for deriving chemical footprints (Rydberg *et al*. 2014). Several initiatives recognize and aim to address the need for coherence, comparability and transparency (SASB 2015; Future-Fit Foundation 2017; WBCSD

2018; GRI n.d.). Efforts at the international level to streamline approaches and facilitate coherence are under way, including in the framework of the Life Cycle Initiative (UNEP 2017), the Society of Environmental Toxicology and Chemistry (2018) and the EU Product Environmental Footprint.

The role of metrics and reporting in chemicals and waste management beyond 2020

Despite the wide use of metrics and reporting, little of the information gathered currently feeds into international chemicals and waste frameworks such as SAICM. Stakeholders may wish to consider whether, and to what extent, the integration of such reporting could help to evaluate progress under a future platform for sound management of chemicals and waste beyond 2020.

Of equal interest may be the question of how efforts at the international level could help increase the visibility of sustainability reporting efforts, while at the same time holding stakeholders accountable. It could be worthwhile to consider mechanisms for bringing together the sustainability reporting schemes of the chemical industry and relevant downstream sectors, respective external partners and independent bodies to facilitate sharing of lessons learned, and to identify steps towards increased coherence (along with transparency). This could facilitate collaboration in order to accelerate progress towards the sound management of chemicals and waste.

7.5 Potential measures to advance sustainability metrics and reporting

Private sector metrics and reporting are proliferating and have significant potential to complement existing mechanisms in a beyond 2020 framework. Nevertheless, further efforts may be needed to align approaches, ensure that reporting is meaningful, increase transparency, and address the lack of a common green/sustainable chemistry assessment framework. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to further advance sustainability metrics and reporting:

- Integrate chemicals and waste considerations into existing sustainability metrics and reporting systems, where needed, and ensure that all stages of the life cycle are covered.
- Explore the need for harmonized/aligned metrics and reporting standards at relevant levels (e.g. at the sectoral level), drawing on existing international standards.
- Scale up the use of sustainability reports in all chemical and downstream industries, including through use of harmonized methods and indicators at the relevant levels (e.g. sectoral).
- Ensure that reporting is carried out using quality standards, and use, where appropriate, external reviewers and independent certification.
- Bring together relevant stakeholders to advance a common understanding of metrics, including exploring potential elements of a practical guidance on sustainable chemistry.
- Encourage investors to systematically take into account sustainability reporting in their investment decisions.
- Consider ways that relevant metrics and reporting can play a more formal role in measuring progress in order to implement the 2020 goal for the sound management of chemicals and waste.

8/ Empowering and protecting citizens, workers and consumers

Chapter Highlights

Citizens play a key role in shaping demand for safer and more sustainable products, and in shaping relevant policies and action by governments and the private sector.

Providing workers, consumers and communities with access to chemical information is a requisite for implementing the public's right-to-know, and for ensuring effective public participation.

New information tools and mobile applications are available to engage citizens in collecting and processing knowledge relevant to chemicals and waste management.

Use of human rights laws may complement other legislation to advance the sound management of chemicals and waste, and to ensure protection or seek remedies.

Research and policy development within the framework of the Human Rights Council suggests that human rights violations have been caused by chemical pollution.

A number of leading chemical companies have embraced a human rights approach in advancing sustainability.

The management of chemicals and waste is complex and often highly technical. Specialists, including toxicologists and risk managers, are at the forefront of decision-making. Yet workers, consumers, citizens and institutional purchasers also have important roles to play in advancing sound chemicals and waste management. They can stimulate market transformation through their purchasing decisions, participate in decision-making and, when necessary, access the courts.

8.1 The role of citizens and consumers in shaping markets and policies

Consumer awareness can drive market transformation

Consumers can have a major impact through purchasing products with desirable environmental properties (OECD 2018). By means of their purchasing decisions, consumers are able to influence the chemical content and other characteristics of products placed on the market. While ethical-value products were once a niche with a small consumer base, mainstream consumer demand has been increasing for products associated with environmental and social responsibility and sustainability (Caruana and Chatzidakis 2014). Unilever, one of the world's largest consumer goods companies, reports that its sustainable brands (which it describes as combining "a strong purpose delivering a social or environmental benefit") grew 40 per cent faster than the rest of its business in 2016 (Hancock 2017).

Consumers weigh environmental, social and economic benefits when they shop for "green" products (Maniatis 2016). Other important factors include a consumer's green self-identity and peer influence (Khare 2015). Shopping decisions are also determined by the impacts they are likely to have in the future (Buerke *et al*. 2017). Women have a particularly influential role to play, as they control the large majority of consumer spending (Silverstein and Sayre 2009). When awareness of products' health and environmental impacts influences consumer choices, this suggests that information dissemination (and access to information) can lead to more responsible consumer behaviour (Scherer, Emberger-Klein and Menrad 2017).

The chemicals and waste dimension of consumer choices

Today consumers are more sensitive to environmental, social and ethical concerns than at any time in the past (BCG 2017). In East-Central Europe the health effects of chemicals have been ranked fourth among environmental concerns, with some one-third of the population interested in receiving more information about this topic (Luca *et al*. 2018). In many countries there has been a steady increase in the number of consumers concerned about health and wellness, as well as the short-term and long-term effects of chemicals in food (Deloitte, Food Marketing Institute and Grocery Manufacturers Association 2016; Nielsen 2016; International Food Information Council [IFIC] Foundation 2018). Food manufacturers, retailers and restaurant chains have responded to such concerns by reformulating products to eliminate the use of artificial colouring and flavouring, among other initiatives. However, redesigning products and marketing them can be a longer and far more expensive process than many consumers are aware of, while a newly introduced product

(or one with different ingredients) may not be popular with some traditional customers (Klara 2018).

In the IFIC Foundation's most recent annual Food and Health Survey, 59 per cent of respondents said it was important for the foods they purchase and consume to be produced in a sustainable way, compared with 50 per cent in 2017. The respondents also indicated that their two most important individual factors with respect to sustainability were reducing the use of pesticides, followed by ensuring an affordable food supply. In addition, when asked which sources of information most influenced their opinions on food safety issues, only 16 per cent of those aged 18 to 34 cited news articles or headlines, compared with 44 per cent of those aged 65 and older (IFIC Foundation 2018).

Understanding factors that affect consumer behaviour

Consumers in selected developing countries expressed greater concern about the environmental impact of their consumption patterns than did those in some higher-income countries (National Geographic and Globescan 2014). "Green" consumers in India were willing to support environmental protection and accept environmental responsibilities and were inclined to look for green product-related information (Kumar and Ghodeswar 2015). In many countries price is an important factor, even when there is a preference for green products (Drozdenko, Jensen and Coelho 2011; Biswas and Roy 2015; Hancock 2017). Pro-environmental attitudes are not automatically converted into green purchasing behaviour if this means paying a considerable premium or settling for poorer performance (Olson 2013). At the same time, economic benefits or efficacy issues normally outweigh social or environmental benefits in purchasing decisions (O'Rourke and Ringer 2016). Nevertheless, in a recent survey in the United States more than half of consumers said they would drive a greater distance (up to 14 miles) and pay more (up to 19 per cent) in order to shop at a "responsible store" (American Family Life Assurance Company of Columbus and American Family Life Assurance Company of New York 2017).

At a time of rapid environmental and social change, younger consumers are playing an important role in market transformation. According to a recent survey, 92 per cent of millennials are more likely to buy products from ethical companies, while 82 per cent believe ethical brands outperform those of similar companies that lack a commitment to ethical principles (Shewan 2017). Some companies have responded to consumer concerns by adopting better sustainability practices and transparency in their value and supply chains (BCG 2017; Unilever 2018). Behavioural insights can help policymakers obtain a better understanding of the behavioural mechanisms that contribute to environmental problems, and design and implement effective policy interventions to encourage more sustainable consumption, investment and compliance decisions by both individuals and firms. The policy areas in which behavioural sciences have been integrated include water and food consumption and waste management (OECD 2017).

According to a recent UNIDO report, while consumers are influenced by the medium- and long-term savings associated with the consumption of more energy-efficient products, they do not always shift their preferences to goods with a lower environmental footprint fast enough to decouple economic growth and environmental degradation. In that report three stages in the purchasing of an environmental good are identified: 1) consumers become aware of the environmental threat and are eager to help mitigate it through their consumption choices; 2) they obtain information about the impact of environmental goods on the environment; and 3) they buy the environmental good based on their pro-environment attitude and their trust that the good will deliver the expected environmental impact. However, at all three stages the following biases may affect consumer behaviour: too little public awareness about the seriousness of the impending environmental threat; lack of information about products, costs and, in some cases, potential savings; and perceptions that companies may make exaggerated claims or even lie about their products' environmental attributes (UNIDO 2017, pp. 19-20).

8.2 Procedural environmental rights: exploring the chemicals and waste dimension

To empower citizens, consumers, workers and the public, through informing them and engaging them in environmental actions, individual countries as well as several international bodies have promulgated a range of policy measures, also referred to as "procedural environmental rights" (Peters 2018). An early measure taken at the international level was the adoption of Principle 10 of the Rio Declaration at the UN Conference on Environment and Development in 1992. Principle 10 states that "Environmental issues are best handled with the participation of all concerned citizens, at the relevant level. At the national level, each individual shall have appropriate access to information concerning the environment that is held by public authorities, including information on hazardous materials and activities in their communities, and the opportunity to participate in decision-making processes. States shall facilitate and encourage public awareness and participation by making information widely available. Effective access to judicial and administrative proceedings, including redress and remedy, shall be provided."

The first treaty to address procedural environmental rights was the UNECE Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (or the Aarhus Convention), which entered into force in 2001. Most recently, the 2018 Regional Agreement on Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean (the Escazú Agreement) was adopted. Its purpose is to guarantee full and effective implementation of the rights of access to environmental information, public participation and access to justice in environmental matters. It is the first treaty in the world to include specific provisions to ensure a safe and enabling environment for environmental human rights defenders (UN 2018a). Although the scope of these agreements is broader in scope than

© Sasin Tipchai

chemicals and waste management, they support chemicals and waste management actions under topics such as labelling of chemicals, providing communities with data on chemical releases by major facilities in their vicinity, and accessing the courts when citizens' rights to a healthy environment have been violated.

8.3 Advancing sound management of chemicals and waste through the right-to-know

Sustainable Development Goal (SDG) Target 4.7 specifically aims to ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including through education for sustainable development and sustainable life styles, which will enable citizens to take informed decisions (UNESCO 2017). If citizens are to develop knowledge and make informed choices, the right-to-know about chemicals and waste is a key factor. It is also an important market mechanism. Several studies have shown that mandatory disclosure of information can have an impact on consumer behaviour and health (Mathios 2000).

Under the right to information, people have a right-to-know whether they are, or may be, exposed to hazardous chemicals. Right-to-know is essential in order to give effect to other rights, such as the right to participate in decision-making and policymaking, due process, and the right to an effective remedy. To realize the right to information, information about the potential impacts of substances must be available, accessible, functional and non-discriminatory (United Nations Special Rapporteur on Human Rights and Toxics [UN Special Rapporteur] 2016a).

International environmental agreements advancing right-to-know

A number of international chemicals and waste agreements have provisions to advance right-to-know. The Minamata Convention on Mercury is a recent expression of the principle that information about chemicals and hazards belongs in the public domain. It includes several provisions about access to information, public registries, environmental education and awareness, and public participation. It also provides that information relating to the health and safety of people and the environment shall not be considered confidential. The Minamata Convention is consistent with the Aarhus Convention, which specifically provides that commercial confidentiality cannot be used as grounds for refusal to disclose information about emissions to the environment. Negotiated through a multi-stakeholder process, the SAICM Overarching Policy Strategy (OPS) adopted in 2006 includes a range of provisions striking a balance between the disclosure of information and protecting legitimate, legally protected interests (Box 8.1).

The Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, which entered into force in 2004, also provides for the right-to-know through public awareness and outreach activities. Other relevant measures in the Convention include the prior informed consent (PIC) procedure, the need for export notifications for substances that are not listed to Annex III (providing parties with information on chemicals coming through their borders), as well as the requirements set out under Article 13 of the Convention, which require labelling (to ensure adequate availability of information with regard to risks and/or hazards to human health or the environment) and the inclusion of a safety data sheet (for occupational purposes).

Both the Aarhus Convention and the 2018 Escazú Agreement establish an enforceable right to access environmental information, including information on chemicals and waste management. Outside these two regions, there are general freedom of information acts in many countries with enforcement provisions in the spirit of Article 19 of the Universal Declaration of Human Rights ("Everyone has the right to freedom of opinion and expression; this right includes freedom to hold opinions without interference and to seek, receive and impart information and ideas through any media and regardless of frontiers.").

Box 8.1 Excerpts from paragraph 15 of the SAICM Overarching Policy Strategy (OPS) (UNEP 2015)

"The objectives of the Strategic Approach [to International Chemicals Management] with regard to knowledge and information are:

A. To ensure that knowledge and information on chemicals and chemicals management are sufficient to enable chemicals to be adequately assessed and managed safely throughout their life cycle;

B. To ensure, for all stakeholders:
   1. That information on chemicals throughout their life cycle, including, where appropriate, chemicals in products, is available, accessible, user-friendly, adequate and appropriate to the needs of all stakeholders. Appropriate types of information include their effects on human health and the environment, their intrinsic properties, their potential uses, their protective measures and regulation;
   2. That such information is disseminated in appropriate languages by making full use of, among other things, the media, hazard communication mechanisms such as the Globally Harmonized System of Classification and Labelling of Chemicals and relevant provisions of international agreements;

C. To ensure that, in making information available in accordance with paragraph 15 (b), confidential commercial and industrial information and knowledge are protected in accordance with national laws or regulations or, in the absence of such laws or and regulations, are protected in accordance with international provisions. In the context of this paragraph, information on chemicals relating to the health and safety of humans and the environment should not be regarded as confidential ...."

National and sub-national right-to-know

Laws around the world provide for public access to information held by public authorities. These laws can often be used to gain access to information about chemicals and waste management. Where countries do not have such provisions, they can adopt them pursuant to Guideline 15 in the UNEP Guidelines for the Development of National Legislation on Access to Information, Public Participation and Access to Justice in Environmental Matters (the Bali Guidelines), adopted by the UNEP Governing Council in 2010. Guideline 15 establishes that "States should ensure that any natural or legal person who considers that his or her request for environmental information has been unreasonably refused, in part or in full, inadequately answered or ignored, or in any other way not handled in accordance with applicable law, has access to a review procedure before a court of law or other independent and impartial body to challenge such a decision, act or omission by the public authority in question."

An example of right-to-know schemes advanced at the sub-national level is Proposition 65 (or the Safe Drinking Water and Toxic Enforcement Act of 1986), promulgated in the State of California in the United States (California Office of Environmental Health Hazard Assessment 2013). It requires businesses in California to provide warnings about significant exposures to chemicals in products, homes or workplaces, or those released to the environment, that cause cancer, birth defects and other types of reproductive harm. This enables people living in that state to make informed decisions about their exposures to these chemicals. Proposition 65 requires California to publish a list (updated once a year) of such chemicals. It has grown to include approximately 900 chemicals since it was first published in 1987.

Providing chemical product information: consumers' right-to-know

An example of consumers' right-to-know is a provision under the European REACH

(Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation. For substances of very high concern (SVHC) on a "candidate list", consumers have the right to receive information from the suppliers of an article about the presence of any SVHC in that article, and the supplier is obliged to provide the information within 45 days (Klaschka 2017). Box 8.2 describes the US EPA's Chemical Access Data Tool.

While initiatives like the one under REACH support consumers' right-to-know, some consumers may not be capable of using information about hazardous substances in products adequately, even if they have a high educational level. Consumers may also assume, wrongly, that products with eco-labelling, natural personal care products or products without hazard pictograms do not contain harmful substances. Organic food or untreated food, homeopathic medicines and natural personal care products may all contain harmful substances (Klaschka 2016; United States Food and Drug Administration 2017). An enhanced strategy to communicate chemical risks in consumer products may be thus warranted, including extensive participation by target groups. Furthermore, greater efforts by authorities and manufactures are important in building trust and providing easily understandable information (Hartmann and Klaschka 2017).

Providing chemical pollution information to the public: community right-to-know

Community right-to-know provisions help increase the public's knowledge and access to information on chemicals at individual facilities, as well as their uses and releases to the environment. These provisions allow public concerns to be addressed regarding environmental and safety hazards due to the storage, handling and emissions of toxic chemicals in the vicinity of industrial installations.

The public's right-to-know about chemicals and waste is greatly enhanced by the use of structured, accessible databases, such as Pollutant Release and Transfer Registers (PRTRs), which enable informed participation in environmental decision-making. PRTRs collect and provide information on chemicals released to the environment or otherwise managed as waste. They support the public's right-to-know and provide useful information for evaluating the performance of facilities, sectors and governments (Wine *et al.*

Box 8.2 **The US EPA's Chemical Access Data Tool (US EPA 2017)**

The Chemical Data Access Tool (CDAT) provides a range of chemical-specific information submitted to the United States Environmental Protection Agency (US EPA) under the Toxic Substances Control Act (TSCA). The CDAT enables searches of the following databases:

- The CDR database includes non-confidential information on the manufacture (including import), processing and use of chemicals reported under the Chemical Data Reporting (CDR) rule.
- The eDoc database includes a broad range of health and safety information reported by industry under TSCA Sections 4, 5, 8(d) and 8(e).
- The TSCA Test Submissions (TSCATS) database is an online index to unpublished, non-confidential studies covering chemical testing results and adverse effects of chemicals on health and ecological systems.
- The High Production Volume Information System (HPVIS) database provides access to health and environmental effects information obtained through the High Production Volume (HPV) Challenge.
- The declassified CBI database includes health and safety studies, and other information, submitted to the EPA in which chemical identities have been declassified as part of its effort to increase transparency in TSCA.

2014). An early example was the Toxics Release Inventory under the Emergency Planning and Community Right-to-Know Act in the United States.

Many countries, including in low- and middle-income regions, subsequently introduced PRTRs. Chile's PRTR, for example, contains accessible information through a website including a FAQ page in Spanish and English that explains the sources of air and water pollutants, their impact on health and how they can be avoided, among other information (Registro de Emisiones y Transferencias de Contaminantes n.d.). While China does not have a PRTR system in place, it established a set of Open Environmental Information measures in 2008 requiring local governments to disclose information on, among others, environmental laws and regulations; the allocation of emission quotas and permits; pollution fees and penalties collected; and lists of violators of environmental regulations. These measures have given citizens the ability to request information, leading to greater NGO participation in environmental governance (although with limited impact) (Tan 2014). Such initiatives could provide a good starting point for developing a PRTR or similar system.

The private sector also plays an important role in advancing communities' right-to-know. The ZDHC Group, for example, is a coalition of textile, leather and footwear industries and related chemical industry and other solution providers that supports the improvement of chemicals management and the development of publicly available indicators throughout the apparel and footwear supply chains to reduce discharges of hazardous chemicals to the environment. ZDHC member brands encourage their supply partners to proactively disclose PRTR information (ZDHC 2014; ZDHC 2018). Another important example is the Clean Electronics Production Network (CEPN) (Green America Center for Sustainability Solutions n.d. a; Green America Center for Sustainability Solutions n.d. b).

Workers' right-to-know

Workers' right-to-know refers to their right to information about chemicals in the workplace. The ILO Chemicals Convention of 1990 (No. 170) states that "workers have a need for, and right to, information about the chemicals they use at work" and includes specific obligations in this regard. Employers can use specific measures and tools such as labelling, hazard symbols, safety data sheets and training to inform workers about chemical hazards. The United States Occupational Safety and Health Administration (US OSHA) acknowledges workers' right-to-know about hazards present in the workplace and how to protect themselves (US OSHA 2016). In Canada all employees have a right-to-know what hazards are present on the job and how these hazards can affect them (Canadian Centre for Occupational Health and Safety 2018). In Europe workers' right-to-know about workplace hazards is managed by the European Agency for Safety and Health at Work (European Agency for Safety and Health at Work 2018).

Using the internet and apps to disseminate chemical information and knowledge

New information and communication technologies, such as mobile applications, are now available to help citizens, consumers and workers better understand the chemical composition of certain products and their potential exposure (Box 8.3). While these applications cannot replace a full risk assessment, many of them feature chemical hazard information, thus providing information about intrinsic properties of chemicals and/or information on chemicals subject to regulatory processes. This information allows users to consider a range of possible measures. For example, after a consumer using the Toxfox app sent a SVHC information request for a bicycle care set to the sporting goods manufacturer Decathlon, the company discontinued sales of the product, which contained the hazardous plasticizer Bis(2-ethylhexyl) phthalate (DEHP) (LIFE AskREACH 2018).

Box 8.3 Examples of mobile applications for disseminating chemical information

- ToxFox, a smartphone app by Friends of the Earth Germany, provides information about endocrine-disrupting chemicals in cosmetics and allows users to submit SVHC inquiries. It has a continuously growing database, in which suppliers' responses are saved. Suppliers can also enter data about the SVHC content of their articles (Klaschka 2017).
- The AskREACH mobile app, similar to ToxFox, is scheduled to be launched in April 2019. It will be available throughout Europe and may be adapted for use in each EU Member State (Lovell 2018).
- The Dirty Dozen app helps consumers determine which fruits and vegetables are best bought organic by identifying those with maximum pesticide residues. Another app for food is EWG's Healthy Living app, which allows users to scan a product, review its rating and buy the better, healthier choice (Sammons 2016).
- For cosmetics and personal care products, apps such as Cosmetifique and Think Dirty allow consumers to make better beauty choices by listing potentially toxic ingredients when they scan a product and even to find cleaner alternatives to toxic products (Sammons 2016).
- GoodGuide provides consumers with product information to help guide more informed buying decisions. Products are assessed by a team of over 50 scientific and regulatory professionals with expertise in chemicals and chemical-containing products. The team includes chemists, toxicologists, and life cycle assessment and regulatory experts (GoodGuide 2019).

While these apps are evolving, information is still scattered and it may not be easy to find comprehensive information. A user-friendly, central coordinated information hub could be helpful in raising awareness and enabling citizens to easily find comprehensive information from scatted sources.

Figure 8.1 DOZN scoring example (adapted from Sigma-Aldrich 2018)

Beta-amylase

Principe	% improvements	Remarks
1. Waste prevention	55	Eliminated organic solvent usage and reduced overall waste generation by 50%
2. Atom economy	52	Increased yields and reduced amount of raw materials used
3. Less hazardous synthesis	96	Replaced organic solvents with water-based solutions and removes toxic filtering agents
5. Safer solvents	100	Eliminated all organic solvent usage
6. Energy efficiency	100	New process eliminated need for elevated temperature and pressure
7. Renewable feedstock	71	More efficient environmental impact with new procedure
10. Design for degradation	No change	No increased environmental impact with new practice
12. Accident prevention	54	Eliminated flammability and reactivity dangers
Total	**95%**	

Aggregate score	Previous process	Re-engineered process	**Scoring matrix** (0 = most desirable)
	43	2	100 … 0

DOZN (Quantitative Green Chemistry Evaluator) is an interactive web-based scoring matrix based on the 12 Principles of Green Chemistry which allows users to calculate the relative greenness of chemical products and processes (ACS Green Chemistry Institute 2017).

8.4 Public participation in chemicals and waste management

International agreements, statutory legislation and public bodies around the world are providing the public with rights and opportunities to contribute to and participate in decision-making related to the environment, including with respect to chemicals and waste management. The requirement to assess the environmental impacts of a proposed project as part of a permitting process has become a global standard. As part of this assessment, it is generally considered necessary to provide for public participation. The UNECE Convention on Environmental Impact Assessment in a Transboundary Context (the Espoo Convention), which entered into force in 1997, and the UNECE Aarhus Convention together establish a good international standard for public participation in environmental decision-making.

Public participation in chemicals management

The European Chemicals Agency, for example, organizes public consultations to obtain feedback from interested parties and gather the widest possible range of scientific information for regulatory processes. This includes public consultations for making the final decision on which substances cannot be placed on the market, or used after a given date, unless they meet specific authorization requirements (ECHA 2018). The US EPA has public participation processes for certain pesticide registration actions as part of its Pesticide Program, providing an opportunity for the public to comment on risk assessments and proposed registration actions (US EPA 2018). In China citizens increasingly make use of information communication technologies, such as social media and blogging websites, to further citizen participation in environmental sustainability initiatives and influence governmental decision-making (He *et al.* 2017). In Canada, under the Chemicals Management Plan, there are opportunities for the public and interested stakeholders to provide comments and relevant information on risk assessments and risk management measures (regulations, pollution prevention planning notices, codes of practice and guidelines) developed under the Canadian Environmental Protection Act, 1999

(Government of Canada 2016; Government of Canada 2017).

Public participation in private sector initiatives is important and evolving. Under the International Council of Chemical Associations (ICCA) Responsible Care® programme, senior executives of member organizations sign the Responsible Care® Global Charter, which is a public commitment to sound chemicals management globally through enhancing the organization's environmental, health, safety and security performance. Through the Global Charter organizations also commit to engage stakeholders along the value chain and within their communities. In addition, members commit to respond to community concerns about operations and chemicals; report information on relevant chemical-related health or environmental hazards promptly to appropriate authorities, employees, customers and any affected sectors of the public, as well as recommending protective measures; and increase knowledge through conducting and supporting relevant research on the safety, health and environmental effects of products, processes and waste materials, among others (ICCA 2015; Chemical & Allied Industries' Association 2017).

Initiatives triggered from within civil society are an important aspect of public participation. In 2015, for example, NGOs from 15 countries convened and developed the Chemical Challenge to the Global Electronics Industry (GoodElectronics 2015). More than 200 civil society groups and activists from electronics production countries and from across the globe challenged the electronics industry to improve its actions on chemicals management during the production process. In response, leading electronics companies are now working with NGOs in the Clean Electronics Production Network (CEPN) with the goal of eliminating workers exposures to hazardous chemicals.

Use of social media to advance public participation

Social media have become platforms where consumers, end users and NGOs can share information about how a product is manufactured and sold, as well as the materials and chemicals used in the product or during its manufacture. On Facebook and LinkedIn a number of groups share views and information on toxic chemicals and sustainable chemistry. As major users of social media, 61 per cent of millennials think social media is the "new power of youth" and 70 per cent consider it a force for change (Euro RSCG Worldwide 2011). With the rise of "complaint-vertising" it has also become common for users to make their complaints known on social media, and these complaints may go viral (Eisenhardt 2015). Companies have struggled with the right way to respond to complaint-vertising; social media are therefore steering companies towards sound management of chemicals that goes beyond compliance (Sanders 2017).

As participants in environmental governance, citizens may exchange information, especially in the Information Age. Through direct communication they can extend their influence towards shaping policies (Soma *et al*. 2016). An example of social media supporting chemical risk management actions is the banning of plastic microbeads in various products. In the United States, for example, after it emerged through social media that 8 trillion microbeads entered aquatic habitats in that country per day, public support for a ban on microbeads grew, leading to prohibition of the selling and distribution of products containing them (Imam 2015). Similarly, through a social media campaign 385,000 people signed a petition by Greenpeace urging the United Kingdom (UK) Government to ban microbeads (Casson 2017), leading to a ban on microplastics in that country (Carrington 2018). More broadly, NGOs in more than 30 countries worked on or helped to pass legislation to ban microbeads in personal care products using social media (Rochman *et al.* 2015), motivating cosmetic companies to use alternatives (Conick 2018).

Participation by citizens and workers in scientific knowledge generation

"Citizen science", sometimes also referred to as "community science" or "public participation in scientific research", is a growing movement that enlists the public in scientific discovery, monitoring and experimentation across a wide range of disciplines (Theobald *et al.* 2015). There is growing evidence that citizen science projects can achieve gains in knowledge and increase public awareness of the diversity of scientific research (Bonney *et al.* 2016). One concern about citizen science projects is data quality; however, it has been shown that participants can provide accurate and complete information as long as scientists have a sufficiently flexible or inclusive view of a citizen scientist's role (Wiersma, Parsons and Lukyanenko 2016).

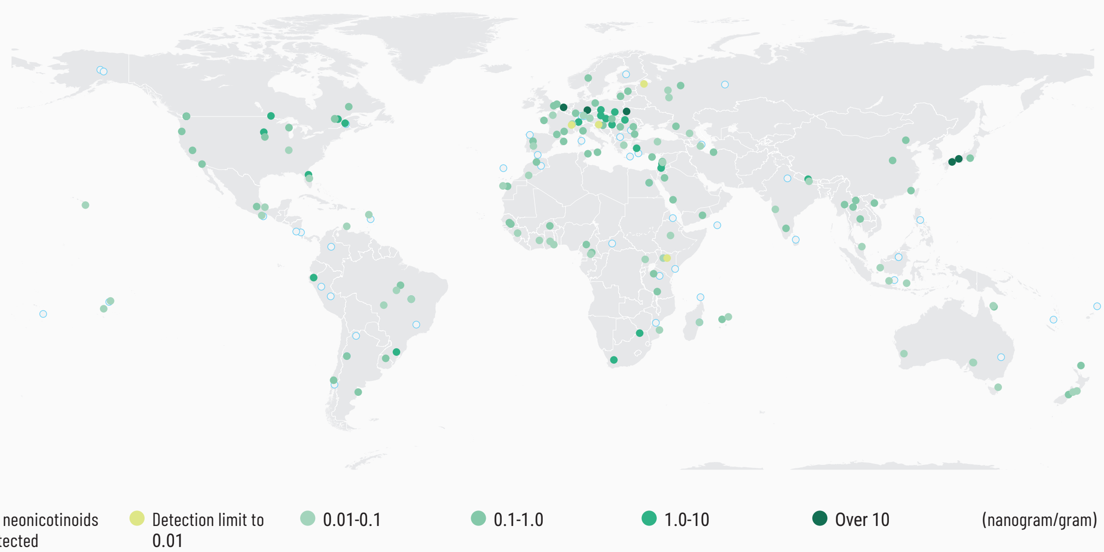
As a part of a citizen science project to monitor concentrations of neonicotinoids in honey, researchers in Switzerland analyzed honey brought back by travellers from various world regions (Mitchell *et al.* 2017) (Figure 8.2). The International Coastal Cleanup is another example of a citizen science project. Volunteers around the world collect debris from local beaches and tally it using the Ocean Conservancy's standardized data format (Zettler *et al.* 2016). A collaborative effort between researchers at Washington State University in the United States and a small town is an example of community involvement in waste management research and decision-making (Youngquist *et al.* 2015). In Contra Costa County, California, citizens used low-cost air monitoring technology based on the use of inexpensive plastic buckets to measure emissions from a local petroleum refinery in view of lack of support from the US EPA. Similar citizen action groups have used these buckets to collect and validate data about exposures, and the buckets have been approved as a reliable source of data for exposures (Joyce and Senier 2017).

Workers, too, can contribute to data collection. Based on data collected from silicone-based wristband passive samplers worn by fire fighters, a study revealed that the fire fighters could be exposed to VOCs and risk management was undertaken (Santiago *et al.* 2018). Real-time toxic gas detection during working hours may be carried out using a smartphone coupled hand-held array reader. Signals from a colorimetric reader can be transferred to a smartphone, where an app displays the detected toxic gases and their exposure levels (Devadhasan *et al.* 2017).

8.5 Access to justice in chemicals and waste management

Access to justice is a basic principle of the rule of law. In the absence of access to justice, people are unable to make their voices heard,

Figure 8.2 **Citizen science project to monitor the concentration of neonicotinoids in honey, November 2012 and February 2016 (adapted from Mitchell *et al.* 2017, p. 110)**



exercise their rights, challenge discrimination or hold decision-makers accountable (UN 2018b). Access to justice helps ensure public authorities' accountability to the public. It also provides the public with assured final recourse to justice with a view to ensuring correct implementation of environmental law (Pan-European Coalition of Environmental Citizens Organisations 2016).

Under Article 9.1 of the Aarhus Convention, Parties have agreed on standards for access to justice in respect to information requests. For example, a person does not need to show an interest in the information requested in order to have standing to challenge a refusal to provide the information in whole or in part. The Convention is also concerned with matters of judicial administration, including costs, fairness and timeliness. Similarly, members of the public whose rights to participate in environmental decision-making are not respected have the option to seek access to justice under Article 9.2 of the Aarhus Convention. The same principle is expressed in the UNEP Bali Guidelines (Guideline 16) as follows: "States should ensure that the members of the public concerned have access to a court of law or other independent and impartial body to challenge the substantive and procedural legality of any decision, act or omission relating to public participation in decision-making in environmental matters."

Access to justice in matters of law enforcement

Public concern about the environment, human health and exposure to chemicals, and other hazards and risks, can be harnessed to help public authorities enforce environmental laws. This role is contained within the Aarhus Convention (Article 9.3), the Escazú Agreement (Article 8.2(c)) and the Bali Guidelines (Guideline 17). Such provisions give the public opportunities to meet their duty to protect and improve the environment for the benefit of present and future generations, as recognized in Principle 1 of the Declaration of the United Nations Conference on the Human Environment, agreed in Stockholm in 1972. For example, in 2015 China amended its Environmental Protection Law to allow any duly registered NGO that had been engaged in

environmental protection activities for at least five consecutive years to initiate public interest environmental litigation. Before this amendment went into effect there were as few as eight cases a year, but since 2015 there have been over 117 public interest environmental cases (UNEP 2018).

Standing requirements to access courts

Countries are increasingly recognizing the standing of environmental civil society organizations to bring cases in the public interest aimed at protecting human health and the environment. Most legal systems have required that members of the public challenging such decisions meet certain standing requirements, expressed as the "public concerned." However, there is a trend towards eliminating formal requirements such as those related to the registration of organizations or of the organizations' purposes. For example, Mexico now recognizes "collective actions" by social groups that may not be legally registered (UNEP 2015). In California, Proposition 65 (the Safe Drinking Water and Toxic Enforcement Act of 1986) provides citizen standing to sue. Any individual acting in the public interest may enforce Proposition 65 by filing a lawsuit against a business alleged to be in violation of it (California Office of Environmental Health Hazard Assessment 2013). Under the Aarhus Convention, certain established environmental NGOs should be granted standing to challenge decisions even when they would not meet the strict legal interest test under some legal systems. On the other hand, under United States jurisprudence an organization must have suffered an "injury in fact" to have standing to challenge a government decision.

Science in judicial proceedings

Judicial systems around the world have addressed the challenges presented by complex scientific considerations in environmental cases by establishing specialized courts. To expand and deepen systems of access to remedy in India, the Green Tribunal Act was passed in 2010. This Act stemmed from the 1996 *Indian Council for EnviroLegal Action v. Union of India* case, where the court stated that a system of green tribunals with jurisdiction over civil and criminal aspects of environmental claims could help achieve expediency of justice, establish panels of experts to resolve highly technical cases, and help reduce large caseloads (UNDP 2014). Other prominent examples of specialized environmental courts may be found in Australia, Chile, Kenya, Pakistan and the Philippines. Altogether at least 44 countries have some form of environmental court. The Escazú Agreement includes a reference to shifting the burden of proof in certain cases where chemicals and hazardous wastes could be involved. Article 8.3(e) refers to "measures to facilitate the production of evidence of environmental damage, when appropriate and as applicable, such as the reversal of the burden of proof and the dynamic burden of proof."

8.6 Human rights law with respect to chemicals and waste management

Linkages to a range of human rights

The use of human rights-based approaches complements and provides a back-up to legislative and regulatory measures in ensuring protection and access to effective remedies. Hazardous substances and wastes, including toxic chemicals, are associated with a broad range of civil, cultural, economic, political and social rights. Under a number of international human rights instruments, countries have a duty to protect human rights, including those threatened by the presence of hazardous chemicals and waste (UN Special Rapporteur 2016b). Every country has recognized one or more human rights that are directly or indirectly implicated by the management of chemicals and waste. For example, virtually every country has ratified the UN Convention on the Rights of the Child, which recognizes the right of the child to the highest attainable standard of health and requires that states shall take appropriate measures to combat disease and malnutrition, taking into consideration the dangers and risks of environmental pollution.

The right-to-know about possible exposures to chemicals and hazardous wastes has also been guaranteed through human rights instruments. An example is the European Convention on Human Rights, Article 8, which provides for respect for one's "private and family life, his home and his correspondence." In *Guerra v. Italy* the Court interpreted Article 8 in a case where authorities had failed to provide information about the risks associated with a chemical factory or about emergency procedures. It affirmed that severe environmental pollution could interfere with the right to respect for home, private life and family and held that the authorities had not taken the necessary measures to ensure effective protection of this right by providing essential information. A similar result was reached in the Inter-American Court of Human Rights in the case of *Claude-Reyes v. Chile.* In interpreting Article 13 of the American Convention on Human Rights, which addresses the right to freedom of expression (Inter-American Commission on Human Rights 2011), the Court held that this right includes the right of the public to have access to State-held information, as well as the State's obligation to provide the information subject to limited exceptions. Thus, the failure of a State body to disclose information on environmental matters requested by an NGO violates Article 13 of the American Convention on Human Rights.

The right to a healthy environment

A large majority of UN Member States have constitutional provisions that include the right to a healthy environment in some form, which can be considered an economic, social or cultural right.

As elaborated in Stockholm Principle 1 adopted in 1972, the natural environment is essential to the enjoyment of basic human rights and the right to life itself. Violations of environmental rights may have a profound impact in regard to a wide variety of human rights, including those to life, self-determination, food, water, health, sanitation, housing, and other cultural, civil and political rights.

Enforcing such rights has traditionally presented challenges, but recently certain developments in international jurisprudence have clarified that they are capable of direct enforcement (Box 8.4).

Box 8.4 Cases of human rights protection in matters of chemicals and waste

The use of environmental rights and human rights to obtain protection or seek remedies related to chemicals and waste is widespread. Examples include:

- In Mexico, the Comisión Nacional de los Derechos Humanos (CNDH) issued a number of recommendations related to environmental protection even before the right to a healthy environment was included in the Mexican Constitution in 2012. In 2010 CNDH found that the National Water Commission did not comply with environmental standards, which caused the death of a child and affected the health of people living in the vicinity of the Santiago River. It recommended that the National Water Commission warn residents of the risk of pollution and take steps to clean up and restore the affected areas (Environmental Rights Database [ERDb] n.d. a).

- The Supreme Court of India has been active in protecting the right to life from environmental degradation. It ordered the closing down of limestone quarries and mining operations, among others, to protect citizens' right to life (ERDb n.d. b).

- In the United Kingdom, the Trafigura waste dumping case is an example of justice successfully accessed for crimes committed abroad. A group action by approximately 30,000 claimants from Côte d'Ivoire against Trafigura Ltd. was heard by the High Court of Justice in London in 2006. In 2009 the parties reached a settlement, with Trafigura agreeing to pay each claimant approximately US dollars 1,500 (A/HRC/36/41/Add.1).

A recent case is *Lagos del Campo v. Peru* of 2017 in the Inter-American Court of Human Rights, the first decision of that court which recognized the direct enforceability of economic, social or cultural rights. In this case the subject right was the right to work (International Network for Economic, Social & Cultural Rights 2018). Even in federal systems where there is no such right at the constitutional level, many constituent states, provinces or republics establish such rights in their own laws.

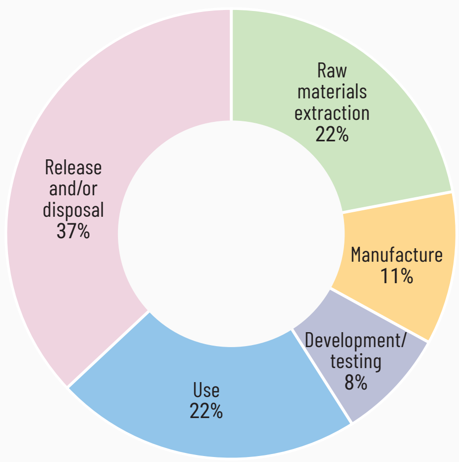
UN Human Rights Council initiatives and appointments

Since 1995 the Commission on Human Rights and its successor, the Human Rights Council (HRC), have mandated a Special Rapporteur to report on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes. While the Commission on Human Rights mandate in 1995 covered waste, the HRC expanded the mandate in 2011 and appointed a UN Special Rapporteur on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes. The mandate includes monitoring and reporting on the human rights impacts of such substances throughout their life cycle, including production, management, handling, distribution and final disposal.

In 2011 the HRC affirmed "that the way hazardous substances and wastes are managed throughout their lifecycle, including manufacturing, distribution, use and final disposal, may have an adverse impact on the full enjoyment of human rights". Similarly, the Special Rapporteur has emphasized that the right to information on hazardous substances and wastes is central to the enjoyment of human rights and fundamental freedoms. He also makes the case that information should be available, accessible and functional for everyone, consistent with the principle of non-discrimination (United Nations Human Rights Council [UN HRC] 2015; Office of the United Nations High Commissioner for Human Rights 2018).

Research recently undertaken within the mandate of the Special Rapporteur suggests that human rights violations and abuses caused by chemical pollution are still prevalent. A UK-based non-profit, the Business & Human Rights Resource Centre (BHRRC), has collaborated with the UN Special Rapporteur to analyze trends concerning alleged cases of human rights abuse relating to the chemical industry, along with responses by States and companies. The analysis notes that despite positive steps to address toxic pollution from the chemical industry, critical gaps remain, particularly in protecting the rights of workers, children, low-income communities and other vulnerable groups. Figure 8.3 shows human rights impacts by life cycle stage, as identified

Figure 8.3 Human rights impacts by life cycle stage, information received between 2012-2017 (adapted from BHRRC 2018, p. 3)



in the report. It concludes by recommending that States and businesses strengthen chemical industry regulations and practices in line with human rights standards (BHRRC 2018).

In an August 2018 report to the HRC, the Special Rapporteur recommended that "States must ensure that legislation and other practices reflect their duty to respect, protect and fulfil human rights obligations implicated by hazardous substances and wastes [...] [and] that victims of the effects of hazardous substances and wastes have access to an effective remedy", further noting that "the right to information is critical in the context of toxics". This report sets out findings from four years of monitoring in industries and countries around the world, with a focus on the situation of workers exposed to toxic and otherwise hazardous substances worldwide. It argues that many companies and national governments are not meeting their duty to uphold the rights of workers under the Universal Declaration of Human Rights and the International Covenant on Economic, Social and Cultural Rights. These stipulate the right to safe and healthy working conditions.

The report proposes 15 principles which are relevant to strengthening chemicals and waste management beyond 2020. They aim at helping governments and businesses ensure protection from exposure to hazardous chemicals, which the Special Rapporteur referred to as a global health crisis. The proposed principles broadly cover the responsibilities and duties of businesses and governments; worker access to information; and "remedies" to hold those who violate workers' rights accountable (UN HRC 2018). A subsequent report in October 2018 explored opportunities to further integrate the human rights dimension of chemicals and waste into the beyond 2020 framework.

Corporate responsibility, accountability and human rights

The role of corporations in achieving sustainability was recognized as long ago as the World Commission on Environment and Development report *Our Common Future*, published in 1987. The corporate sustainability or corporate social responsibility movement has proceeded through various certification schemes, membership organizations, guidelines and standards, such as the ISO 26000 standards for corporate social responsibility, the Global Reporting Initiative, the Equator Principles and the UN Global Compact. In parallel, critics of the voluntary approach have advocated for the adoption of binding norms governing corporate behaviour with social and environmental impacts, largely under the rubric of corporate accountability (Antypas and Paszkiewicz 2015).

In 2008 the UN Human Rights Council adopted the UN Protect, Respect and Remedy Framework for Business and Human Rights, commonly known as "the Ruggie Framework" after the UN Special Rapporteur, Professor John Ruggie. This framework expresses the global standard of expected corporate conduct and provides the baseline for corporate responsibility with respect to human rights as "part of the company's social license to operate". It centres on three "differentiated but complementary" pillars of responsibility: the State's duty to protect against human rights abuses by third parties (including business); corporate responsibility to protect human rights; and the need for more effective access to remedies.

The Ruggie Framework was followed by the endorsement in 2011 of the UN's Guiding Principles on Business and Human Rights (Antypas and Paszkiewicz 2015). The international community indicated its commitment to these Guiding Principles through the UN General Assembly's adoption of the 2030 Agenda for Sustainable Development in 2015. In response to the adoption of these Guiding Principles, major chemical companies such as BASF and Merck have committed to protect human rights (Merck 2017; BASF 2018). Important steps companies may take to prevent and address human rights impacts related to their production and products include the use of a life cycle approach. Hence, everyone in the entire chain of a product's life cycle has a responsibility to consider the environmental, social and economic impacts of a product at every stage of its life cycle (BHRRC 2018).

8.7 Potential measures to empower and protect citizens, workers and consumers

The roles of citizens and consumers in advancing the sound management of chemicals and waste are crucial. Enabling policies, including the right-to-know of workers, consumers and communities, public participation, and access to justice, coupled with innovative technologies, can reap the full potential of citizens to engage and protect their rights to a healthy environment. Taking into account the preceding analysis, stakeholders may wish to consider the following measures to empower and protect workers, consumers and citizens:

- Take steps so that consumers have appropriate knowledge concerning chemicals in products in order to make informed decisions, including through innovative technology applications.
- Develop and strengthen worker, consumer and community right-to-know policies and laws, and ensure that relevant and complete information concerning hazards and possible exposures to chemicals is made available.
- Engage citizens and the public in collecting data relevant for scientific chemical analysis and effective chemicals risk management policies.
- Consider stricter regulation that requires clear and consumer-friendly advice for using harmful products in a safe way.
- Initiate corporate campaigns, multi-stakeholder collaborations, and working with socially responsible investors.
- Ensure that citizens can access the courts in matters of chemical pollution and human health protection related to chemicals and waste.
- Encourage all chemical companies to embrace the UN Guiding Principles on Business and Human Rights.

References

Chapter 1

Abraham, M.A. and Nguyen, N. (2003). 'Green engineering: defining the principles'- results from the Sandestin conference. *Environmental Progress* 22(4), 233-236. https://doi.org/10.1002/ep.670220410.

American Chemical Society (2019). History of green chemistry. https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/history-of-green-chemistry.html. Accessed 21 February 2019.

American Sustainable Business Council and Green Chemistry & Commerce Council (2015). *Making the Business & Economic Case for Safer Chemistry*. http://asbcouncil.org/sites/default/files/asbcsaferchemicalsreportpresred.pdf.

Anastas, P.T. and Warner, J.C. (1998). *Green Chemistry: Theory and Practice*. Oxford University Press. https://global.oup.com/academic/product/green-chemistry-theory-and-practice-9780198506980?cc=ch&lang=en&.

Anastas, P.T. and Zimmerman, J.B. (2003). Design through the 12 Principles of Green Engineering: sustainability requires objectives at the molecular, product, process, and system levels. *Environmental Science & Technology* 37(5), 94A-101A. https://doi.org/10.1021/es032373g.

Anastas, P.T. and Zimmerman, J.B. (2018). The United Nations sustainability goals: how can sustainable chemistry contribute? *Current Opinion in Green and Sustainable Chemistry* 13, 150-153. https://doi.org/10.1016/j.cogsc.2018.04.017.

BCC Research (2016). Global concerns promoting growth of 'green' chemistry markets, reports BCC Research, 4 April. *Markertwired*. http://www.marketwired.com/press-release/global-concerns-promoting-growth-of-green-chemistry-markets-reports-bcc-research-2111318.htm. Accessed 3 June 2018.

Bernick, L. (2016). The $100 billion business case for safer chemistry, 6 May. *Greenbiz*. https://www.greenbiz.com/article/100-billion-business-case-safer-chemistry. Accessed 30 January 2019.

Bhattacharjee, N. and Swamynathan, Y. (2017). Chemical giants see growth in green, clean tech, 27 July. *Reuters*. https://www.reuters.com/article/us-dupont-results-health-idUSKBN1AC2ZP. Accessed 6 August 2018.

Blum, C., Bunke, D., Hungsberg, M., Roelofs, E., Joas, A., Joas, R., Blepp, M. and Stolzenberg, H.-C. (2017). The concept of sustainable chemistry: key drivers for the transition towards sustainable development. *Sustainable Chemistry and Pharmacy* 5, 94-104. https://doi.org/10.1016/j.scp.2017.01.001.

Cayuela, R. and Hagan, A. (2019). *The Chemical Industry Under the 4th Industrial Revolution: The Sustainable, Digital and Citizens One*. Not yet published. Hoboken, NJ: Wiley-VCH Verlag GmbH.

Cisco (2017). Industry 4.0: 11 questions answered, 1 September. *Cisco Canada Blog*. https://gblogs.cisco.com/ca/2017/09/01/industry-4-0-11-questions-answered/. Accessed 3 December 2018.

Clark, J.H. (2006). Green chemistry: today (and tomorrow). *Green Chemistry* 8(1), 17-21. https://doi.org/10.1039/b516637n.

Deloitte and German Chemical Industry Association (2017). *Chemistry 4.0: Growth through Innovation in a Transforming World*. https://www2.deloitte.com/content/dam/Deloitte/global/Documents/consumer-industrial-products/gx-chemistry%204.0-full-report.pdf.

Erythropel, H.C., Zimmerman, J.B., de Winter, T.M., Petitjean, L., Melnikov, F., Lam, C.H., Lounsbury, A.W., Mellor, K.E., Janković, N.Z., Tu, Q., Pincus, L.N., Falinski, M.M., Shi, W., Coish, P., Plata, D.L. and Anastas, P.T (2018). The green ChemisTREE: 20 years after taking root with the 12 principles. *Green Chemistry* 20(9), 1929-1961. https://doi.org/10.1039/c8gc00482j.

European Commission (1996). Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control. *Official Journal of the European Comminities* L(257), 26-40. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.1996.257.01.0026.01.ENG&toc=OJ:L:1996:257:TOC.

European Commission (2017). *Germany: Industrie 4.0*. https://ec.europa.eu/growth/tools-databases/dem/monitor/sites/default/files/DTM_Industrie%204.0.pdf.

German Environment Agency (2016). Sustainable chemistry: what is sustainable chemistry? 3 May. https://www.umweltbundesamt.de/en/topics/chemicals/chemicals-management/sustainable-chemistry#textpart-1. Accessed 19 February 2019.

Hill, J., Kumar, D.D. and Verma, R.K. (2013). Challenges for chemical education: engaging with green chemistry and environmental sustainability. *Journal of the American Institute of Chemists* 86(1), 24-31. http://www.theaic.org/pub_thechemist_journals/Vol-86-No-1/Vol-86-No1-Article-5.pdf.

Jakobsen, S., Naik, K., Raberger, N. and Winkler, G. (2017). Demystifying digital marketing and sales in the chemical industry, February. *McKinsey*. https://www.mckinsey.com/industries/chemicals/our-insights/demystifying-digital-marketing-and-sales-in-the-chemical-industry. Accessed 16 September 2018.

Kirkpatrick, P. and Ellis, C. (2004). Chemical space. *Nature* 432(7019), 823-823. https://doi.org/10.1038/432823a.

Klei, A., Moder, M., Stockdale, O., Weihe, U. and Winkler, G. (2017). Digital in chemicals: from technology to impact, July. *McKinsey & Company*. https://www.mckinsey.com/industries/chemicals/our-insights/digital-in-chemicals-from-technology-to-impact. Accessed 20 September 2018.

Kümmerer, K. (2017). Sustainable chemistry: a future guiding principle. *Angewandte Chemie International Edition* 56(52), 16420-16421. https://doi.org/10.1002/anie.201709949.

Linthorst, J.A. (2010). An overview: origins and development of green chemistry. *Foundations of Chemistry* 12(1), 55-68. https://doi.org/10.1007/s10698-009-9079-4.

Mubofu, E.B. (2016). Castor oil as a potential renewable resource for the production of functional materials. *Sustainable Chemical Processes* 4(1), 11. https://doi.org/10.1186/s40508-016-0055-8.

Organisation for Economic Co-operation and Development (2012). *The Role of Government Policy in Supporting the Adoption of Green/Sustainable Chemistry Innovations*. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2012)3&doclanguage=en.

Organisation for Economic Co-operation and Development (2018). Sustainable chemistry. http://www.oecd.org/chemicalsafety/risk-management/sustainablechemistry.htm. Accessed 20 February 2019.

Philp, J.C., Ritchie, R.J. and Allan, J.E.M. (2013). Biobased chemicals: the convergence of green chemistry with industrial biotechnology. *Trends in Biotechnology* 31(4), 219-222. https://doi.org/10.1016/j.tibtech.2012.12.007.

Pike Research (2011). Green chemistry: biobased chemicals, renewable feedstocks, green polymers, less-toxic alternative chemical formulations, and the foundations of a sustainable chemical industry. *Industrial Biotechnology* 7(6), 431-433. https://doi.org/10.1089/ind.2011.1003.

Sarathy, V., Gotpagar, J. and Morawietz, M. (2017). The next wave of innovation in the chemicals industry, 5 June. *Strategy+Business*. https://www.strategy-business.com/article/The-Next-Wave-of-Innovation-in-the-Chemicals-Industry.

Sheldon, R.A. (2008). Green and sustainable chemistry: challenges and perspectives. *Green Chemistry* 10(4), 359-360. https://doi.org/10.1039/b804163f.

Stieger, G. (2015). Popcorn without fluorinated chemicals: retailer coop denmark introduces microwave oven popcorn containing no fluorinated substances in the food packaging, aims to phase out further chemicals of concern by 2017, 30 October. *Food Packaging Forum*. https://www.foodpackagingforum.org/news/popcorn-without-fluorinated-chemicals. Accessed 14 September 2018.

United Nations Environment Programme (2019). *Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution 2/7*. http://www.saicm.org/Portals/12/Documents/meetings/OEWG3/inf/OEWG3-INF-22-Analysis.pdf.

United States Government Accountability Office (2018). *Chemical Innovation: Technologies to Make Processes and Products More Sustainable*. https://www.gao.gov/products/GAO-18-307.

World Economic Forum (2017). *Digital Transformation Initiative: Chemistry and Advanced Materials Industry*. http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/dti-chemistry-and-advanced-materials-industry-white-paper.pdf.

Zuin, V.G. (2016). Circularity in green chemical products, processes and services: innovative routes based on integrated eco-design and solution systems. *Current Opinion in Green and Sustainable Chemistry* 2, 40-44. https://doi.org/10.1016/j.cogsc.2016.09.008.

Chapter 2

American Chemical Society (2019a). Green chemistry: history. https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/history-of-green-chemistry.html. Accessed 21 February 2019.

American Chemical Society (2019b.). 12 Design Principles of Green Chemistry. https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/principles/12-principles-of-green-chemistry.html. Accessed 21 February 2019.

American Chemical Society (2019c). Green chemistry: education roadmap. https://www.acs.org/content/acs/en/greenchemistry/students-educators/education-roadmap.html. Accessed 21 February 2019.

Anastas, N.D. (2015). Embedding toxicology into the chemistry curriculum. In *Worldwide Trends in Green Chemistry Education*. Zuin, V.G. and Mammino, L. (eds.). Cambridge: Royal Society of Chemistry. Chapter 9. 137-156. https://doi.org/10.1039/9781782621942-00137.

Armstrong, L.B., Rivas, M.C., Douskey, M.C. and Baranger, A.M. (2018). Teaching students the complexity of green chemistry and assessing growth in attitudes and understanding. *Current Opinion in Green and Sustainable Chemistry* 13, 61-67. http://doi.org/10.1016/j.cogsc.2018.03.008.

Aubrecht, K.B., Padwa, L., Shen, X. and Bazargan, G. (2015). Development and implementation of a series of laboratory field trips for advanced high school students to connect chemistry to sustainability. *Journal Chemical Education* 92(4), 631-637. http://doi.org/10.1021/ed500630f.

Barra, R. and González, P. (2018). Sustainable chemistry challenges from a developing country perspective: education, plastic pollution, and beyond. *Current Opinion in Green and Sustainable Chemistry* 9, 40-44. http://doi.org/10.1016/j.cogsc.2017.12.001.

Beyond Benign (2019). Green chemistry education. https://www.beyondbenign.org/. Accessed 21 February 2019.

Burmeister M. and Eilks I. (2012). An example of learning about plastics and their evaluation as a contribution to education for sustainable development in secondary school chemistry teaching, *Chemistry Education Research and Practice* 13(2), 59-68. http://doi.org/10.1039/c1rp90067f.

Cannon, A.S. Finster, D. Raynie, D. and Warner, J.C. (2017). Models for integrating toxicology concepts into chemistry courses and programs. *Green Chemistry Letters and Reviews* 10(4), 436-443. https://doi.org/10.1080/17518253.2017.1391880.

Centi, G. and Perathoner, S. (2009) From green to sustainable industrial chemistry. In *Sustainable Industrial Processes*. Cavani, F., Centi, G., Perathoner, S. and Trifiró, F. (eds.). Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA. Chapter 1. 1-72. https://doi.org/10.1002/9783527629114.ch1.

CHEM21 (n.d.). Pharmaceuticals and universities working together on multi million pound project. https://www.chem21.eu/. Accessed 21 February 2019.

Clarivate (2018). ISI Web of Science. www.webofknowledge.com. Accessed 13 September 2018.

Clark, J.H. (2016). Green and sustainable chemistry: an introduction. In *Green and Sustainable Medicinal Chemistry: Methods, Tools and Strategies for the 21st Century Pharmaceutical Industry*. London: The Royal Society of Chemistry. Chapter 1. 1-11. https://doi.org/10.1039/9781782625940-00001.

Cohn, R. (2012). Taking green chemistry out of the lab and into products, 16 May. *Yale Environment 360*. https://e360.yale.edu/features/taking_green_chemistry_out_of_the_lab_and_into_products. Accessed 13 September 2018.

Collins, T. (2001). Toward sustainable chemistry. *Science* 291(5501), 48-49. http://doi.org/10.1126/science.291.5501.48

Collins, T. (2017). Review of the twenty-three year evolution of the first university course in green chemistry: teaching future leaders how to create sustainable societies. *Journal of Cleaner Production* 140, 93-110. https://doi.org/10.1016/j.jclepro.2015.06.136

Eilks, I. and Rauch, F. (2012). Sustainable development and green chemistry in chemistry education. *Chemistry Education Research and Practice* 13(2) 57-58. http://doi.org/10.1039/C2RP90003C.

Eissen, M., Bahadir, M., König, B. and Ranke, J. (2008). Developing and disseminating NOP: an online, open-access, organic chemistry teaching resource to integrate sustainability concepts in the laboratory. *Journal of Chemical Education* 85(7), 1000-1005. http://doi.org/10.1021/ed085p1000.

Ellen MacArthur Foundation (2017). Universities. https://www.ellenmacarthurfoundation.org/programmes/education/universities. Accessed 2 April 2018.

Global Network of Chemistry Centres (2016). A global network of chemistry centres. G2C2 and GCN: a new partnership, working together to further the cause of green chemistry. http://g2c2.greenchemistrynetwork.org/. Accessed 20 April 2018.

Green Chemistry & Commerce Council (n.d.). Advancing green chemistry across sectors and supply chains. https://greenchemistryandcommerce.org/. Accessed 2 January 2019.

Gross, E.M. (2013) Green chemistry and sustainability: an undergraduate course for science and nonscience majors. *Journal of Chemical Education* 90(4), 429-431. http://doi.org/10.1021/ed200756z.

Haack, J.A. and Hutchison, J.E. (2016). Green chemistry education: 25 years of progress and 25 years ahead. *ACS Sustainable Chemistry and Engineering* 4(11), 5889-5896. http://doi.org/10.1021/acssuschemeng.6b02069.

Haley, R.A., Ringo, J.M., Hopgood, R., Denlinger, K.L., Das, A. and Waddell, D.C. (2018). Graduate student designed and delivered: an upper-level online course for undergraduates in green chemistry and sustainability. *Journal of Chemical Education* 95(4), 560-569. http://doi.org/10.1021/acs.jchemed.7b00730.

Hamidah, N., Prabawati, S., Fajriati, I. and Eilks, I. (2017). Incorporating sustainability in higher chemistry education in Indonesia through green chemistry: inspirations by inquiring the practice in a German university. *International Journal of Physics and Chemistry Education* 9(1), 1-7. https://doi.org/10.12973/ijpce/79220.

Holme, T.A. and Hutchison, J.E. (2018). A central learning outcome for the central science. *Journal of Chemical Education* 95(4), 499-501. http://doi.org/10.1021/acs.jchemed.8b00174.

International Sustainable Chemistry Collaborative Centre (2018). ISC3 – International Sustainable Chemistry Collaborative Centre. https://www.isc3.org/en/home.html. Accessed 20 August 2018.

International Union of Pure and Applied Chemistry (2018). Systems thinking, and green and sustainable chemistry, 26 September. https://iupac.org/systems-thinking-and-green-and-sustainable-chemistry/. Accessed 21 February 2019.

Italian National Committee for IUPAC of the National Research Council of Italy (2016). Interdivisional Committee on Green Chemistry for Sustainable Development: mission. http://www.iupac.cnr.it/interdivisional-committee-on-green-chemistry-for-sustainable-development-icgcsd. Accessed 21 February 2019.

Juntunen, M. and Aksela, M. (2014). Education for sustainable development in chemistry – challenges, possibilities and pedagogical models in Finland and elsewhere. *Chemistry Education Research and Practice* 15(4), 488-500. http://doi.org/10.1039/c4rp00128a.

Karpudewan, M., Ismail, Z. and Roth, W.-M. (2012). Promoting pro-environmental attitudes and reported behaviors of Malaysian pre-service teachers using green chemistry experiments. *Environmental Education Research* 18(3), 375-389. http://doi.org/10.1080/13504622.2011.622841.

Kennedy, S.A. (2016). Design of a dynamic undergraduate green chemistry course. Journal of Chemical Education 93(4), 645-649. http://doi.org/10.1021/acs.jchemed.5b00432.

Kitchens, C., Charney, R., Naistal, D., Farrugia, J., Clarens, A., O'Neil, A., Lisowski, C. and Braun, B. (2006). Completing our education. green chemistry in the curriculum. *Journal of Chemical Education* 83(8), 1126 http://doi.org/10.1021/ed083p1126.

Kümmerer, K. (2017). Sustainable chemistry: a future guiding principle. *Angewandte Chemie-International Edition* 56(52), 16420-16421. https://doi.org/10.1002/anie.201709949.

Lee, K￾H. (2009). Why and how to adopt green management into business organizations? The case study of Korean SMEs in manufacturing industry. *Management Decision* 47(7), 1101-1121. http://doi.org/10.1108/00251740910978322.

Leitner, W. (2004). Focus on education in green chemistry. *Green Chemistry* 6(8), 351. http://doi.org/10.1039/B412202J.

Levy, I.J. and Middlecamp, C.H. (eds.). (2015). *Teaching and Learning about Sustainability*. Washington, D.C.: American Chemical Society. http://doi.org/10.1021/bk-2015-1205.

Lozano, R. and Watson, M.K. (2013). Chemistry education for sustainability: assessing the chemistry curricula at Cardiff University. *Educación Química* 24(2), 184-192. https://doi.org/10.1016/S0187-893X(13)72461-3.

Mahaffy, P.G., Krief, A., Hopf, H., Mehta, G. and Matlin, S.A. (2018). Reorienting chemistry education through systems thinking. *Nature Reviews Chemistry* 2(4), 1-3. https://doi.org/10.1038/s41570-018-0126.

Mammino, L. (2015). A great challenge of green chemistry education: the interface between provision of information and behaviour patterns. In *Worldwide Trends in Green Chemistry Education*. Zuin, V. and Mammino, L. (eds.). Cambridge: Royal Society of Chemistry. 1-15. https://doi.org/10.1039/9781782621942-00001.

Matus, K.J.M., Clark, W.C., Anastas, P.T. and Zimmerman, J.B. (2012). Barriers to the implementation of Green Chemistry in the United States. *Environmental Science and Technology* 46(20), 10892-10899. http://doi.org/10.1021/es3021777.

Network Operations Portal (2018). Sustainability in the organic chemistry lab course, 23 May. https://www.oc-praktikum.de/nop/en-entry. Accessed 15 July 2018.

Shuang, L. and Yanqi, Z. (2018). A metrology analysis of articles published on green chemistry from 1999 to 2016. *Chemistry Bulletin* (HUAXUE TONGBAO) 81(7), 660-666. In Chinese.

Sjöström, J., Eilks, I. and Zuin, V. G. (2016). Towards eco-reflexive science education: a critical reflection about educational implications of Green Chemistry. *Science & Education* 25(3-4), 1-21. http://doi.org/10.1007%2Fs11191-016-9818-6.

Sjöström, J. and Talanquer, V. (2018). Eco-reflexive chemical thinking and action. *Current Opinion in Green and Sustainable Chemistry* 13, 16-20. http://doi.org/10.1016/j.cogsc.2018.02.012.

Summerton, L., Hurst, G.A. and Clark, J.A. (2018) Facilitating active learning within green chemistry. *Current Opinion in Green and Sustainable Chemistry* 13, 56-60. http://doi.org/10.1016/j.cogsc.2018.04.002.

United Nations Educational, Social and Cultural Organization (2014). *Shaping the Future We Want - UN Decade of Education for Sustainable Development (2005-2014) (Final Report).* https://sustainabledevelopment.un.org/content/documents/1682Shaping%20the%20future%20we%20want.pdf.

United Nations Educational, Social and Cultural Organization (2018). Education for sustainable development. https://en.unesco.org/themes/education-sustainable-development. Accessed 13 September 2018.

United Nations Industrial Development Organization (2018). Guidance development and case study documentation of green chemistry and technologies. *Open Data Platform*. https://open.unido.org/projects/M0/projects/150185?_ga=2.177078181.1470394430.1535145283-246569987.1525458642. Accessed 20 July 2018.

United States Environmental Protection Agency (2017). Pollution Prevention Act of 1990, 30 March. https://www.epa.gov/p2/pollution-prevention-act-1990. Accessed 21 February 2019.

University of Oregon (2018). The place for green. http://greenchem.uoregon.edu/. Accessed 2 May 2018.

Vallée, M. (2016). Obstacles to curriculum greening: the case of green chemistry. In *The Contribution of Social Sciences to Sustainable Development at Universities.* Filho, W.L. and Zint, M. (eds.). Cham: Springer. 245-258. https://doi.org/10.1007/978-3-319-26866-8_15.

Wang, M.-Y., Li, X.-Y. and He, L.-N. (2018). Green chemistry education and activity in China. *Current Opinion in Green and Sustainable Chemistry* 13, 123-129. http://doi.org/10.1016/j.cogsc.2018.07.001.

Welton, T. Thakur, V. Gupta, R.K., Matharu, A.S., Eilks, I. and Zuin, V.G. (eds.). (2018). Special issue: UN SGDs: how can sustainable chemistry contribute? / reuse and recycling / green chemistry in education. *Current Opinion in Green and Sustainable Chemistry* 13, A1-A10, 1-174. https://www.sciencedirect.com/journal/current-opinion-in-green-and-sustainable-chemistry/vol/13.

Yale University (n.d.). Global green chemistry initiative (GGCI). https://www.global-green-chemistry-initiative.com/. Accessed 2 May 2018.

Zuin, V.G. and Mammino, L. (eds.). (2015). *Worldwide Trends in Green Chemistry Education*. Cambridge, MA: Royal Society of Chemistry. https://doi.org/10.1039/9781782621942.

Zuin, V.G. (2016). Circularity in green chemical products, processes and services: innovative routes based on integrated eco-design and solution systems. *Current Opinion in Green and Sustainable Chemistry* 2, 40-44. http://doi.org/10.1016/j.cogsc.2016.09.008.

Chapter 3

American Sustainable Business Council and Green Chemistry & Commerce Council (2015). *Making the Business & Economic Case for Safer Chemistry*. http://asbcouncil.org/sites/default/files/asbcsaferchemicalsreportpresred.pdf.

Baldwin, J.R., Gorecki, P., Caves, R.E., Dunne, T. and Haltiwanger, J. (1995). *The Dynamics of Industrial Competition: A North American Perspective*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511664700.

Bøllingtoft, A. and Ulhøi, J.P. (2005). The networked business incubator-leveraging entrepreneurial agency? *Journal of Business Venturing* 20(2), 265-290. https://doi.org/10.1016/j.jbusvent.2003.12.005.

Brigl, M., Roos, A., Schmieg, F. and Watten, D. (2014). *Incubators, Accelerators, Venturing, and More: How Leading Companies Search for Their Next Big Thing*. Boston, Ma: Boston Consulting Group. https://www.elkarbide.com/sites/default/files/incubators_accelerators_venturing_more_jun_2014_tcm80-163819.pdf.

Brigl, M., Hong, M., Roos, A., Schmieg, F. and Wu, X. (2016). Corporate venturing shifts gears. *Boston Consulting Group*, 25 April. https://www.bcg.com/en-ch/publications/2016/innovation-growth-corporate-venturing-shifts-gears-how-largest-companies-apply-tools-innovation.aspx. Accessed 18 February 2019.

Clark, B.R. (1998). *Creating Entrepreneurial Universities: Organizational Pathways of Transformation*. Issues in Higher Education. New York, NY: Pergamon Press. https://eric.ed.gov/?id=ED421938.

Coyle, P.E. (2011). *National Defense Industrial Association Science & Engineering Technology Division Executive Breakfast: The Missing Middle*. Washington, D.C.: United States Office of Science and Technology Policy. https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2011/SET/CoyleNDIA.pdf.

Dempwolf, C.S., Auer, J. and D'Ippolito, M. (2014). *Innovation Accelerators: Defining Characteristics Among Startup Assistance Organizations*. Washington, D.C.: United States Small Business Administration, Office of Advocacy. https://www.sba.gov/sites/default/files/rs425-Innovation-Accelerators-Report-FINAL.pdf.

Edmondson, G., Valigra, L., Kenward, M., Hudson, R.L. and Belfield, H. (2012). *Making Industry-University Partnerships Work. Lessons from Successful Collaborations.* Brussels: Science | Business Innovation Board. https://www.sciencebusiness.net/sites/default/files/archive/Assets/94fe6d15-5432-4cf9-a656-633248e63541.pdf.

Elgie, S. and Brownlee, M. (2017). *Accelerating Clean Innovation in Canada*. Ottawa: Smart Prosperity Institute. https://institute.smartprosperity.ca/sites/default/files/acceleratingcleaninnovationincanada.pdf.

Elschami, M. and Kümmerer, K. (2018). Sustainable Chemistry and the International Sustainable Chemistry Collaborative Centre. *GAIA – Ecological Perspectives for Science and Society* 27(2), 247-249. https://doi.org/10.14512/gaia.27.2.13.

Ernst & Young (2016). *Green Bonds: A Fresh Look at Financing Green Projects.* https://www.ey.com/Publication/vwLUAssets/Green_bonds-a-fresh-look-at-financing-green-projects/$FILE/EY-Green%20bonds-a-fresh-look-at-financing-green-projects.pdf.

Etzkowitz, H. (2002). *MIT and the Rise of Entrepreneurial Science*. Abingdon: Taylor & Francis. https://doi.org/10.4324/9780203216675.

Etzkowitz, H., Ranga, M., Benner, M., Guaranys, L., Maculan, A.M. and Kneller, R. (2008). Pathways to the entrepreneurial university: towards a global convergence. *Science and Public Policy* 35(9), 681-695. https://doi.org/10.3152/030234208x389701.

European Commission (2012). *Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions: 'A European Strategy for Key Enabling Technologies – A Bridge to Growth and Jobs'.* Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012DC0341&from=EN.

European Commission and Organisation for Economic Co-operation and Development (2012). *A Guiding Framework for Entrepreneurial Universities*. https://www.oecd.org/site/cfecpr/EC-OECD%20Entrepreneurial%20Universities%20Framework.pdf.

Faulkner, A. and Berenshteyn, Y. (2013). *Advanced Materials: Creating Chemistry between Innovators and Investors.* San Francisco, CA: Cleantech Group. http://www.phoenix-vp.com/wp-content/uploads/2015/10/Advanced-Materials_Creating-Chemistry_0713.pdf.

Forrest, C. (2018). Accelerators vs. incubators: what startups need to know, 25 June. *TechRepublic*. https://www.techrepublic.com/article/accelerators-vs-incubators-what-startups-need-to-know/

Global Innovation through Science and Technology (2018). Startups. http://www.gistnetwork.org/content/startups. Accessed 18 February 2019.

Green Chemistry & Commerce Council (n.d. a). Members of the GC3 Startup Network. https://greenchemistryandcommerce.org/startup-network/list-of-startups. Accessed 18 February 2019.

Green Chemistry & Commerce Council (n.d. b). Advancing green chemistry across supply chains and Sectors. https://greenchemistryandcommerce.org/. Accessed 02 January 2019.

Hoffman, D.L. and Radojevich-Kelley, N. (2012). Analysis of accelerator companies: an exploratory case study of their programs, processes, and early results. *Small Business Institute® Journal* 8(2),54-70. https://www.sbij.org/index.php/SBIJ/article/view/136.

Huizingh, E.K.R.E. (2011). Open innovation: state of the art and future perspectives. *Technovation* 31(1), 2-9. https://doi.org/10.1016/j.technovation.2010.10.002.

IESE Business School (2017). *Corporate Venturing: Achieving Profitable Growth Through Startups. Whitepaper.* https://www.iese.edu/research/pdfs/ST-0429-E.pdf.

International Bank for Reconstruction and Development and World Bank (2017). *What Are Green Bonds?* http://documents.worldbank.org/curated/en/400251468187810398/pdf/99662-REVISED-WB-Green-Bond-Box393208B-PUBLIC.pdf.

International Council of Chemical Associations (2017). *Global Chemical Industry Contributions to the Sustainable Development Goals.* https://www.icca-chem.org/wp-content/uploads/2017/02/Global-Chemical-Industry-Contributions-to-the-UN-Sustainable-Development-Goals.pdf.

International Energy Agency (2008). *Energy Technology Perspectives 2008: Scenarios & Strategies to 2050*. https://www.iea.org/media/etp/etp2008.pdf.

Jackson, D.J. (2011). *What Is an Innovation Ecosystem?* Arlington, VA: National Science Foundation. http://www.sustainablescale.org/ConceptualFramework/UnderstandingScale/BasicConcepts/EcosystemFunctionsServices.aspx.

Kirchhoff, B.A., Newbert, S.L., Hasan, I., and Armington, C. (2007). The influence of university R&D expenditures on new business formations and employment growth. *Entrepreneurship Theory and Practice* 31(4),543-559. https://doi.org/10.1111/j.1540-6520.2007.00187.x.

Klofsten, M., and Jones-Evans, D. (2000). Comparing academic entrepreneurship in Europe – the case of Sweden and Ireland. *Small Business Economics* 14(4), 299-309. https://doi.org/10.1023/A:1008184601282.

Kutzhanova, N., Lyons, T.S. and Lichtenstein, G.A. (2009). Skill-based development of entrepreneurs and the role of personal and peer group coaching in enterprise development. *Economic Development Quarterly* 23(3), 193-210. https://doi.org/10.1177/0891242409336547.

Langenheim, J. (2018). Could seaweed solve Indonesia's plastic crisis? 27 June. *Guardian*. https://www.theguardian.com/environment/blog/2018/jun/27/could-seaweed-solve-indonesias-plastic-crisis. .

Lockett, N., Jack, S. and Larty, J. (2012). Motivations and challenges of network formation: entrepreneur and intermediary perspectives. *International Small Business Journal* 31(8), 866-889.https://doi.org/10.1177/0266242612448383.

Lopes Da Silva, C.E., Baptista Narcizo, R. and Cardoso, R. (2012). The proximity between academy, industry and government: towards a more sustainable development of a Brazilian oil region. Selection and/or peer review under responsibility of Institut Teknologi Bandung. *Procedia-Social and Behavioral Sciences* 52, 100-109. https://doi.org/10.1016/j.sbspro.2012.09.446.

Malairaja, C. and Zawdie, G. (2008). Science parks and university–industry collaboration in Malaysia. *Technology Analysis & Strategic Management* 20(6), 727-739. https://doi.org/10.1080/09537320802426432.

Mbaka, C. (2018). Gjenge Makers is providing alternative building materials and products made from recycled plastics, 27 February. *TechMoran*. https://techmoran.com/2018/02/27/gjenge-makers-providing-alternative-building-materials-products-made-recycled-plastics/. Accessed 25 February 2019.

Mirowski, P. and Sent, E.-M. (2007). The commercialization of science, and the response of STS. In *The Handbook of Science and Technology Studies*. Lynch, M. and Wajcman, J. (eds.). Cambfidge, MA: MIT Press. 635-689. https://philpapers.org/rec/MIRTCO-5.

National Aeronautics and Space Administration of the United States (2012). Technology readiness level, 28 October. https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html. Accessed 20 September 2018.

Organisation for Economic Co-operation and Development (1997). *National Innovation Systems*. https://www.oecd.org/science/inno/2101733.pdf.

Organisation for Economic Co-operation and Development (2011). *Invention and Transfer of Environmental Technologies*. OECD Studies on Environmental Innovation. http://dx.doi.org/10.1787/9789264115620-en.

Organisation for Economic Co-operation and Development (2012). *OECD Science, Technology and Industry Outlook 2012*. http://www.oecd-ilibrary.org/science-and-technology/oecd-science-technology-and-industry-outlook-2012_sti_outlook-2012-en.

Organisation for Economic Co-operation and Development (2016). *OECD Science, Technology and Innovation Outlook 2016*. https://doi.org/10.1787/sti_in_outlook-2016-en.

Oviatt, B.M., and Mc Dougall, P.P. (2005). Toward a theory of international new ventures. *Journal of International Business Studies* 36(1), 29-41. https://doi.org/10.1057/palgrave.jibs.8400128.

Root, A. (2017). *Scale Up! Entrepreneurs' Guide to Investment in Kenya*. Kariuki, M., Schwaab, J. and Wiedner, S. (eds.). Bonn: German Development Agency. https://make-it-initiative.org/africa/activities/guides-investment/.

Ryzhonkov, V. (2013). Innovation ecosystem model. *Entrepreneurship, Business Incubation, Business Models & Strategy Blog*. https://worldbusinessincubation.wordpress.com/2013/08/04/demand-not-the-infrastructure-is-the-cornerstone-of-successful-innovation-ecosystem/innovation-ecosystem-model-2/. Accessed 15 September 2018.

Schumpeter, J.A. (1954). *History of Economic Analysis*. Schumpeter. E.B. (ed.). New York: Oxford University Press. http://www.urbanlab.org/articles/economics/Schumpeter%201954%20-%20history%20economic%20analysis.pdf.

Sergey, A.B., Alexandr, D.B. and Sergey, A.T. (2015). Proof of Concept Center – a promising tool for innovative development at entrepreneurial universities. *Procedia – Social and Behavioral Sciences* 166, 240-245. https://doi.org/10.1016/j.sbspro.2014.12.518.

Şimşek, K. and Yıldırım, N. (2016). Constraints to open innovation in science and technology parks. *Procedia - Social and Behavioral Sciences* 235, 719-728. https://doi.org/10.1016/j.sbspro.2016.11.073.

Söderblom, A. and Samuelsson, M. (2014). *Sources of Capital for Innovative Startup Firms: An Empirical Study of the Swedish Situation.* Stockholm: Entreprenörskaps Forum. https://entreprenorskapsforum.se/wp-content/uploads/2014/05/NaPo_Sourcesofcapital_webb.pdf.

Storey, D.J. (1994). *Understanding the Small Business Sector*. London: Routledge. https://www.taylorfrancis.com/books/9781134838554.

SusChem (2017). *Strategic Innovation and Research Agenda*. http://www.suschem.org/publications.

Sworder, C., Salge, L. and van Soest, H. (2017). *Global Cleantech Innovation Index 2017: Which Countries Look Set to Produce the Next Generation of Start-Ups?* Cleantech Group and World Wide Fund for Nature. https://wwf.fi/mediabank/9906.pdf.

Sworder, C., Zhang, L. and Matheson, H. (2018). *Global'18 Cleantech 100: A Barometer of the Changing Face of Global Cleantech Innovation*. Steger, M. and Youngman, R. (eds.). Cleantech Group. http://info.cleantech.com/rs/151-JSY-946/images/2018Global100Report_weboptimized.pdf.

United Nations Economic Commission for Africa (2016a). *Enabling Measures for an Inclusive Green Economy in Africa*. http://www.greengrowthknowledge.org/sites/default/files/downloads/resource/UNECA_Enabling%20measures%20for%20an%20inclusive%20green%20economy%20in%20Africa.pdf.

United Nations Economic Commission for Africa (2016b). *Inclusive Green Economy Policies and Structural Transformation in Selected African Countries*. http://repository.uneca.org/bitstream/handle/10855/23004/b11560265.pdf?sequence=3.

United Nations Economic Commission for Europe (2012). *Innovation Review Performance Kazakhstan*. https://www.unece.org/fileadmin/DAM/ceci/publications/icp5.pdf.

United Nations Environment Programme (2017). *Advancing Entrepreneurship and Start-up Initiatives for Sustainable Chemistry: Learning from Case Studies. Compilation of Case Studies.* http://wedocs.unep.org/bitstream/handle/20.500.11822/22044/SC%20Startup%20WS_Case%20Studies%20Compilation_Final.pdf?sequence=1&isAllowed=y.

United Nations Industrial Development Organization (2017). *Industrial Development Report 2018. Demand for Manufacturing: Driving Inclusive and Sustainable Industrial Development*. https://www.unido.org/news/industrial-development-report-2018-launched.

United States Government Accountability Office (2018). *Chemical Innovation: Technologies to Make Processes and Products More Sustainable*. https://www.gao.gov/products/GAO-18-307.

Whitesides, G. (2015). Reinventing Chemistry. *Angewandte Chemie International Edition* 54(11), 3196-3209. https://doi.org/10.1002/anie.201410884.

Wilson, K.E. (2015). *Policy Lessons from Financing Innovative Firms*. OECD Science, Technology and Industry Policy Papers No. 24. Paris: Organisation for Economic Co-operation and Development. https://doi.org/10.1787/5js03z8zrh9p-en.

Wissema, J.G. (2009). *Towards the Third Generation University: Managing the University in Transition*. Cheltenham: Edward Elgar Publishing Limited. https://doi.org/10.4337/9781848446182.

World Economic Forum (2018). *Chemistry and Advanced Materials: Collaborative Innovation towards the Sustainable Development Goals*. Forthcoming. https://www.weforum.org/

Wu, J.J. and Atkinson, R.D. (2017). *How Technology-Based Start-Ups Support U.S. Economic Growth*. Information Technology & Innovation Foundation. http://www2.itif.org/2017-technology-based-start-ups.pdf.

Yuan and Powell (2013). *MOOCs and Open Education: Implications for Higher Education*. Bolton: Centre for Educational Technology, Interoperability and Standards. https://publications.cetis.org.uk/wp-content/uploads/2013/03/MOOCs-and-Open-Education.pdf.

Chapter 4

Agarwal, D., Bersin, J., Lahiri, G., Schwartz, J. and Volini, E. (2018). *The Rise of the Social Enterprise: 2018 Deloitte Global Human Capital Trends*. Kaji, J., Edelman, K., Khan, A., Garia, N., Budman, M., Thomas, R. and Devan, P. (eds.). Deloitte. https://www2.deloitte.com/content/dam/insights/us/articles/HCTrends2018/2018-HCtrends_Rise-of-the-social-enterprise.pdf.

Agrawal, V.V. and Bellos, I. (2015). Servicizing in supply chains and environmental implications. In *Environmentally Responsible Supply Chains*. Atasu, A. (ed.). Cham: Springer. Chapter 7. 109-124. https://doi.org/10.1007/978-3-319-30094-8_7.

Alibaba (2018). Product listing policy, 10 May. http://rule.alibaba.com/rule/detail/2047.htm#p2.2. Accessed 16 September 2018.

Amazon (2018). Hazardous and dangerous items, 28 September. https://sellercentral.amazon.com/gp/help/external/200164570?language=en-US&ref=mpbc_200277300_cont_200164570. Accessed 22 February 2019.

American Institute of Chemical Engineers (2011). *Chemical Parks: Industry Landscaping à la Germany*. https://www.aiche.org/sites/default/files/cep/20111044.pdf.

Askar, Y. (2006). *Chemical Management Services: Advantages, Barriers and Opportunities in the Egyptian Market*. Lund: Lunds universitet Internationella miljöinstitutet. http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=1329423&fileOId=1329424.

Azimi, P., Zhao, D., Pouzet, C., Crain, N.E. and Stephens, B. (2016). Emissions of ultrafine particles and volatile organic compounds from commercially available desktop three-dimensional printers with multiple filaments. *Environmental Science & Technology* 50(3), 1260-1268. https://doi.org/10.1021/acs.est.5b04983

Beltramello, A., Haie-Fayle, L. and Pilat, D. (2013). *Why New Business Models Matter for Green Growth*. OECD Green Growth Papers. 2013-01. Paris: Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/content/paper/5k97gk40v3ln-en.

Bierma, T.J. and Waterstraat, F.L. (1997). *Innovative Chemical Supply Contracts: A Source of Competitive Advantage*. Champaign, IL: Waste Management and Research Center. https://www.ideals.illinois.edu/handle/2142/2042.

Bilsen, V., Blondiau, T., Debergh, P. and Lukach, R. (2013). *Exchange of Good Policy Practices Promoting Innovative/Green Business Models.* Brussels: European Commission Directorate-General Enterprise and Industry. http://ec.europa.eu/DocsRoom/documents/4668.

Bocken, N.M.P., Short, S.W., Rana, P. and Evans, S. (2014). A literature review to develop sustainable business model archetypes. *Journal of Cleaner Production* 65, 42-56. http://dx.doi.org/10.1016/j.jclepro.2013.11.039.

Chemical Leasing (2016). Joint declaration signed, 21 november 2016. https://chemicalleasing.org/news/joint-declaration-signed-21-november-2016. Accessed 22 February 2019.

Chemical Strategies Partnership (n.d. a) *Chemical Management Services: A New Strategy for Pollution Prevention.* https://www.dtsc.ca.gov/PollutionPrevention/upload/P2_FLY_Chemical_Management.pdf.

Chemical Strategies Partnership (n.d. b). *Chemical Strategies Partnership: A Supply-Chain Approach to Reducing Chemical Use*. http://www.chemicalstrategies.org/pdf/workshop_events/2008/JKJ_CMS101.pdf.

Chertow, M. and Park, J. (2016). Scholarship and practice in industrial symbiosis: 1989-2014. In *Taking Stock of Industrial Ecology*. Clift, R. and Druckman, A. (eds.). Cham: Springer. Chapter 5. 87-116. https://doi.org/10.1007/978-3-319-20571-7_5.

Clarity (2015). B2B eCommerce considerations for the chemical industry, 18 February. https://www.clarity-ventures.com/articles/b2b-ecommerce-considerations-for-the-chemical-industry. Accessed 17 September 2018.

Crawford, M. (2015). 3D printed drugs: what does the future hold? December. *American Society of Mechanical Engineers*. https://www.asme.org/engineering-topics/articles/manufacturing-design/3dprinted-drugs-does-future-hold. Accessed 14 August 2018.

Dambmann, D. and Allford, L. (2003). *A Walk in the Chemical Park – Process Safety Perspectives*. Institution of Chemical Engineers Symposium Series. No. 149. Manchester: Institution of Chemical Engineers. https://www.researchgate.net/publication/306255205_A_walk_in_the_chemical_park-_process_safety_perspectives.

Ding, L. (2017). How China's social enterprises can prosper alongside the country's state-run businesses, 27 June. *World Economic Forum*. https://www.weforum.org/agenda/2017/06/how-china-s-social-enterprises-can-prosper-alongside-the-country-s-state-run-businesses/. Accessed 14 August 2018.

Duffy, K. (2016). How 3D printing is driving the growth of small businesses, 17 May. https://www.manufacturing.net/article/2016/05/how-3d-printing-driving-growth-small-businesses. Accessed 18 September 2018.

Ebay (2018). Hazardous, restricted or regulated materials policy. https://www.ebay.com/help/policies/prohibited-restricted-items/hazardous-restricted-regulated-materials-policy?id=4335. Accessed 16 September 2018.

Erkman, S. and Van Hezik, C. (2016). *Global Assessment of Eco-Industrial Parks in Developing and Emerging Countries*. https://sofiesgroup.com/en/news/global-assessment-eco-industrial-parks-developing-emerging-countries/.

Ernst & Young (2013). *The Journey Toward Greater Customer Centricity*. https://www.ey.com/Publication/vwLUAssets/The_journey_toward_greater_customer_centricity/$FILE/Customer_Centricity_Paper_29_April_Final.pdf.

European Agency for Safety and Health at Work (2017). *3D Printing and Additive Manufacturing – the Implications for OSH.* https://osha.europa.eu/en/tools-and-publications/publications/3d-printing-new-industrial-revolution.

Evonik (2017). Evonik opens online flagship store on Alibaba, 7 November. https://corporate.evonik.com/en/media/search/pages/news-details.aspx?NewsId=70974. Accessed 22 August 2018.

Fairphone (2016). How we're tackling e-waste with the Fairphone 2, 25 February. https://www.fairphone.com/en/2016/02/25/tackling-e-waste-with-fairphone-2/. Accessed 15 September 2018.

Faludi, J. (2013). Is 3D printing an environmental win? 19 July. *GreenBiz*. https://www.greenbiz.com/blog/2013/07/19/3d-printing-environmental-win. Accessed 18 September 2018.

Faludi, J., Hu, Z., Alrashed, S., Braunholz, C., Kaul, S. and Kassaye, L. (2015). Does material choice drive sustainability of 3D printing? *International Journal of Mechanical and Mechatronics Engineering* 9(2), 216-223. http://scholar.waset.org/1307-6892/10000327.

Ford, S. and Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production* 137, 1573-1587 https://doi.org/10.1016/j.jclepro.2016.04.150.

Gebler, M., Schoot Uiterkamp, A. and Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy* 74, 158-167. https://doi.org/10.1016/j.enpol.2014.08.033.

Gładyszewski, K. and Skiborowski, M. (2018). Additive manufacturing of packings for rotating packed beds. *Chemical Engineering and Processing – Process Intensification* 127, 1-9. https://doi.org/10.1016/j.cep.2018.02.024.

Government of the United Kingdom (2016). Social investment tax relief: guidance, 23 November. https://www.gov.uk/government/publications/social-investment-tax-relief-factsheet/social-investment-tax-relief. Accessed 14 August 2018.

Guertzgen, S. (2017). How 3D printing will energize the chemical industry – Part 1: Key opportunity areas, 4 January. *Digitalist Magazine*. https://www.digitalistmag.com/digital-supply-networks/2017/01/04/3d-printing-energize-chemical-industry-part-1-04824179. Accessed 13 August 2018.

Hänsch Beuren, F., Gomez Ferreira, M.G. and Cauchick Miguel, P.A. (2013). Product-service systems: a literature review on integrated products and services. *Journal of Cleaner Production* 47, 222-231. https://doi.org/10.1016/j.jclepro.2012.12.028.

Hauthal, H. and Salonen, T. (n.d.) *Chemical Industrial Parks in China*. Achema World Wide News. https://dechema.de/dechema_media/Downloads/Presse/ACHEMA+worldwide/851_S_14_16-p-1146.pdf.

Ibrahim, A.M.S., Jose, R.R., Rabie, A.N., Gerstle, T.L., Lee, B.T. and Lin, S.J. (2015). Three-dimensional printing in developing countries. *Plastic and Reconstructive Surgery Global Open* 3(7), e443 1-8. https://doi.org/10.1097/gox.0000000000000298.

Independent Chemical Information Service Chemical Business (2018). Alibaba for chemicals as Covestro, BASF sign up, 26 April. https://www.icis.com/resources/news/2018/04/26/10215762/alibaba-for-chemicals-as-covestro-basf-sign-up/. Accessed 22 August 2018.

Independent Chemical Information Service News (2016). US Amazon now sells DVDs, books and caustic soda, 26 October. https://www.icis.com/resources/news/2016/10/26/10048495/us-amazon-now-sells-dvds-books-and-caustic-soda/. Accessed 22 August 2018.

Ishengoma, F.R. and Mtaho, A.B. (2014). 3D printing: developing countries perspectives. *International Journal of Computer Applications* 104(11), 30-34. https://www.researchgate.net/publication/267029274_3D_Printing_Developing_Countries_Perspectives.

Jakl, T. (2011). Global chemical leasing award 2010. *Technology and Investment* 2(1), 20-26. http://doi.org/10.4236/ti.2011.21003.

Jakl, T. and Schwager, P. (eds.) (2008). *Chemical Leasing Goes Global – Selling Services Instead of Barrels: A Win-Win Business Model for Environment and Industry*. Vienna: Springer Link. https://doi.org/10.1007/978-3-211-73752-1.

Joas, R. Abraham, V. and Joas, A. (2018). Chemical leasing: a business model to drive resource efficiency in the supply chain, In *Factor X*. Chapter 28. 395-403. https://doi.org/10.1007/978-3-319-50079-9_28

Kechichian, E. and Jeong, M.H (2016). *Mainstreaming Eco-Industrial Parks.* Washington, D.C.: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/24921/Mainstreaming00020150event0in0Seoul.pdf?sequence=5&isAllowed=y.

Keizer, A., Stikkers, A., Heijmans, H., Carsouw, R. and Van Aanholt, W. (2016). *Scaling the Impact of the Social Enterprise Sector.* McKinsey & Company. https://www.social-enterprise.nl/files/9314/7809/5072/Scaling-the-impact-of-the-social-enterprise-sector.pdf.

Kreiger, M., Mulder, M., Glover, A. and Pearce, J. (2014). Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. *Journal of Cleaner Production* 70, 90-96. https://doi.org/10.1016/j.jclepro.2014.02.009.

Kroner, E. (2014). The 7 pillars of customer centricity, 6 October. *American Marketing Association*. https://www.ama.org/publications/eNewsletters/MarketingInsightsNewsletter/Pages/7-pillars-of-customer-centricity.aspx. Accessed 13 August 2018.

LeBlanc, R., Tranchant, C., Gagnon, Y. and Côté, R. (2016). Potential for eco-industrial park development in Moncton, New Brunswick (Canada): a comparative analysis. *Sustainability* 8(5), 1-18. https://doi.org/10.3390/su8050472.

Ling, M. and Pflug, K. (2015). E-Business and chemical distribution: disintermediation 2.0? *China Chemical Reporter* 26(14), 8-9. http://www.mc-chemicals.com/sites/mc-chemicals.com/files/Ebusiness%20and%20Chemical%20Distribution%20CCR%202015.pdf.

March, R. (2015). 3D printing – exploring a technology and its sustainability potential, 21 December. http://sustainability.com/our-work/insights/3d-printing-exploring-a-technology-and-its-sustainability-potential/. Accessed 7 August 2018.

Mardani, S., Ojala, L.S., Uusi-Kyyny, P. and Alopaeus, V. (2016). Development of a unique modular distillation column using 3D printing. *Chemical Engineering and Processing: Process Intensification* 109, 136-148. https://doi.org/10.1016/j.cep.2016.09.001.

Market Research Engine (2017). Additive manufacturing market by end user analysis; by type analysis and by regional analysis – global forecast by 2016 – 2022, November. https://www.marketresearchengine.com/reportdetails/additive-manufacturing-market. Accessed 6 July 2018.

Mohammed, M.I., Mohan, M., Das, A., Johnson, M.D., Badwal, P.S., McLean, D. and Gibson, I. (2017). A low carbon footprint approach to the reconstitution of plastics into 3D- printer filament for enhanced waste reduction. *The International Conference on Design and Technology* 2017, 234-241. https://doi.org/10.18502/keg.v2i2.621.

Molitch-Hou, M. (2014). How a medical clinic in the Bolivian rainforest might use 3D printing, 18 February. https://3dprintingindustry.com/news/medical-clinic-bolivian-rainforest-might-use-3d-printing-23735/. Accessed 7 August 2018.

Moser, F. and Jakl, T. (2014). Chemical leasing – a review of implementation in the past decade. *Environmental Science and Pollution Research* 22, 6325-6348. https://doi.org/10.1007/s11356-014-3879-3.

Muhammed, A. (2018). Four challenges (millennial) social entrepreneurs should account for when running their businesses, 4 March. *Entrepreneurs*. https://www.entrepreneur.com/article/309905. Accessed 18 September 2018.

Okeugo, P. (2015). Wecyclers: Nigeria's sustainable waste recycling social enterprise, 22 September. http://www.nudgesustainabilityhub.com/initiatives/2015/9/21/wecyclers-nigerias-sustainable-waste-recycling-social-enterprise. Accessed 18 September 2018.

Organisation for Economic Co-operation and Development (2013). *Environmental Performance Review of Austria.* http://www.oecd.org/env/country-reviews/EPR%20Highlights%20AUSTRIA%202013%20web.pdf.

Organisation for Economic Co-operation and Development (2017). *Economic Features of Chemical Leasing.* Series on Risk Management. No. 37. https://www.oecd.org/chemicalsafety/risk-management/The%20Economic%20Features%20of%20Chemical%20Leasing.pdf.

Organisation for Economic Co-operation and Development and European Commission (2013). *Policy Brief on Social Entrepreneurship: Entrepreneurial Activities in Europe.* https://www.oecd.org/cfe/leed/Social%20entrepreneurship%20policy%20brief%20EN_FINAL.pdf.

Oskui, S.M., Diamante, G., Liao, C., Shi, W., Gan, J., Schlenk, D. and Grover, W.H. (2016). Assessing and reducing the toxicity of 3D-printed parts. *Environmental Science & Technology Letters* 3(1), 1-6. https://doi.org/10.1021/acs.estlett.5b00249.

Panum, K. and Hansen, M. (2014). *Successful Social Enterprises in Africa: Case Studies of Six Social Enterprises in Kenya*. CBDS Working Paper Series Working Paper No. 02. Copenhagen: Copenhagen Business School http://openarchive.cbs.dk/bitstream/handle/10398/9002/Panum_and_hansen_2014_2.pdf.

Perrini F. and Vurro C. (2006). Social entrepreneurship: innovation and social change across theory and practice. In *Social Entrepreneurship*. Mair, J., Robinson J. and Hockerts, K. (eds.). London: Palgrave Macmillan. Chapter 5. 57-85. https://doi.org/10.1057/9780230625655_5.

Phansey, A. (2014). How 3D printing can revolutionize sustainable design, 29 May. https://www.greenbiz.com/blog/2014/05/29/3d-printing-revolutionize-sustainable-design. Accessed 7 August 2018.

Planète Énergies (2016). Eco-industrial parks looking to enhance economic and environmental performance, 24 June. https://www.planete-energies.com/en/medias/close/eco-industrial-parks-looking-enhance-economic-and-environmental-performance. Accessed 19 September 2018.

Pullen, J.P. (2014). What 3D printing means for small business, 14 January. https://www.entrepreneurmag.co.za/advice/starting-a-business/launch/what-3d-printing-means-for-small-business/. Accessed 19 September 2018.

Ramus, T. and Vaccarus, A. (2017). Stakeholders matter: how social enterprises address mission drift. *Journal of Business Ethics* 143(2), 307-322. https://link.springer.com/article/10.1007/s10551-014-2353-y.

Renjen, P. (2018). Industry 4.0: are you ready? *Deloitte Review* (22), 9-11. https://www2.deloitte.com/content/dam/insights/us/collections/issue-22/DI_Deloitte-Review-22.pdf.

Roy, S. (2018). This startup has recycled over 4 tonnes of cigarette butts into useful products, 9 January. *YourStory Media*. https://yourstory.com/2018/01/code-enterprises/. Accessed 19 September 2018.

Sanchez, B. (2016). 10 policy tools that governments are implementing to spur social enterprise, 9 January. *World Bank*. http://blogs.worldbank.org/dmblog/10-policy-tools-governments-are-implementing-spur-social-enterprise. Accessed 9 August 2018.

Service, R. (2018). You could soon be manufacturing your own drugs—thanks to 3D printing, 18 January. *Science*. http://www.sciencemag.org/news/2018/01/you-could-soon-be-manufacturing-your-own-drugs-thanks-3d-printing. Accessed 22 February 2019.

Shockley, G.E. and Frank, P.M. (2011). The functions of government in social entrepreneurship: theory and preliminary evidence. *Regional Science Policy & Practice* 3(3), 181-198. https://doi.org/10.1111/j.1757-7802.2011.01036.x.

SIDBI Venture Capital (n.d.). Maharashtra state social venture fund (MS Fund). http://www.sidbiventure.co.in/ms_fund.html. Accessed 14 August 2018.

Smith, F. (2016). Trash to treasure: the social enterprises transforming recycling, 20 November. https://www.theguardian.com/sustainable-business/2016/nov/21/social-enterprises-transforming-recycling. Accessed 19 September 2018.

Social Enterprise Mark CIC (2018). The social enterprise mark – what it means. https://www.socialenterprisemark.org.uk/what-the-social-enterprise-mark-means/. Accessed 4 September 2018.

Solvay (2018). Alibaba! Solvay opens flagship e-store, 23 January. https://www.solvay.com/en/article/solvay-opens-alibaba-e-store. Accessed 22 August 2018.

Stringer, L. (2018). E-commerce: the challenges of enforcing a chemicals policy, June. *Chemical Watch*. https://chemicalwatch.com/67611/e-commerce-the-challenges-of-enforcing-a-chemicals-policy. Accessed 8 August 2018.

Technical Progress. (2018). Chemical Management Services (CMS) market 2018-2025: global industry report by product and region. https://thetechnicalprogress.com/2018/05/chemical-management-services-cms-market-2018-2025-global-industry-report-by-product-and-region/. Accessed 6 June 2018.

United Kingdom Chemicals Stakeholder Forum (2013). *A Guide to Chemical Services: An Information Note from the UK Chemicals Stakeholder Forum*. https://www.gov.uk/government/groups/uk-chemicals-stakeholder-forum.

United Nations Industrial Development Organization (2016). *Global Promotion and Implementation of Chemical Leasing Business Models in Industry*. http://www.recpnet.org/wp-content/uploads/2016/08/10-Years-Chemical-Leasing-Report.pdf.

United Nations Industrial Development Organization (2017). *Implementation Handbook for Eco-industrial Parks.* https://www.unido.org/sites/default/files/files/2018-05/UNIDO%20Eco-Industrial%20Park%20Handbook_English.pdf.

United Nations Industrial Development Organization (2019). Chemical leasing. https://www.unido.org/our-focus/safeguarding-environment/resource-efficient-and-low-carbon-industrial-production/chemical-leasing. Accessed 11 February 2019.

United Nations Industrial Development Organization, World Bank Group and German Corporation for International Cooperation (2017). *An International Framework for Eco-Industrial Parks*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/29110.

Villeneuve-Smith, F. and Temple, N. (2015). *State of Social Enterprise Survey 2015: Leading the World in Social Enterprise.* https://www.socialenterprise.org.uk/Handlers/Download.ashx?IDMF=828443a9-2f80-4c2a-ab2b-81befed6ed05.

Walker, C. (2017). Perpetual plastics – 3D printing with waste, 27 October. *Elsevier*. https://chemical-materials.elsevier.com/chemical-rd/perpetual-plastics-3d-printing-waste/. Accessed 13 August 2018.

Wayne, J. (2017). How 3D printing is empowering SMBs in manufacturing's digital transformation, 6 October. *Entrepreneur*. https://www.entrepreneur.com/article/300966. Accessed 13 August 2018.

World Bank (2018). Eco-industrial parks emerge as an effective approach to sustainable growth, 23 January. https://www.worldbank.org/en/news/feature/2018/01/23/eco-industrial-parks-emerge-as-an-effective-approach-to-sustainable-growth. Accessed 6 August 2018.

World Business Council for Sustainable Development (2018). *Chemical Sector SDG Roadmap*. https://www.wbcsd.org/Programs/People/Sustainable-Development-Goals/Resources/Chemical-Sector-SDG-Roadmap.

Yale School of Forestry & Environmental Studies (2017). Additive manufacturing and sustainability: the environmental implications of 3-D printing, 14 November. *ScienceDaily*. https://www.sciencedaily.com/releases/2017/11/171114142343.htm. Accessed 7 August 2018.

Yoon, D. (2018). Putting toxic chemicals on the map, 13 June. *International Chemical Secretariat*. http://chemsec.org/putting-toxic-chemicals-on-the-map/. Accessed 14 August 2018.

Yu, F., Han, F. and Cui, Z. (2015). Evolution of industrial symbiosis in an eco-industrial park in China. *Journal of Cleaner Production* 87, 339-347. https://doi.org/10.1016/j.jclepro.2014.10.058.

Zeng, G. and Bathelt, H. (2011). Divergent growth trajectories in China's chemical industry: the case of the newly developed industrial parks in Shanghai, Nanjing and Ningbo. *GeoJournal* 76(6), 675-698. https://doi.org/10.1007/s10708-009-9313-6.

Zhu, Q., Geng, Y., Sarkis, J. and Lai, K-H. (2014). Barriers to promoting eco‐industrial parks development in China. *Journal of Industrial Ecology* 19(3), 457-467. https://doi.org/10.1111/jiec.12176.

Chapter 5

Böcker, T. and Finger, R. (2016). European pesticide tax schemes in comparison: an analysis of experiences and developments. *Sustainability* 8(4), 1-22. https://doi.org/10.3390/su8040378.

Canadian Association of Tire Recycling Agencies (2018). *Annual Report 2017.* https://www.catraonline.ca/storage/files/shares/publications-en/catra-annualreport-2017-final-feb-16-2018-english.pdf.

Convery, F., McDonnell, S. and Ferreira, S. (2007). The most popular tax in Europe? lessons from the Irish plastic bags levy. *Environmental and Resource Economics* 38(1), 1-11. https://doi.org/10.1007/s10640-006-9059-2.

Coria, J. (2018). The economics of toxic substance control and the REACH directive. *Review of Environmental Economics and Policy* 12(2), 342-358. http://dx.doi.org/10.1093/reep/rey003.

Dikgang, J., Leiman, A. and Visser, M. (2010). *Analysis of the Plastic-Bag Levy in South Africa*. Policy Paper. No. 18. https://econrsa.org/papers/p_papers/pp18.pdf.

Finger, R., Möhring, N., Dalhaus, T. And Böcker, T. (2017). Revisiting pesticide taxation schemes. *Ecological Economics* 134, 263-266. https://doi.org/10.1016/J.ECOLECON.2016.12.001.

Government of Denmark (2006). *Ftalater - Reguleringsmæssig Status, Ftalatafgiftens Effekter Og Overvejelser Om Differentieret Afgift (Phthalates - Regulatory Status, Effects of the Fee on Phthalates and Considerations about a Differentiated Charge)*. Miljø- og Planlægningsudvalget. Appendix 343. https://www.ft.dk/samling/20051/almdel/mpu/bilag/343/267804.pdf.

Groothuis, F. (2016). *New Era. New Plan: A Fiscal Strategy for an Inclusive, Circular Economy*. Gersen, P. (ed.). LX Houten: Ex'tax Project. http://www.neweranewplan.com/wp-content/uploads/2016/12/New-Era-New-Plan-Europe-Extax-Report-DEF.compressed.pdf.

Gu, Y.F., Wu, Y.F., Xu, M., Wang, H.D. and Zuo, T.Y. (2017). To realize better extended producer responsibility: redesign of WEEE fund mode in China. *Journal of Cleaner Production*, 164, 347-356. https://doi.org/10.1016/J.JCLEPRO.2017.06.168.

Gulati, A. and Banerjee, P. (2015). *Rationalising Fertiliser Subsidy in India: Key Issues and Policy Option*. Working Papers. No. 307. New Delhi: Indian Council for Research on International Economic Relations. https://ideas.repec.org/p/ess/wpaper/id11083.html.

Harrington, W., Morgenstern, R. and Sterner, T. (eds) (2004). *Choosing Environmental Policy: Comparing Instruments and Outcomes in the United States and Europe*. 1st edn. Washington, D.C.: Routledge. https://www.taylorfrancis.com/books/9781936331468.

Kalimo, H., Lifset, R., Atasu, A., Van Rossem, C. and Van Wassenhove, L. (2015). What roles for which stakeholders under extended producer responsibility? *Review of European Comparative & International Environmental Law* 24(1), 40-57. https://doi.org/10.1111/reel.12087.

Kjäll, K. (2012). *Hur väl Fungerar Miljöskatter Inom Kemikalieområdet? Effekter av Miljöskatter på Växtskydd och Klorerade Lösningsmedel i Sverige, Danmark, Norge och Frankrike*. Stockholm: Swedish Chemicals Agency.

Loblaw Companies Limited. (2017). *2017 Corporate Social Responsibility Report.* http://www.loblaw.ca/CSRReport.pdf.

Organisation for Economic Co-operation and Development. (n.d.). Database on policy instruments for the environment. https://pinedatabase.oecd.org/. Accessed 13 July 2018.

Ørum, J.E., Kudsk, P. and Jensen, P.K. (2017). Economics of site-specific and variable-dose herbicide application. In *Precision Agriculture: Technology and Economic Perspectives*. Springer, Cham. Chapter 4. 93-110. https://doi.org/10.1007/978-3-319-68715-5_4.

Praveen, K.V., Aditya, K.S, Nithyashree, M.L. and Sharma, A. (2017). Fertilizer subsidies in India: an insight to distribution and equity issues. *Journal of Crop and Weed* 13(3), 24-31. https://www.cabdirect.org/cabdirect/abstract/20183048688.

Slunge, D. and Sterner, T. (2001). Implementation of policy instruments for chlorinated solvents: a comparison of design standards, bans, and taxes to phase out trichloroethylene. *European Environment* 11(5), 281-296. https://doi.org/10.1002/eet.271.

Söderholm, P. (2009). *Economic Instruments in Chemicals Policy: Past Experiences and Prospects for Future Use*. Copenhagen: Copenhagen: Nordic Council of Ministers. https://www.elibrary.imf.org/abstract/IMF931/21827-9789289319201/21827-9789289319201/21827-9789289319201.xml?rskey=OZFzjS&result=8.

Söderholm, P. & Christiernsson, A. (2008). Policy effectiveness and acceptance in the taxation of environmentally damaging chemical compounds. *Environmental Science and Policy* 11(3), 240-252. Https://Doi.Org/10.1016/J.ENVSCI.2007.10.003.

Stavins, R.N. (2001). *Experience with Market-Based Environmental Policy Instruments*. Discussion Paper. No. 01-58. Washington, D.C.: Resources for the Future. https://ageconsearch.umn.edu/record/10909/files/dp010058.pdf.

Sterner, T. and Coria, J. (2011). *Policy Instruments for Environmental and Natural Resource Management*. 2nd edn. Washington, D.C.: Resources for the Future. https://doi.org/10.4324/9781315780894.

Stringer, L. (2017). Denmark to scrap tax on PVC and phthalates, 16 November. *Chemical Watch*. https://chemicalwatch.com/61121/denmark-to-scrap-tax-on-pvc-and-phthalates. Accessed 12 September 2018.

Turner, J.M. and Nugent, L.M. (2016). Charging up battery recycling policies extended producer responsibility for single-use batteries in the European Union, Canada, and the United States. *Journal of Industrial Ecology* 20(5), 1148-1158. https://doi.org/10.1111/jiec.12351.

United Kingdom Department for Environment, Food & Rural Affairs (2018). Single-use plastic carrier bags charge: data in England for 2016 to 2017, 27 September. https://www.gov.uk/government/publications/carrier-bag-charge-summary-of-data-in-england/single-use-plastic-carrier-bags-charge-data-in-england-for-2016-to-2017. Accessed 21 February 2018.

Vatn, A. (1998). Input versus emission taxes: environmental taxes in a mass balance and transaction costs perspective. *Land Economics* 74(4), 514. https://doi.org/10.2307/3146882.

Weitzman, M. L. (1974). Prices vs quantities. *The Review of Economic Studies* 41(4), 477-491. https://doi.org/10.2307/2296698.

Zeng, X. L., Duan, H. B., Wang, F. and Li, J. H. (2017). Examining environmental management of e-waste: China's experience and lessons. *Renewable & Sustainable Energy Reviews* 72, 1076-1082. https://doi.org/10.1016/J.RSER.2016.10.015.

Chapter 6

amfori (2019). amfori BEPI Supply Chain Chemical Management Module (SCCM). https://www.amfori.org/content/bepi-supply-chain-chemical-management-module-sccm. Accessed 20 February 2019.

BASF (2015). Chemical initiative "together for sustainability" (TfS). https://www.basf.com/en/company/about-us/suppliers-and-partners/sustainability-in-procurement/together-for-sustainability.html. Accessed 9 September 2018.

Blome, C., Foerstl, K., Schleper, M.C., (2017). Antecedents of green supplier championing and greenwashing: An empirical study on leadership and ethical incentives. *Journal of Cleaner Production* 152, 339-350. https://doi.org/10.1016/j.jclepro.2017.03.052.

Bomgardner, M. (2016). Cleaning the clothing industry. *Chemical and Engineering News* 94(26), 30-32. https://cen.acs.org/articles/94/i26/Cleaning-clothing-industry.html

Boström, M., Jönsson, A.M., Lockie, S., Mol, A.P.J., Oosterveer, P., (2015). Sustainable and responsible supply chain governance: challenges and opportunities. *Journal of Cleaner Production* 107, 1-7. https://doi.org/10.1016/j.jclepro.2014.11.050.

Dora, M., Bhatia, M.S., Gallear, D. (2016). *Supply Chain in a Circular Economy: A Multidimensional Research Agenda*. 3rd International Conference on Green Supply Chain. London: Brunel University. https://bura.brunel.ac.uk/handle/2438/13002.

EcoVadis (2015). *Collaboration Drives Sustainability Efficiently, in the Chemical Industry Supply Chain.* https://www.ecovadis.com/library/together-sustainability-chemical-industry-supply-chain/#download.

EcoVadis (2017). Four beauty industry leaders and EcoVadis launch the Responsible Beauty Initiative, a shared vision to strengthen sustainability throughout the beauty supply chain, 14 November. https://www.ecovadis.com/four-beauty-industry-leaders-ecovadis-launch-responsible-beauty-initiative/. Accessed 14 September 2018.

Ernst & Young Global Limited (2016). *The State of Sustainable Supply Chains: Building Responsible and Resilient Supply Chains.* https://www.ey.com/Publication/vwLUAssets/EY-the-state-of-sustainable-supply-chains/$FILE/EY-building-responsible-and-resilient-supply-chains.pdf.

European Chemicals Agency (2018). New database on Candidate List substances in articles by 2021, 11 July. https://echa.europa.eu/-/new-database-on-candidate-list-substances-in-articles-by-2021. Accessed 30 December 2018.

European Commission (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Closing the Loop - an EU Action Plan for the Circular Economy*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614.

European Commission (2018). *Communication from the Commission - On the Implementation of the Circular Economy Package: Options to Address the Interface Between Chemical, Product and Waste Legislation*. http://ec.europa.eu/information_society/newsroom/cf/dae/document.cfm?doc_id=2733.

Fick, J., Söderström, H., Lindberg, R.H., Phan, C., Tysklind, M., Larsson, D.G.J., (2009). Contamination of surface, ground, and drinking water from pharmaceutical production. *Environmental Toxicology and Chemistry* 28, 2522-2527. https://doi.org/10.1897/09-073.1.

Foerstl, K., Reuter, C., Hartmann, E., Blome, C., (2010). Managing supplier sustainability risks in a dynamically changing environment - sustainable supplier management in the chemical industry. *Journal of Purchasing and Supply Management* 16(2), 118-130. https://doi.org/10.1016/j.pursup.2010.03.011.

Foerstl, K., Azadegan, A., Leppelt, T., Hartmann, E., (2015). Drivers of supplier sustainability: Moving beyond compliance to commitment. *Journal of Supply Chain Management* 51(1), 67-92. https://doi.org/10.1111/jscm.12067.

Forum for the Future (2018). Beauty and Personal Care Sustainability Project. https://www.forumforthefuture.org/bpc. Accessed 20 February 2018.

Friege, H., (2017). Sustainable Chemistry - a concept with important links to waste management. *Sustainable Chemistry and Pharmacy* 6, 57-60. https://doi.org/10.1016/j.scp.2017.08.001.

Genovese, A., Acquaye, A.A., Figueroa, A., Koh, S.C.L., (2017). Sustainable supply chain management and the transition towards a circular economy: evidence and some applications. *Omega* 66, 344-357. https://doi.org/10.1016/j.omega.2015.05.015.

Goldenman, G., Holland, M., Lietzmann, J. and Meura, L. (2017). *Study for the Strategy for a Non-Toxic Environment of the 7th Environment Action Programme: Final Report*. Brussels: European Commission DG Environment. https://doi.org/10.2779/025.

Goodnight, H., (2017). Blockchain: the best way to decentralize supply chains, 6 September. *Supply Chain Drive*. https://www.supplychaindive.com/news/blockchain-Sweetbridge-decentralization-supply-chain-management/504362/. Accessed 6 June 2018.

Ho, W., Zheng, T., Yildiz, H., Talluri, S. (2015). Supply chain risk management: a literature review. *International Journal of Production* Research 53(16), 5031-5069. https://doi.org/10.1080/00207543.2015.1030467.

Homrich, A.S., Galvão, G., Abadia, L.G., Carvalho, M.M., (2018). The circular economy umbrella: Trends and gaps on integrating pathways. *Journal of Cleaner Production* 175, 525-543. https://doi.org/10.1016/j.jclepro.2017.11.064.

International Business Machines Corporation (2018). *Blockchain Can Help Transform Supply Chain Networks in the Chemicals and Petroleum Industry: Blockchain Enables Immutable, Transparent and Auditable Business Transactions among Participants and Suppliers, Distributors and Partners.* https://www-01.ibm.com/common/ssi/cgi-bin/ssialias?htmlfid=CHJ12351USEN.

International Council of Chemical Associations (2015). Value chain outreach (VCO). https://www.icca-chem.org/value-chain-outreach-vco/. Accessed 14 September 2018.

Khan, O., Stolte, T., Creazza, A. and Hansen, Z. (2016). Integrating product design into the supply chain. *Cogent Engineering.* Zhou, Z. (ed.) 3(1), 1-24. https://doi.org/10.1080/23311916.2016.1210478.

Kingfisher (2018). *Chemicals Policy*. http://files.the-group.net/library/kgf/sustainability_policies/2017/pdfs/cr_10.pdf.

Kirchherr, J., Reike, D., Hekkert, M., (2017). Conceptualizing the circular economy: an analysis of 114 definitions. *Resources, Conservation and Recycling* 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Leppelt, T., Foerstl, K., Reuter, C., Hartmann, E., (2013). Sustainability management beyond organizational boundaries–sustainable supplier relationship management in the chemical industry. *Journal of Cleaner Production* 56, 94-102. https://doi.org/10.1016/j.jclepro.2011.10.011.

Lo, S. (2013). Effects of supply chain position on the motivation and practices of firms going green. *International Journal of Operations & Production Management* 34(1), 93-114. https://doi.org/10.1108/ijopm-04-2012-0133.

Marquis, C., Toffel, M. and Zhou, Y. (2016). Scrutiny, norms and selective disclosure: a global study of greenwashing. *Organization Science.* 27(2), 483-504. https://doi.org/10.1287/orsc.2015.1039

Metta, H. and Badurdeen, F. (2013). Integrating sustainable product and supply chain design: modeling issues and challenges. *IEEE Transactions on Engineering Management* 60(2), 438-446. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6336806.

Mezaros, S. (2017). *The Pharmaceutical Supply Chain Initiative: An Overview.* http://www.industrialgreenchem.com/pdf-docs/Vizag%20Conference%202017/Day%20I/The%20Pharmaceutical%20Supply%20Chain%20Initiative%20%E2%80%93%20An%20Overview%20by%20Steven%20Meszaros.pdf.

Patel, M. (2016). ICCA consults on value chain communication principles: safety information should be disclosed if 'based on science and risk', 15 December. *Chemical Watch*. https://chemicalwatch.com/51633/icca-consults-on-value-chain-communication-principles. Accessed 14 September 2018.

Perlmutter, A. (2015). *Advancing Safer Chemicals in Products: The Key Role of Purchasing.* Lowell Center for Sustainable Production, University of Massachusetts Lowell. https://www.epa.gov/sites/production/files/2015-09/documents/uml-rpt_greenpurchasing_7_15_14-2_0.pdf.

Porter, G. (2018). Apple, Target, Walmart get best grades in chemical policy review, 14 November. *Bloomberg* https://www.bloomberg.com/news/articles/2018-11-14/apple-target-walmart-get-best-grades-in-chemical-policy-review. Accessed 20 February 2019

Responsible Business Alliance (2018). *Responsible Business Alliance Code of Conduct Version 6.0.* http://www.responsiblebusiness.org/media/docs/RBACodeofConduct6.0_English.pdf

Retail Industry Leaders Association (n.d). *Chemicals and Toxics in Retail and its Supply Chain*. RILA Issue Brief: Chemicals and Toxics. http://www.retailcrc.org/sustainability/Lists/Briefings/Attachments/9/RILA%20issue%20brief%20-%20Chemicals%20and%20Toxics.pdf.

Rossi, M. (2014). *The Business Case for Knowing Chemicals in Products and Supply Chains.* http://web.unep.org/chemicalsandwaste/sites/unep.org.chemicalsandwaste/files/publications/UNEP CiP Business case_En.pdf.

Sager-Rosenthal, I. (2019). Major retailers phasing out worst of the worst chemicals: chemical laws help ensure safer products for all, 18 February. *Toxic-Free Future*. https://toxicfreefuture.org/major-retailers-phasing-out-worst-of-the-worst-chemicals/. Accessed 20 February 2019.

Scruggs, C. (2013). Reducing hazardous chemicals in consumer products: proactive company strategies. *Journal of Cleaner Production* 44, 105-114. https://doi.org/10.1016/j.jclepro.2012.12.005.

Sebastiani R., Corsaro D., Montagnini F. and Tzannis A. (2015). Sustainability in the supply chain: the retailers' perspective. In: *Marketing in Transition: Scarcity, Globalism, & Sustainability. Developments in Marketing Science: Proceedings of the Academy of Marketing Science.* Campbell C.L (ed.). 8-12. https://doi.org/10.1007/978-3-319-18687-0_5.

Sheldon, R.A., (2016). Green chemistry and resource efficiency: towards a green economy. *Green Chemistry* 18(11), 3180-3183. https://doi.org/10.1039/C6GC90040B.

Stringer, L. (2018). Cross-sector initiative sets full materials disclosure goal, 14 June. *Chemical Watch*. https://chemicalwatch.com/67695/cross-sector-initiative-sets-full-materials-disclosure-goal. Accessed 1 January 2019.

Sturcken, E. (2017). Walmart effect: Retailers lead the way on chemical safety at a critical time, 10 October. *Environmental Defense Fund*. https://www.edf.org/blog/2017/10/10/walmart-effect-retailers-lead-way-chemical-safety-critical-time. Accessed 9 September 2018.

Sustainable Brands (2017). Walmart's updated policy aims to drive toxic chemicals out of 90k household products, 28 September. https://www.sustainablebrands.com/news_and_views/chemistry_materials/sustainable_brands/walmarts_updated_policy_aims_drive_toxic_chemi. Accessed 14 September 2018.

Swedish Chemical Agency (2016). *Chemicals in Products: Challenges and Approaches.* https://www.kemi.se/global/broschyrer/chemicals-in-products.pdf.

Target (2017). Target announces new chemical strategy including policy and goals for its products and operations, 25 January. https://corporate.target.com/article/2017/01/chemical-policy-and-goals. Accessed 15 September 2018.

United Nations Environment Programme (2014). *Sustainability of Supply Chains and Sustainable Public Procurement: A Pre Study.* http://www.oneplanetnetwork.org/sites/default/files/sustainability_of_supply_chains_and_sustainable_public_procurement.pdf.

United Nations Environment Programme (2015). *The Chemicals in Products Programme: Guidance for Stakeholders on Exchanging Chemicals in Products Information*. http://www.saicm.org/Portals/12/Documents/EPI/Guidance%20for%20Stakeholder%20in%20Exchanging%20CiP%20Information_October2015.pdf.

United States Green Building Council (2019). Integrative Analysis of Building Materials. https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-healthca-87. Accessed 20 February 2019.

Van Hamelen, E. (2018). *Without Chemistry There Can Be No Circular Economy: The Imperative of a New Perspective on Chemicals and Materials Management.* Planegg: The Natural Step. https://thenaturalstep.org/wp-content/uploads/2018/05/20180508-_Circular-chemistry-EN-BioEDIT-TNSinternational.pdf.

Waerder, B., Stinnes, S. and Erdenberger, O. (2017). Design thinking as driver for innovation in the chemical industry. *Journal of Business Chemistry* 14(2), 41-50. http://www.businesschemistry.org/article/?article=247.

Chapter 7

Ahi, P. and Searcy, C. (2015). An analysis of metrics used to measure performance in green and sustainable supply chains. *Journal of Cleaner Production* 86, 360–377. https://doi.org/10.1016/j.jclepro.2014.08.005.

Berrone, P. (2016). How to succeed at sustainability (and why greenwashing doesn't work), 25 September. *Forbes*. https://www.forbes.com/sites/iese/2016/09/15/how-to-succeed-at-sustainability-and-why-greenwashing-doesnt-work/#152316c3124e. Accessed 14 September 2018.

Blasco, J.L., King, A., McKenzie, M. and Karn, M. (2017). *The Road Ahead: The KPMG Survey of Corporate Responsibility Reporting 2017*. https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2017/10/kpmg-survey-of-corporate-responsibility-reporting-2017.pdf.

Bluesign (2018). Bluesign® system. http://www.bluesign.com. Accessed 14 September 2018.

Britzelmaier, B., Franziska, F., Landwehr, M. and Salerno, L. (2015). Evidences for sustainability in the chemical industry - An international comparison. *International Journal of Sales, Retailing and Marketing* 4(2), 3-21. http://www.ijsrm.com/ijsrm/Current_&_Past_Issues_files/IJSRM4-2.pdf.

Chemie3 (2018). Die initiative: Fortschrittsindikatoren von Chemie³ [Progress Indicators of Chemie³]. https://www.chemiehoch3.de/de/home/die-initiative/fortschrittsindikatoren.html. Accessed 14 September 2018.

Cleary, S. (2015). *Inquiry: Design of a Sustainable Financial System - Stock Exchanges and Sustainability.* Inquiry Working Paper. Geneva: United Nations Environment Programme. http://unepinquiry.org/wp-content/uploads/2015/12/Stock_Exchanges_and_Sustainability.pdf.

Cockcroft, L.-J. and Persich, T. (2017). *Insights on the Impact of REACH & CLP Implementation on Industry's Strategies in the Context of Sustainability: ECHA Corporate Sustainability Strategies - Final Report*. Risk & Policy Analysts Limited. https://echa.europa.eu/documents/10162/13637/echa_css_report_without_case_studies_en.pdf/a0a6f46f-16c8-fbea-8b41-9ff683aafe5c.

Cradle to Cradle Products Innovation Institute (2018). Product certification overview - get certified. https://www.c2ccertified.org/get-certified/product-certification. Accessed 14 September 2018.

Deloitte (2016). *Sustainability Disclosure*: *Getting Ahead* of the *Curve*. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/risk/us-risk-sustainability-disclosure.pdf.

Diamond, M.L., de Wit, C.A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., Arvidsson, R., Bergman, Å., Hauschild, M., Holoubek, I., Persson, L., Suzuki, N., Vighi, M. and Zetzsch, C. (2015). Exploring the planetary boundary for chemical pollution. *Environment International* 78, 8-15. https://doi.org/10.1016/j.envint.2015.02.001.

Dow Chemical Company (2015). *2015 Sustainability Goals: The Sustainable Chemistry Index*. http://storage.dow.com.edgesuite.net/dow.com/sustainability/goals/50409-SustainableChemistry-WPaper-Digital.pdf.

Dow Chemical Company (2017). *2017 Dow Sustainability Report*. https://corporate.dow.com/-/media/dow/corporate/dow-corporate/sustainability/2025-goals/pdf/dow-2017-sustainability-report.ashx.

Eccles, R.G., Ioannou, I. and Serafeim, G. (2014). The impact of corporate sustainability on organizational processes and performance. *Management Science* 60(11), 2835–2857. https://doi.org/10.1287/mnsc.2014.1984.

Equator Principles (2013). *The Equator Principles: A Financial Industry Benchmark for Determining, Assessing and Managing Environmental and Social Risk in Projects*. http://equator-principles.com./wp-content/uploads/2017/03/equator_principles_III.pdf.

Financial Times (n.d.). Definition of ESG. *Lexicon*. http://lexicon.ft.com/Term?term=ESG. Accessed 15 August 2018

Fink, L. (2018). Larry Fink's letter to CEOs: a sense of purpose. *BlackRock*. https://www.blackrock.com/corporate/investor-relations/2018-larry-fink-ceo-letter. Accessed 14 September 2018.

Follette, C., Jung, U., Kharisov, I., zum Felde, A.M. and Rubel, H. (2017). Making a business case for sustainability in chemicals, 19 April. *The Boston Consulting Group*. https://www.bcg.com/publications/2017/making-business-case-sustainability-chemicals.aspx. Accessed 14 September 2018.

Future-Fit Foundation (2017). Business Benchmark. http://futurefitbusiness.org. Accessed 14 September 2018.

German Environment Agency (2011). *Guide on Sustainable Chemicals: A Decision Tool for Substance Manufacturers, Formulators and End Users of Chemicals*. https://www.umweltbundesamt.de/publikationen/guide-on-sustainable-chemicals.

German Environment Agency (2016). SubSelect - guide for the selection of sustainable chemicals, 15 November. https://www.umweltbundesamt.de/en/document/subselect-guide-for-the-selection-of-sustainable. Accessed 21 February 2019.

German Environment Agency (2018). Das instrument SMART 5 zur bewertung der nachhaltigkeit von chemikalienleasing [The instrument SMART 5 for the evaluation of the sustainability of chemical leasing]. https://www.umweltbundesamt.de/dokument/das-instrument-smart-5-zur-bewertung-der. Accessed 21 February 2019.

Global Reporting Initiative (2016). Sustainability disclosure database: SDG target 12.6 global real time tracker. http://database.globalreporting.org/SDG-12-6/Global-Tracker. Accessed 14 September 2018.

Global Reporting Initiative (n.d.). *Materiality: What Topics Should Organizations Include in Their Reports? Draft*. https://www.globalreporting.org/resourcelibrary/Materiality.pdf.

GoodGuide (2018). Let us guide you to what's good: search for healthier products. https://www.goodguide.com/#/. Accessed 14 September 2018.

Green Chemistry & Commerce Council (n.d. a). *S.C. Johnson Is Transforming Its Supply Chain to Create Products That Are Better for the Environment: Case Study for the Green Chemistry and Commerce Council (GC3)*. http://www.greenchemistryandcommerce.org/downloads/SCJ_final.pdf.

Green Chemistry & Commerce Council (n.d. b). Advancing green chemistry across sectors and supply chains. https://greenchemistryandcommerce.org/. Accessed 2 January 2019.

Haffar, M. and Searcy. C. (2018). The use of context-based environmental indicators in corporate reporting. *Journal of Cleaner Production* 192. 496-513. https://doi.org/10.1016/j.jclepro.2018.04.202.

International Chemical Secretariat (2017). Investor analysis of chemicals management increases thanks to ChemSec and RobecoSAM, 30 March. http://chemsec.org/investor-analysis-of-chemicals-management-increases-thanks-to-chemsec-and-robecosam/. Accessed 14 September 2018.

International Council of Chemical Associations (2015). *2015 Responsible Care Status Report*. https://www.icca-chem.org/wp-content/uploads/2015/09/2015-Responsible-Care-Status-Report.pdf.

International EPD System (2017). *Environmental Product Declarations*. https://www.environdec.com/News-archive/New-brochures-to-explain-EPDs-available/.

International Organization for Standardization (2019). Standards catalogue 13.020.50 – ecolabelling. https://www.iso.org/ics/13.020.50/x/. Accessed 1 January 2019.

KPMG, Global Reporting Initiative, United Nations Environment Programme and Center for Corporate Governance in Africa (2016). *Carrots & Sticks: Global trends in sustainability reporting regulation and policy*. https://www.carrotsandsticks.net/wp-content/uploads/2016/05/Carrots-Sticks-2016.pdf.

Kropp, R. (2014). Why companies need context-based sustainability metrics, 24 June. *GreenBiz*. https://www.greenbiz.com/blog/2014/06/26/context-based-sustainability-metrics. Accessed 14 September 2018.

McElroy, M.W. and Baue, B. (2013). Research needs and opportunities in context-based sustainability. *Financial Reporting* 2, 47-70. https://www.researchgate.net/publication/261653975_Research_Needs_and_Opportunities_in_Context-Based_Sustainability.

Principles for Responsible Investment (n.d.). PRI: ESG issues. https://www.unpri.org/esg-issues. Accessed 21 February 2019.

PUMA (2018). PUMA progress report 2017. https://about.puma.com/en/sustainability/environment/chemicals. Accessed 1 January 2019.

Ridoutt, B., Fantke, P., Pfister, S., Bare, J., Boulay, A.-M., Cherubini, F., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Jolliet, O., Levasseur, A., Margni, M., McKone, T., Michelsen, O., Milà i Canals, L., Page, G., Pant, R., Raugei, M., Sala, S., Saouter, E., Verones, F. and Wiedmann, T. (2015). Making sense of the minefield of footprint indicators. *Environmental Science & Technology* 49(5), 2601-2603. https://doi.org/10.1021/acs.est.5b00163.

Robèrt, K.-H., Broman, G.I. and Basile, G. (2013). Analyzing the concept of planetary boundaries from a strategic sustainability perspective: how does humanity avoid tipping the planet? *Ecology and Society* 18(2), art5 1-9. https://doi.org/10.5751/es-05336-180205.

Rossi, M.S., Edwards, S., Peele, C. and Greiner, T. (2017). *The Chemical Footprint Project: 2017 Annual Report*. Chemical Footprint Project. https://www.chemicalfootprint.org/results/2017-report.

Rydberg, T., Sala, S., Bjorn, A., Molander, S., Payet, J., Posthuma, L., Sörme, L., Vighi, M. and Zijp, M.C. (2014). *Towards a Common Conceptual Framework for Chemical Footprint Bridging Risk Assessment and Life Cycle Assessment: Short Review and Way forward*. Extended Abstract and Oral Presentation at SETAC EU Annual Meeting. No. C 31. Göteborg: IVL Swedish Environmental Research Institute. https://www.ivl.se/download/18.4b1c947d15125e72dda13f6/1449742312935/C31.pdf.

S.C. Johnson & Son (2018). What's inside SC Johnson products. https://www.whatsinsidescjohnson.com/us/en. Accessed 14 September 2018.

Safer Chemicals, Healthy Families (2018a). Mind the store. https://saferchemicals.org/mind-the-store/. Accessed 14 September 2018.

Sigma-Aldrich (n.d.). Environmental Sustainability. https://www.sigmaaldrich.com/globalcitizenship/environmental.html. Accessed 14 September 2018.

Society of Environmental Toxicology and Chemistry (2018). About SETAC. https://www.setac.org/page/AboutSETAC. Accessed 21 February 2019.

Stacchezzini, R., Melloni, G and Lai, A. (2016). Sustainability management and reporting: the role of integrated reporting for communicating corporate sustainability management. *Journal of Cleaner Production* 136, 102-110. https://doi.org/10.1016/j.jclepro.2016.01.109.

Stec, S., Paszkiewicz, M. and Antypas, A. (2017). Is the time ripe for global binding norms for corporate accountability? *International Journal of Innovation and Sustainable Development* 11(2/3) 130-148. https://doi.org/10.1504/IJISD.2017.083321.

Sumitomo Chemical Group (2016). *CSR Report 2016: Sustainable Chemistry*. http://www.sumitomo-chem.co.jp/english/csr/report/docs/csr_report_e2016.pdf.

Sustainability Accounting Standards Board (2015). *Sustainability Accounting Standard Resource Transformation Sector: Chemicals - Sustainability Accounting Standard*. http://www.sasb.org/wp-content/uploads/2015/03/RT0101_Chemical_Standard2.pdf.

Sustainability Accounting Standards Board (2018). SASB materiality map™ https://materiality.sasb.org/?hsCtaTracking=28ae6e2d-2004-4a52-887f-819b72e9f70a%7C160e7227-a2ed-4f28-af33-dff50a769cf4. Accessed 14 September 2018.

Sustainalytics (n.d.). Sustainalytics. https://www.sustainalytics.com/. Accessed 14 September 2018.

Tickner, J.A. and Becker, M. (2016). Mainstreaming green chemistry: the need for metrics. *Current Opinion in Green and Sustainable Chemistry* 1, 1-4. https://doi.org/10.1016/j.cogsc.2016.07.002.

Together for Sustainability (2016). The chemical initiative for sustainable supply chains. https://tfs-initiative.com. Accessed 14 September 2018.

Tranchard, S. (2018). New version of ISO 14024 on ecolabelling just published, 9 March. *International Organization for Standardization*. https://www.iso.org/news/ref2273.html. Accessed 1 January 2019.

United Nations (2012). United Nations Conference on Sustainable Development, Rio+20. https://sustainabledevelopment.un.org/rio20. Accessed 11 September 2018.

United Nations (2018). Sustainable Development Goals Partnerships Platform: VinylPlus. https://sustainabledevelopment.un.org/partnership/?p=91. Accessed 21 February 2019.

United Nations Environment Programme (2017). Life Cycle Initiative. https://www.lifecycleinitiative.org/. Accessed 1 January 2019.

United Nations Environment Programme (2019). *Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution 2/7*. http://www.saicm.org/Portals/12/Documents/meetings/OEWG3/inf/OEWG3-INF-22-Analysis.pdf.

United Nations Environment Programme and World Bank (2017). *Roadmap for a Sustainable Financial System*. Geneva and Washington, D.C.: United Nations Environment Programme and World Bank. http://documents.worldbank.org/curated/en/903601510548466486/pdf/121283-12-11-2017-15-33-33-RoadmapforaSustainableFinancialSystem.pdf.

United States Government Accountability Office (2018). *Chemical Innovation: Technologies to Make Processes and Products More Sustainable*. https://www.gao.gov/products/GAO-18-307.

United States Green Building Council (2018). LEED v4. https://new.usgbc.org/leed-v4. Accessed 14 September 2018.

World Business Council for Sustainable Development (2014). *Life Cycle Metrics for Chemical Products: A Guideline by the Chemical Sector to Assess and Report on the Environmental Footprint of Products, Based on Life Cycle Assessment*. https://www.wbcsd.org/Projects/Chemicals/Resources/Life-Cycle-Metrics-for-Chemical-Products.

World Business Council for Sustainable Development (2018). *Chemical Industry Methodology for Portfolio Sustainability Assessments (PSA)*. https://www.wbcsd.org/Programs/Energy-Circular-Economy/Factor-10/Sector-Deep-Dives/Resources/Chemical-Industry-Methodology-for-Portfolio-Sustainability-Assessments.

World Economic Forum (2019). Shaping the future of collaborative innovation in chemicals and materials. https://cn.weforum.org/projects/shaping-the-future-of-collaborative-innovation-in-chemicals-and-materials. Accessed 21 February 2019.

Zero Discharge of Hazardous Chemicals (2018). About ZDHC. https://www.roadmaptozero.com/about. Accessed 1 January 2019.

Chapter 8

American Chemical Society Green Chemistry Institute (2017). DOZNTM – a quantitative green chemistry evaluator, 16 August. https://communities.acs.org/community/science/sustainability/green-chemistry-nexus-blog/blog/2017/08/16/dozn-a-quantitative-green-chemistry-evaluator. Accessed 16 July 2018.

American Family Life Assurance Company of Columbus and American Family Life Assurance Company of New York (2017). *2017 AFLAC CSR Survey: Storylines and Highlights*. https://www.aflac.com/docs/about-aflac/csr-survey-assets/2017-csr-survey-deck.pdf.

Antypas, A. and Paszkiewicz, M. (2015). Corporate social responsibility and corporate accountability: a historical overview. In *Corporate Responsibility and Sustainable Development: Exploring the Nexus of Private and Public Interests*. Rayman-Bacchus, L. and Walsh, P.R. (eds.). London: Routledge. Chapter 1. 29-48. https://www.taylorfrancis.com/books/e/9781317540991/chapters/10.4324%2F9781315727790-9.

BASF (2018). Our responsibility to respect human rights. https://www.basf.com/en/company/sustainability/employees-and-society/human-rights.html. Accessed 13 July 2018.

Biswas, A. and Roy, M. (2015). Green products: an exploratory study on the consumer behaviour in emerging economies of the east. *Journal of Cleaner Production* 87, 463-468. https://doi.org/10.1016/j.jclepro.2014.09.075.

Bonney, R., Phillips, T.B., Ballard, H.L. and Enck, J.W. (2016). Can citizen science enhance public understanding of science? *Public Understanding of Science* 25(1), 2-16. https://doi.org/10.1177/0963662515607406.

Boston Consulting Group (2017). How innovation and collaboration can accelerate sustainability in fashion, 14 July. https://www.bcg.com/publications/2017/retail-how-innovation-collaboration-accelerate-sustainability-fashion.aspx. Accessed 24 July 2018.

Buerke, A., Straatmann, T., Lin-Hi, N. and Müller, K. (2017). Consumer awareness and sustainability-focused value orientation as motivating factors of responsible consumer behavior. *Review of Managerial Science* 11(4), 959-991. https://doi.org/10.1007/s11846-016-0211-2.

Business & Human Rights Resource Centre (2018). *Business & Human Rights in the Chemical Industry: An Assessment of Company Responses to Human Rights Issues*. https://www.business-humanrights.org/sites/default/files/BHRRC%20Chemical%20Briefing%2030%20Jan%202018.pdf.

California Office of Environmental Health Hazard Assessment (2013). Proposition 65 in plain language, 1 February. https://oehha.ca.gov/proposition-65/general-info/proposition-65-plain-language. Accessed 22 February 2019.

Canadian Centre for Occupational Health and Safety (2018). Employee rights, 29 June. https://www.ccohs.ca/youngworkers/resources/employeerights.html. Accessed 24 July 2018.

Carrington, D. (2018). Plastic microbeads ban enters force in UK, 9 January. *The Guardian*. https://www.theguardian.com/environment/2018/jan/09/plastic-microbeads-ban-enters-force-in-uk. Accessed 30 August 2018.

Caruana, R. and Chatzidakis, A. (2014). Consumer social responsibility (CnSR): toward a multi-level, multi-agent conceptualization of the "other CSR". *Journal of Business Ethics* 121(4), 577-592. https://doi.org/10.1007/s10551-013-1739-6.

Casson, L. (2017). Microbeads - we won! 21 July. *Greenpeace UK*. https://www.greenpeace.org.uk/microbeads-we-won/. Accessed 30 August 2018.

Chemical & Allied Industries' Association (2017). *Responsible Care® Performance Report 2017: South Africa*. https://www.caia.co.za/wp-content/uploads/2017/12/caia-responsible-care-report-2017-report.pdf.

Conick, H. (2018). How marketing banned microbeads, 28 February. *American Marketing Association*. https://www.ama.org/publications/MarketingNews/Pages/how-marketing-banned-microbeads.aspx. Accessed 24 July 2018.

Deloitte, Food Marketing Institute and Grocery Manufacturers Association (2016). *Capitalizing on the Shifting Consumer Food Value Equation*. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/consumer-business/us-fmi-gma-report.pdf.

Devadhasan, J.P., Kim, D., Lee, D.Y. and Kim, S. (2017). Smartphone coupled handheld array reader for real-time toxic gas detection. *Analytica Chimica Acta* 984, 168-176. https://doi.org/10.1016/j.aca.2017.06.036.

Drozdenko, R.G., Jensen, M. and Coelho, D. (2011). Pricing of green products: premiums paid, consumer characteristics and incentives. *International Journal of Business, Marketing, and Decision Sciences* 4(1), 106-116. https://www.researchgate.net/publication/267725435_Pricing_of_Green_Products_Premiums_Paid_Consumer_Characteristics_and_Incentives.

Eisenhardt, K. (2015). #80 – social media influences chemical industry to move beyond compliance, 12 February. *CERM® Risk Insights*. http://insights.cermacademy.com/2015/02/80-social-media-influences-chemical-industry-move-beyond-compliance-kelly-eisenhardt/. Accessed 16 September 2018.

Environmental Rights Database (n.d. a). Mexican national human rights commission's environmental actions. http://environmentalrightsdatabase.org/mexican-national-human-rights-commissions-environmental-actions/. Accessed 24 July 2018.

Environmental Rights Database (n.d. b). Jurisprudence of the Supreme Court of India relating to environmental protection. http://environmentalrightsdatabase.org/jurisprudence-of-the-supreme-court-of-india-relating-to-environmental-protection/. Accessed 16 September 2018.

Euro RSCG Worldwide (2011). New study shows millennials rejecting traditional politics in favor of individual action; heightened expectations of business, 11 March. *PR Newswire*. https://www.prnewswire.com/news-releases/new-study-shows-millennials-rejecting-traditional-politics-in-favor-of-individual-action-heightened-expectations-of-business-119756679.html. Accessed 24 July 2018.

European Agency for Safety and Health at Work (2018). Homepage. https://osha.europa.eu/en. Accessed 13 September 2018.

European Chemicals Agency (2018). How to participate in the public consultation on ECHA's draft recommendation. https://echa.europa.eu/participate-in-the-public-consultation. Accessed 29 August 2018.

GoodElectronics (2015). Challenge to the global electronics industry, 1 March. https://goodelectronics.org/challenge-to-the-global-electronics-industry/. Accessed 21 February 2019.

GoodGuide (2019). Personal care. https://www.goodguide.com/#/categories/152786. Accessed 21 February 2019.

Government of Canada (2016). Risk management of chemical substances: what is risk management? 4 July. https://www.canada.ca/en/health-canada/services/chemical-substances/canada-approach-chemicals/risk-management.html. Accessed 21 February 2019.

Government of Canada (2017). Risk assessment of chemical substances, 16 November. https://www.canada.ca/en/health-canada/services/chemical-substances/canada-approach-chemicals/risk-assessment.html. Accessed 21 February 2019.

Green America Center for Sustainability Solutions (n.d. a). About us. http://www.centerforsustainabilitysolutions.org/introduction#introduction-green-america. Accessed 21 February 2019.

Green America Center for Sustainability Solutions (n.d. b). *Cleaner Electronics Production Network*. https://static1.squarespace.com/static/558b1fe4e4b00725460da07a/t/5b43803888251beed8d49dd3/1531150394640/CEPN+Poster+for+Print.pdf.

Hancock, A. (2017). Younger consumers drive shift to ethical products, 23 December. *Financial Times*. https://www.ft.com/content/8b08bf4c-e5a0-11e7-8b99-0191e45377ec. Accessed 16 September 2018.

Hartmann, S. and Klaschka, U. (2017). Interested consumers' awareness of harmful chemicals in everyday products. *Environmental Sciences Europe* 29(1), 29. https://doi.org/10.1186/s12302-017-0127-8.

He, G., Boas, I., Mol, A.P.J. and Lu, Y. (2017). E-participation for environmental sustainability in transitional urban China. *Sustainability Science* 12(2), 187-202. https://doi.org/10.1007/s11625-016-0403-3.

Imam, J. (2015). Microbead ban signed by President Obama, 31 December. *CNN*. https://edition.cnn.com/2015/12/30/health/obama-bans-microbeads/index.html. Accessed 30 August 2018.

International Council of Chemical Associations (2015). Responsible care global charter. https://www.icca-chem.org/responsible-care-global-charter/. Accessed 16 September 2018.

International Food Information Council Foundation (2018). *2018 Food and Health Survey*. https://www.foodinsight.org/2018-food-and-health-survey.

International Network for Economic Social & Cultural Rights (2018). Lagos del Campo vs Peru, case no. 12.795, judgment of 31 August 2017 (preliminary objections, merits, reparations and costs), 26 April. https://www.escr-net.org/caselaw/2018/lagos-del-campo-vs-peru-case-no-12795-judgment-31-august-2017-preliminary-objections. Accessed 13 September 2018.

Inter-American Commission on Human Rights (2011). Article 13 - American Convention on human rights: freedom of thought and expression, 1 August. *Organization of American States*. http://www.oas.org/en/iachr/expression/showarticle.asp?artID=25&lID=1. Accessed 16 September 2018.

Joyce, K. and Senier, L. (2017). Why environmental exposures? *Environmental Sociology* 3(2), 101-106. https://doi.org/10.1080/23251042.2017.1281375.

Khare, A. (2015). Antecedents to green buying behaviour: a study on consumers in an emerging economy. *Marketing Intelligence & Planning* 33(3), 309-329. https://doi.org/10.1108/mip-05-2014-0083.

Klara, R. (2018). Switching to healthy ingredients is riskier for brands than you might think, 5 January. *Adweek*. https://www.adweek.com/brand-marketing/switching-to-healthy-ingredients-is-riskier-for-brands-than-you-might-think/. Accessed 16 September 2018.

Klaschka, U. (2016). Natural personal care products-analysis of ingredient lists and legal situation. *Environmental Sciences Europe* 28(8), 1-14. https://doi.org/10.1186/s12302-016-0076-7.

Klaschka, U. (2017). Where are the SVHCs? 10 years consumer's right to know' about substances of very high concern. *Environmental Sciences Europe* 29(24), 1-14. https://doi.org/10.1186/s12302-017-0122-0.

Kumar, P. and Ghodeswar, B.M. (2015). Factors affecting consumers' green product purchase decisions. *Marketing Intelligence & Planning* 33(3), 330-347. https://doi.org/10.1108/mip-03-2014-0068.

LIFE AskREACH (2018). Consumer app inquiry results in international company taking product off the market, 7 May. https://www.askreach.eu/consumer-app-inquiry-results-in-international-company-taking-product-off-the-market/. Accessed 30 August 2018.

Lovell, T. (2018). EU-wide app to learn from Danish project problems, 13 March. *Chemical Watch*. https://chemicalwatch.com/64821/eu-wide-app-to-learn-from-danish-project-problems. Accessed 30 August 2018.

Luca, F.-A., Ciobanu, C.-I., Andrei, A., Horodnic, A., Luca, F.-A., Ciobanu, C.-I., Andrei, A.G. and Horodnic, A. V. (2018). Raising awareness on health impact of the chemicals used in consumer products: Empirical evidence from East-central Europe. *Sustainability* 10(1), 209. https://doi.org/10.3390/su10010209.

Maniatis, P. (2016). Investigating factors influencing consumer decision-making while choosing green products. *Journal of Cleaner Production* 132, 215-228. https://doi.org/10.1016/j.jclepro.2015.02.067.

Mathios, A.D. (2000). The impact of mandatory disclosure laws on product choices: an analysis of the salad dressing market. *The Journal of Law and Economics* 43(2), 651-678. https://doi.org/10.1086/467468.

Merck (2017). Merck corporate responsibility report 2016: human rights, 28 April. http://reports.merckgroup.com/2016/cr-report/strategy-management/human-rights.html. Accessed 17 September 2018.

Mitchell, E.A.D., Mulhauser, B., Mulot, M., Mutabazi, A., Glauser, G. and Aebi, A. (2017). A worldwide survey of neonicotinoids in honey. *Science* 358(6359), 109-111. https://doi.org/10.1126/science.aan3684.

National Geographic and Globescan (2014). *Greendex 2014: A Consumer Choice and the Environment - A Worldwide Tracking Survey*. https://globescan.com/wp-content/uploads/2017/07/Greendex_2014_Full_Report_NationalGeographic_GlobeScan.pdf.

Nielsen (2016). *What's in Our Food and on Our Minds: Ingredient and Dining Out Trends Around the World*. https://www.nielsen.com/content/dam/nielsenglobal/eu/docs/pdf/Global%20Ingredient%20and%20Out-of-Home%20Dining%20Trends%20Report%20FINAL%20(1).pdf.

O'Rourke, D. and Ringer, A. (2016). The impact of sustainability information on consumer decision making. *Journal of Industrial Ecology* 20(4), 882-892. https://doi.org/10.1111/jiec.12310.

Office of the United Nations High Commissioner for Human Rights (2018). Special Rapporteur on the implications for human rights of the environmentally sound management and disposal of hazardous substances and wastes. https://www.ohchr.org/en/issues/environment/toxicwastes/pages/srtoxicwastesindex.aspx. Accessed 13 September 2018.

Olson, E.L. (2013). It's not easy being green: the effects of attribute tradeoffs on green product preference and choice. *Journal of the Academy of Marketing Science* 41(2), 171-184. https://doi.org/10.1007/s11747-012-0305-6.

Organisation for Economic Co-operation and Development (2017). *Tackling Environmental Problems with the Help of Behavioural Insights*. http://dx.doi.org/10.1787/9789264273887-en.

Organisation for Economic Co-operation and Development (2018). Green growth and consumer behaviour. http://www.oecd.org/greengrowth/greengrowthandconsumerbehaviour.htm. Accessed 17 September 2018.

Pan-European Coalition of Environmental Citizens Organisations (2016). *People Power for the Planet: How the Aarhus Convention Enables Citizens' Voices to Be Heard*. Silina, M. and Wates, J. (eds.). Brussels: European Environmental Bureau. http://eeb.org/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=106&wpfd_file_id=1493&token=ad69a8ebd1b1324d26331563ee0e323e&preview=1.

Peters, B. (2018). Unpacking the diversity of procedural environmental rights: the European Convention on Human Rights and the Aarhus Convention. *Journal of Environmental Law* 30(1), 1-27. https://doi.org/10.1093/jel/eqx023.

Registro de Emisiones y Transferencias de Contaminantes (n.d.). Últimas noticias. http://www.retc.cl/. Accessed 17 September 2018.

Rochman, C.M., Kross, S.M., Armstrong, J.B., Bogan, M.T., Darling, E.S., Green, S.J., Smyth, A.R. and Veríssimo, D. (2015). Scientific evidence supports a ban on microbeads. *Environmental Science & Technology* 49(18), 10759-10761. https://doi.org/10.1021/acs.est.5b03909.

Sammons, C. (2016). 8 mobile apps to help you reduce your exposure to harmful chemicals (& find toxin free food, cosmetics & household products), 8 August. *TimetoCleanse*. https://www.timetocleanse.com/8-mobile-apps-help-reduce-exposure-harmful-chemicals-find-toxin-free-food-cosmetics-household-products/. Accessed 30 August 2018.

Sanders, M. (2017). *When Compliance Isn't Enough: Protecting Your Brand from Negative Public Perception*. Burlington, MA: Haley & Aldrich. http://www.haleyaldrich.com/Portals/0/Downloads/BrandActionReport.pdf?timestamp=1491325162433.

Santiago, K.M., Caban-Martinez, A.J., Baum, J., Pangborn, J., Dikici, E., Solle, N.S., Sterling, D.A., Moore, K., Grace, K., Daunert, S., Deo, S. and Kobetz, E.N. (2018). Passive monitoring of chemical exposures in south Florida firefighters using silicone wristbands. *Occupational and Environmental Medicine* 75(Suppl 2), A203. https://doi.org/10.1136/oemed-2018-icohabstracts.574.

Scherer, C., Emberger-Klein, A. and Menrad, K. (2017). Biogenic product alternatives for children: consumer preferences for a set of sand toys made of bio-based plastic. *Sustainable Production and Consumption* 10, 1-14. https://doi.org/10.1016/j.spc.2016.11.001.

Shewan, D. (2017). Ethical marketing: 5 examples of companies with a conscience, 21 December. *WordStream*. https://www.wordstream.com/blog/ws/2017/09/20/ethical-marketing. Accessed 17 September 2018.

Sigma-Aldrich (2018). Greener alternatives evaluation matrix. https://www.sigmaaldrich.com/chemistry/greener-alternatives/matrix-scoring.html. Accessed 20 July 2018.

Silverstein, M.J. and Sayre, K. (2009). *The Female Economy*. Harvard Business Review. Cambridge, MA: Harvard Business School. https://hbr.org/2009/09/the-female-economy.

Soma, K., Onwezen, M.C., Salverda, I.E. and van Dam, R.I. (2016). Roles of citizens in environmental governance in the information age - four theoretical perspectives. *Current Opinion in Environmental Sustainability* 18, 122-130. https://doi.org/10.1016/j.cosust.2015.12.009.

Tan, Y. (2014). Transparency without democracy: the unexpected effects of China's environmental disclosure policy. *Governance* 27(1), 37-62. https://doi.org/10.1111/gove.12018.

Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M.A. and Parrish, J.K. (2015). Global change and local solutions: tapping the unrealized potential of citizen science for biodiversity research. *Biological Conservation* 181, 236-244. https://doi.org/10.1016/j.biocon.2014.10.021.

Unilever (2018). *Unilever's Supply Chain*. https://www.unilever.com/Images/unilever-supply-chain-overview---may-2018_tcm244-523172_1_en.pdf.

United Nations (2018a). *Regional Agreement on Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean*. https://repositorio.cepal.org/bitstream/handle/11362/43583/1/S1800428_en.pdf.

United Nations (2018b). United Nations and the rule of law: access to justice. https://www.un.org/ruleoflaw/thematic-areas/access-to-justice-and-rule-of-law-institutions/access-to-justice/. Accessed 29 August 2018.

United Nations Development Programme (2014). *Environmental Justice: Comparative Experiences in Legal Empowerment*. http://www.undp.org/content/dam/undp/library/Democratic%20Governance/Access%20to%20Justice%20and%20Rule%20of%20Law/Environmental-Justice-Comparative-Experiences.pdf.

United Nations Educational Scientific and Cultural Organization (2017). *Unpacking Sustainable Development Goal 4 Education 2030: Guide*. http://unesdoc.unesco.org/images/0024/002463/246300E.pdf.

United Nations Environment Programme (2015). *Putting Rio Principle 10 into Action: An Implementation Guide*. http://wedocs.unep.org/handle/20.500.11822/11201.

United Nations Environment Programme (2018). First environmental law clinic opens in Wuhan University, China, 12 July. https://www.unenvironment.org/news-and-stories/blogpost/first-environmental-law-clinic-opens-wuhan-university-china. Accessed 24 July 2018.

United Nations Human Rights Council (2015). *Report of the Special Rapporteur on the Implications for Human Rights of the Environmentally Sound Management and Disposal of Hazardous Substances and Wastes, Baskut Tuncak*. https://www.ohchr.org/EN/Issues/Environment/ToxicWastes/Pages/Righttoinformation.aspx. Accessed 14 November 2018.

United Nations Human Rights Council (2018). *Report of the Special Rapporteur on the Implications for Human Rights of the Environmentally Sound Management and Disposal of Hazardous Substances and Wastes*. http://www.srtoxics.org/wp-content/uploads/2018/09/2018-HRC-report-on-Workers-Rights-EN.pdf.

United Nations Industrial Development Organization (2017). *Industrial Development Report 2018. Demand for Manufacturing: Driving Inclusive and Sustainable Industrial Development*. https://www.unido.org/news/industrial-development-report-2018-launched.

United Nations Special Rapporteur on Human Rights and Toxics (2016a). Right to information on hazardous substances and wastes. http://www.srtoxics.org/issues-of-interest/right-to-information/. Accessed 29 August 2018.

United Nations Special Rapporteur on Human Rights and Toxics (2016b). Human rights implicated by toxic chemicals. http://www.srtoxics.org/your-rights/. Accessed 29 August 2018.

United States Environmental Protection Agency (2018). Public participation process for registration actions, 21 December. https://www.epa.gov/pesticide-registration/public-participation-process-registration-actions. Accessed 22 February 2019.

United States Environmental Protection Agency (2017). Chemical data access tool, 17 March. *Data Catalog*. https://catalog.data.gov/dataset/chemical-data-access-tool. Accessed 13 September 2018.

United States Food and Drug Administration (2017). FDA confirms elevated levels of belladonna in certain homeopathic teething products, 27 January. https://www.fda.gov/newsevents/newsroom/pressannouncements/ucm538684.htm. Accessed 30 August 2018.

United States Occupational Safety and Health Administration (2016). *Workers' Rights*. United States Department of Labor. https://www.osha.gov/Publications/osha3021.pdf.

Wiersma, Y., Parsons, J. and Lukyanenko, R. (2016). Data quality in citizen science – a research study. *Environmental Scientist* 74–78. https://www.researchgate.net/publication/311206140.

Wine, O., Hackett, C., Campbell, S., Cabrera-Rivera, O., Buka, I., Zaiane, O., DeVito, S.C. and Osornio-Vargas, A. (2014). Using pollutant release and transfer register data in human health research: a scoping review. *Environmental Reviews* 22(1), 51-65. https://doi.org/10.1139/er-2013-0036.

Youngquist, C.P., Goldberger, J.R., Doyle, J. and Jones, S.S. (2015). Public involvement in waste management research and decision-making: a case study. *Regional Science Policy & Practice* 7(3), 141-161. https://doi.org/10.1111/rsp3.12061.

Zero Discharge of Hazardous Chemicals (2014). *2014 Right-to Know Disclosure Methodology Research: Joint Roadmap Version 2 Milestone*. https://www.roadmaptozero.com/fileadmin/layout/media/downloads/en/RightToKnowDisclosureMethodologies.pdf.

Zero Discharge of Hazardous Chemicals (2018). Leading the textile, leather and footwear industries towards zero discharge of hazardous chemicals. https://www.roadmaptozero.com/. Accessed 2 August 2018.

Zettler, E.R., Takada, H., Monteleone, B., Mallos, N., Eriksen, M. and Amaral-Zettler, L.A. (2016). Incorporating citizen science to study plastics in the environment. *Analytical Methods* 9(9), 1392-1403. https://doi.org/10.1039/c6ay02716d.