UN environment programme

GREEN AND SUSTAINABLE CHEMISTRY:

FRAMEWORK MANUAL

Acknowledgements
The United Nations Environment Programme wishes to thank all individuals and organizations that have generously contributed their expertise, time, and energy.
The Framework Manual was prepared by the United Nations Environment Programme, Economy Division, Chemicals and Health Branch with the following support:

Lead author: Achim Halpaap
Project coordinator: Sandra Averous-Monnery
Further valuable input within the United Nations Environment Programme in preparing the manuals was provided by Monika Gail MacDevette, Jacqueline Alvarez, Josiane Aboniyo, Colin Hannahan, Amelie Ritscher and Tapiwa Nxele.

A group of experts served as an advisory group providing guidance, inputs and written comments on the annotated outline and drafts of the Framework Manual. The experts were: Sam Adu-Kumi (Chemicals Control and Management Centre, Ghana), Paul Anastas (Yale University), Ahmad Ansari and Peter Gregory (ZDHC Foundation), Cristina de Avila and Juergen Helbig (European Commission), Marie-Ange Baucher and Bob Diderich (Organisation for Economic Co-operation and Development), Lorena Betancor (Universidad Ort Uruguay), Richard Blume and Dirk Uhlemann (The Natural Step), Ryan Bouldin (International Pollutants Elimination Network), Irene Caldwell (Horizontal and International Policy Division, Canada), William Carroll (University of Indiana), Claudio Cinquemani, Agnes Dittmar, Creta Gambillara and Janina Haubenreißer (International Sustainable Chemistry Collaborative Centre), Atul Bagai, Divya Datt and Bettina Heller (United Nations Environment Programme), Jost Dittkrist (Secretariat of the Basel, Rotterdam and Stockholm Conventions), Jutta Emig, Steffi Richter and Hans-Christian Stolzenberg (German Environment Agency), Claire Gouvary (Ministère de l'Europe et des Affaires Etrangères), Jean Grundy, Suzanne Leppinen and Victoria Tunstall (Health Canada), Servet Gören, (Cefic), Susan Haffmans (PAN Germany), Klaus Kümmerer (Leuphana University), Marie-Claire Lhenry (Direction générale de la prévention des risques), Anna S. Makarova (Mendeleev University of Chemical Technology of Russia), Brandon Morris (Dow Chemical Company / International Congress and Convention Association), Christoph Neumann (Croplife), Carlos Ocampo (Universidad Pontificia Bolivariana), Rory O'Neill (Hazards magazine), Sharma Rajeev (India Glycols Ltd.), Petra Schwager (United Nations Industrial Development Organization), Nydia Suppen (Center for Life Cycle Analysis and Sustainable Design), Blandine Trouille (US Department of Commerce), Pietro Tundo (University of Venice/ International Union of Pure and Applied Chemistry), Luis Humberto Umanzor Hernandez (United Nations Industrial Development Organization), Claudia A. Pena Urrutia (Asociación de la Industria Eléctrica-Electrónica), Meriel Watts (Pesticide Action Network) and Vania Zuin (York University).

Further comments were received from: Laetitia Montero Catusse, Elisa Tonda, Ran Xie (United Nations Environment Programme), Kristof Doucot, Claudia Kamke, Carolin Sanz Noriega and Maryna Yanush (United Nations Economic Commission for Europe), Peter Fantke (Technical University of Denmark), Kei Ohno-Woodall (Secretariat of the Basel, Rotterdam and Stockholm Conventions), Ajiniyaz Reimov (United Nations Development Programme) and Joel Tickner (University of Massachusetts Lowell).

The draft report was circulated for comments to the other members of the Inter-Organization Programme for the Sound Management of Chemicals (IOMC).

The report has been produced with the financial assistance of the Government of Germany and the Government of Sweden.

ISBN No: 978-92-807-3839-1
Job No: DTI/2337/GE

Layout and graphic design: Lowil Espada.

Feedback and contact: The United Nations Environment Programme encourages interested readers of this report to engage and share their views about the report.

Email: science.chemicals@un.org
Website: https://www.unenvironment.org/explore-topics/chemicals-waste

About the Green and Sustainable Chemistry Framework Manual

This Framework Manual on Green and Sustainable Chemistry has been developed pursuant to the mandate received from the United Nations Environment Assembly (UNEA) in 2019 through Resolution 4/8. Its main purpose is to facilitate a better understanding and provide guidance to countries and stakeholders relevant for advancing green and sustainable chemistry. The Manual will be supplemented with an Executive Summary for decision-makers, as well as specific manuals, resources permitting, covering specific topics to be determined.

A group of experts provided guidance on the annotated outline of the Manual at a workshop on 5-6 December 2019 in Geneva, Switzerland. A revised version took into account comments and advice provided. A first draft of the Framework Manual was reviewed at a virtual expert meeting on 22 June 2020. Input received at the meeting as well as written comments provided by experts were taken into account in preparing this revised draft. A final consultative process to provide final input on the draft Manual took place during the fourth quarter of 2020.

Table of Contents

1

INTRODUCTION ›

Background

The concepts of green and sustainable chemistry have gained significant attention around the world, given their potential to innovate and advance chemistry to help achieve global sustainable development goals and targets. While the concept of "green chemistry" was elaborated through the well-known 12 principles published in 1998 (Anastas and Warner 1998), "sustainable chemistry" has recently evolved as a closely related, yet more holistic concept (Blum *et al.* 2017; Kümmerer 2017).

This Manual takes stocks of the evolution of, and developments in the field of green and sustainable chemistry, including their scientific and social dimensions. Building on this discussion, it provides guidance considered relevant for various stakeholders to scale-up green and sustainable chemistry innovation action and assess management practices. The Manual builds on the 2019 United Nations Environment Programme (UNEP) report 'Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution 2/7' (UNEP 2019a), which was discussed at the fourth session of the United Nations Environment Assembly (UNEA-4) in 2019.

The above cited UNEP (2019a) report summarized more than 50 submissions from stakeholders presented as best practices in sustainable chemistry. It noted that despite valuable progress made, identifying best practices is a challenging task, given the absence of common assessment criteria. It also pointed out that stakeholders have a broad understanding of sustainable chemistry. Drawing on the analysis, the report welcomed further cooperation to facilitate a common understanding of the sustainable chemistry concept, including the relationship between green and sustainable chemistry.

The Global Chemicals Outlook II (GCO-II) published by UNEP in 2019 (UNEP 2019b), provides further insights concerning opportunities toward advancing green and sustainable chemistry throughout value and supply chains. It makes a case for transformative action, and highlights opportunities for taking measures to strengthen an enabling framework to advance green and sustainable chemistry.

Mandate for this Manual

Resolution 4/8 on Sound Management of Chemicals and Waste, adopted by UNEA-4 in 2019, welcomed the analysis of best practices in sustainable chemistry by the United Nations Environment Programme and recognized the value to develop a better understanding of sustainable chemistry opportunities globally. The resolution "requested the Executive Director, subject to the availability of resources and, where appropriate, in cooperation with the member organizations of the Inter-Organization Programme for the Sound Management of Chemicals (IOMC), to synthetize UNEP's analysis of best practices in sustainable chemistry into manuals on green and sustainable chemistry, in consultation with relevant stakeholders, by UNEA-5, and to continue the work on a holistic approach for the sound management of chemicals and waste in the long term, taking into account both the importance of the sound management of chemicals and the potential benefits of chemicals for sustainable development".

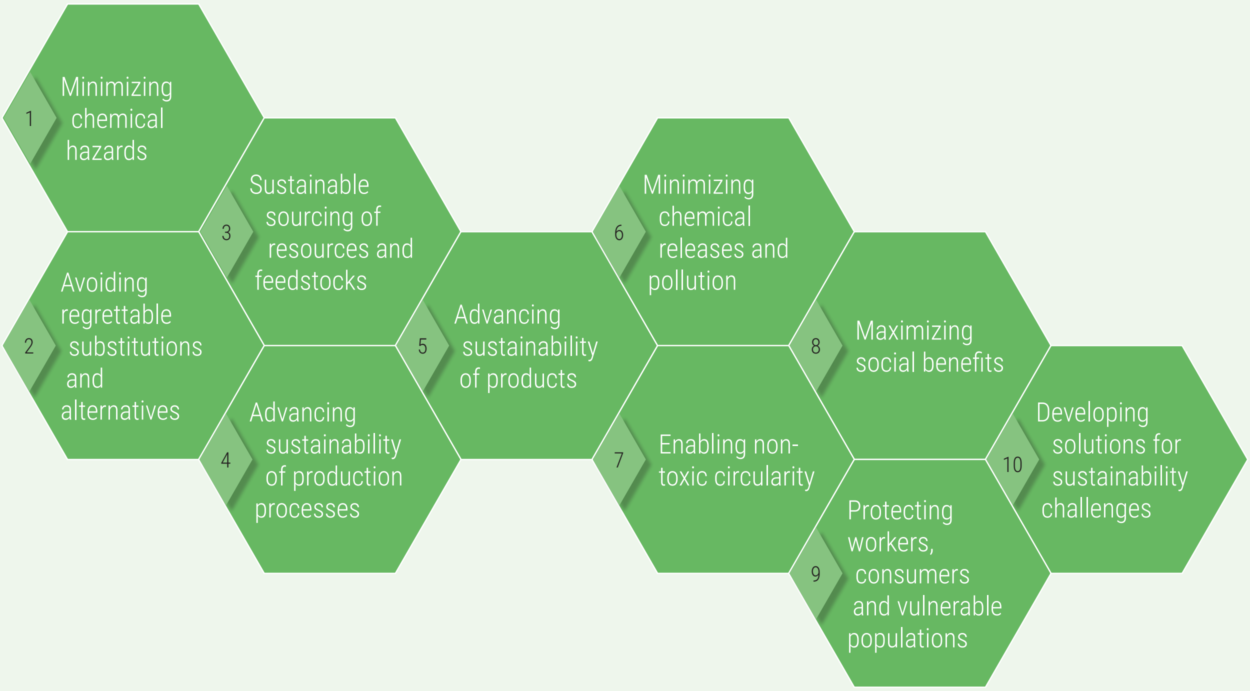
Purpose and approach

The Framework Manual provides a high-level overview of a number of scientific, technical and policy aspects of green and sustainable chemistry, aimed at a broad audience. It discusses various facets of the topic with the intention to foster general learning, reflection and scaling-up action based on a common global understanding of the concept. The topics have been identified following a review of the green and sustainable chemistry literature, the 2019 UNEP report on best practices in sustainable chemistry, and the second edition of the Global Chemicals Outlook (GCO-II). Resources permitting, the Framework Manual will be complemented by specific manuals, covering selected topics of interest to stakeholders. A first manual focusing on green and sustainable chemistry education will be published in 2021.

The Manual also presents a framework which structures and highlights causal linkages among the various topics, ranging from scientific topics to enabling instruments. An important element of the framework are the 10 objectives and guiding considerations for green and sustainable chemistry presented in Chapter 3. The objectives complement traditional approaches in chemistry, by emphasizing sustainability considerations and highlighting what outcomes green and sustainable chemistry seeks to achieve. They also provide practical guidance to stimulate stakeholder action at various levels and in different settings. Ultimately, the objectives seeks to promote innovation to unveil the full potential of chemistry such that it is compatible with and supports the implementation of the 2030 Sustainable Development Agenda.

Green and Sustainable Chemistry Objectives and Guiding Considerations

Chapter 3 of this manual presents 10 green and sustainable chemistry objectives and guiding considerations to motivate stakeholders to reflect on, assess and guide their innovation action and management practices. Stakeholder and actors are encouraged to share them within their networks and encourage their wide application.



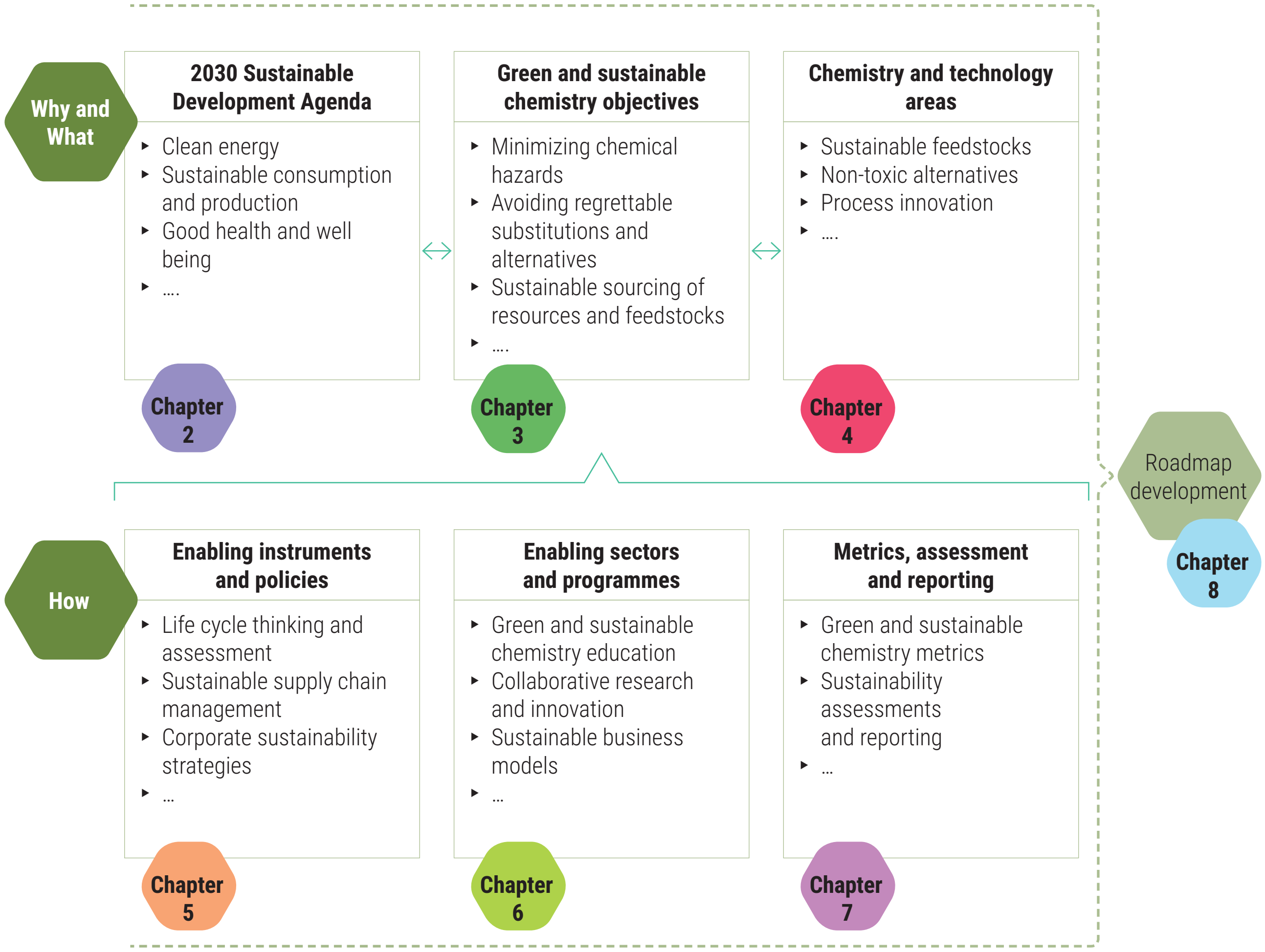
Overview of the framework manual

The Framework Manual is structured into eight chapters. Following this introduction, Chapter 2 discusses challenges and opportunities of chemistry in achieving the UN General Assembly endorsed 2030 Sustainable Development Agenda which seeks to advance meeting human needs within planetary boundaries. Drawing, inter alia, from trends presented in GCO-II, the chapter presents a rationale for advancing green and sustainable chemistry and discusses developments to advance the concepts.

Chapter 3 presents 10 objectives and guiding considerations for stakeholder action to reap the full potential of green and sustainable chemistry in advancing sustainable development in the 21st century. They seek to inform green and sustainable innovations in chemistry but may also be relevant for assessing existing practices throughout the value chains of chemicals and products.

Chapter 4 addresses scientific dimensions of green and sustainable chemistry, by introducing relevant topics of chemistry and technology research and innovation. Chapter 5 introduces enabling management tools, instruments and policies that can help advance green and sustainable chemistry. Closely related, Chapter 6 discusses relevant

Figure 1.1: **Advancing sustainability through green and sustainable chemistry**



enabling sectors and programmes. Chapter 7 takes a look at metrics and reporting schemes relevant for tracking progress and advancing green and sustainable chemistry. Chapter 8 concludes with a call for the "doers and makers" to develop road maps that help advance green and sustainable chemistry action in different settings (e.g. by multiplying good practices).

The Manual is structured alongside the elements of the conceptual framework "Advancing sustainability through green and sustainable chemistry" which was developed through a consultative process and is introduced above (Figure 1.1). Chapters 2, 3 and 4 address the question of: "Why" is green and sustainable chemistry needed and "What" does it aim to achieve, and in which specific innovation areas. Chapters 5, 6 and 7 focus on enabling measures to advance green and sustainable chemistry innovation (the "How"). These action-enabling elements range from promoting life cycle approaches, to strengthening research and innovation policies and programmes. An important enabling and cross-cutting topic is awareness raising and education at all levels that bring the green and sustainable chemistry agenda and knowledge to potential actors, through formal, non-formal and informal education.

Who are the stakeholders encouraged to use this Manual?

This Framework Manual targets a range of audiences and stakeholders concerned with the sound management of chemicals and waste, as well as innovation for green and sustainable chemistry and sustainable product development. They include decision-makers and managers in:

- **Public authorities** responsible for regulating chemicals of concern and promoting innovation for safer chemistry and product sustainability

- **Primary, secondary and tertiary education institutions** engaged in educating the next generation of scientists in the 21st Century .

- **Academic and research institutions** conducting basic and applied research in areas such as chemistry, process engineering and product design.

- **Private sector entities** engaged in all stages of the value chain, from sourcing raw materials and feedstocks, to product design, production, recycling and disposal.

- **Consumers** who can shape the market demand towards safer and more sustainable products, with the choices they make.

- **Civil society organizations** involved in promoting sound management of chemicals and waste by public and private actors and consumers.

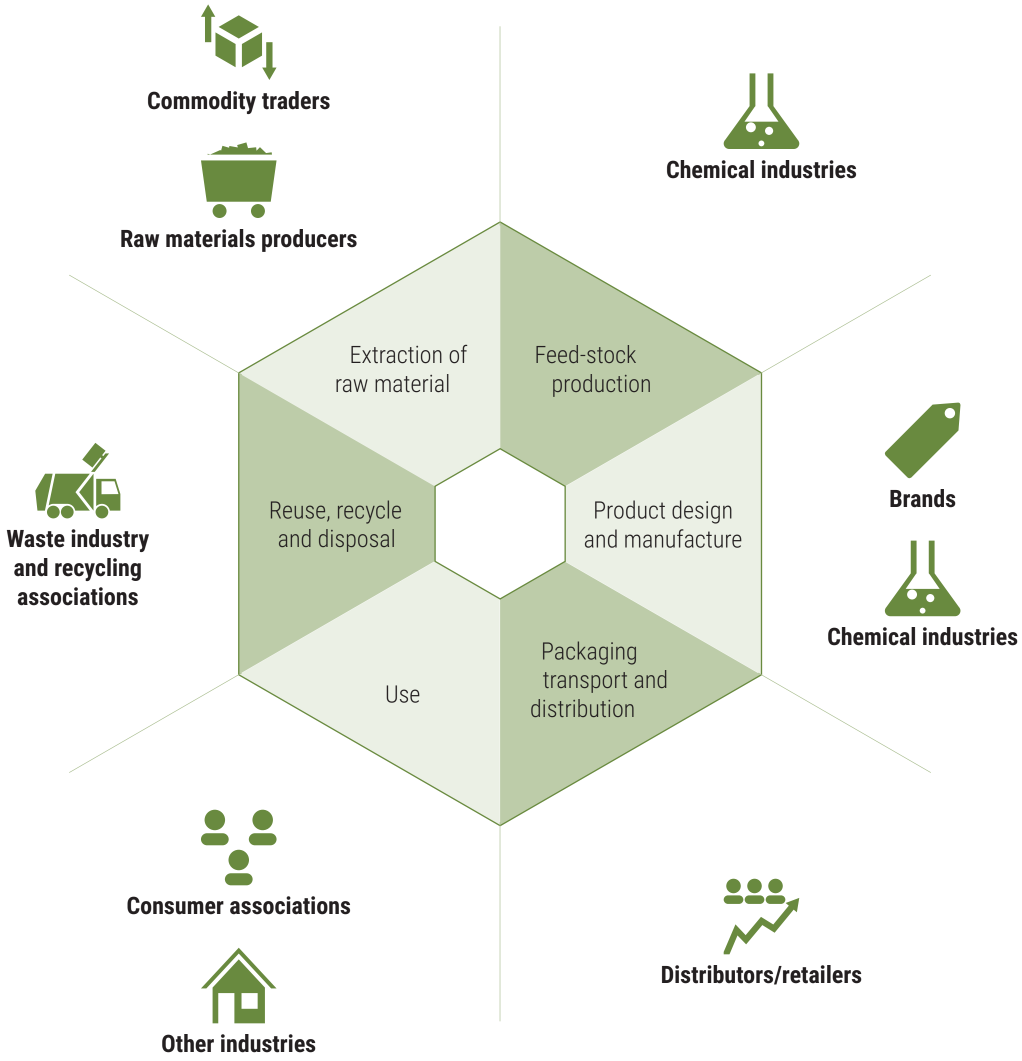
- **Labour organizations** seeking to protect workers from hazardous chemicals.

- **Citizens and the public at large** aspiring for more sustainable lifestyles and societies.

Encouraging private sector action across the value chain

An important stakeholder group which the Manual seeks to reach and stimulate are **private sector** entities. The various actors presented in Figure 1.2 have different roles to play in advancing green and sustainable chemistry during various stages of the chemicals and product value chain. While the list provided in Figure 3.2 is not exhaustive, it seeks to present the main actors involved. A practical measure which private sector actors are encouraged to undertake is to widely disseminate and use the 10 objectives and guiding considerations presented in Chapter 3 to assess and guide their innovation programs and assess current management practices.

Figure 1.2: **Private sector actors in the value chain and product life cycle**



Stakeholder engagement in preparing the manual

An initial outline of the Framework Manual was reviewed during a technical briefing at the third intersessional meeting on chemicals and waste management beyond 2020, September 2019 in Bangkok, Thailand. In-depth discussions took place at a global workshop on 5-6 December 2019 in Geneva, Switzerland. A revised version of the annotated outline was made available in early 2020 considering comments and perspectives provided by participants of the workshop. A first draft of the Framework Manual was reviewed at a virtual expert meeting on 22 June 2020. Input received at the meeting as well as written comments provided by experts were taken into account in preparing a revised draft. A final consultative process took place during the fourth quarter of 2020.

2

CHEMISTRY AND SUSTAINABLE DEVELOPMENT: **CHALLENGES AND OPPORTUNITIES** >

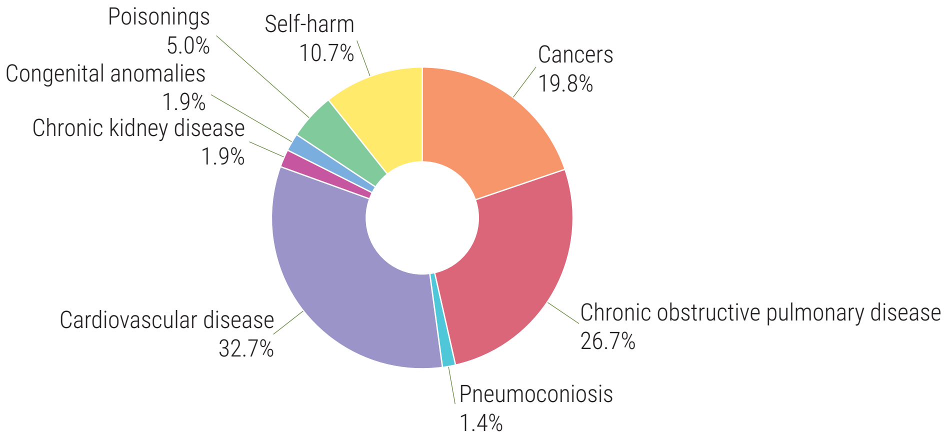
2.1 Why is systemic action to advance green and sustainable chemistry needed?

The following sections draw upon, further elaborate, and feature selected trends, developments and figures presented in the recently published Global Chemicals Outlook-II (UNEP 2019b) and provide the rationale for advancing green and sustainable chemistry action..

Global trends cause significant concerns

The GCO-II recognises that innovations in chemistry can work towards achieving the SDGs, and presents a number of trends that cause concern from a human health, environmental and sustainability perspective. The report provides evidence that the number of chemicals is ever increasing, and that hazardous chemicals and other pollutants continue to be released to indoor and outdoor environments including as waste in large quantities, affecting individuals and communities worldwide. Synthetic chemicals are now ubiquitous in the human body and the environment. Chemical pollution has become a major cause of human disease and premature death. The World Health Organization (WHO) estimated the burden of disease from selected chemicals at 1.6 million lives lost and 44.8 million disability-adjusted life years (DALYs) in 2016 (WHO 2018a) which is likely to be an underestimate. Workers, women, and children are particularly at risk (UNEP 2019b). Furthermore, chemicals accumulate in significant amounts in material stocks and products, creating potentials liabilities in the future.

Figure 2.1: **Deaths (total: 1.6 million) attributed to selected chemicals (per cent) 2016** (adapted from WHO 2018a, p. 2)



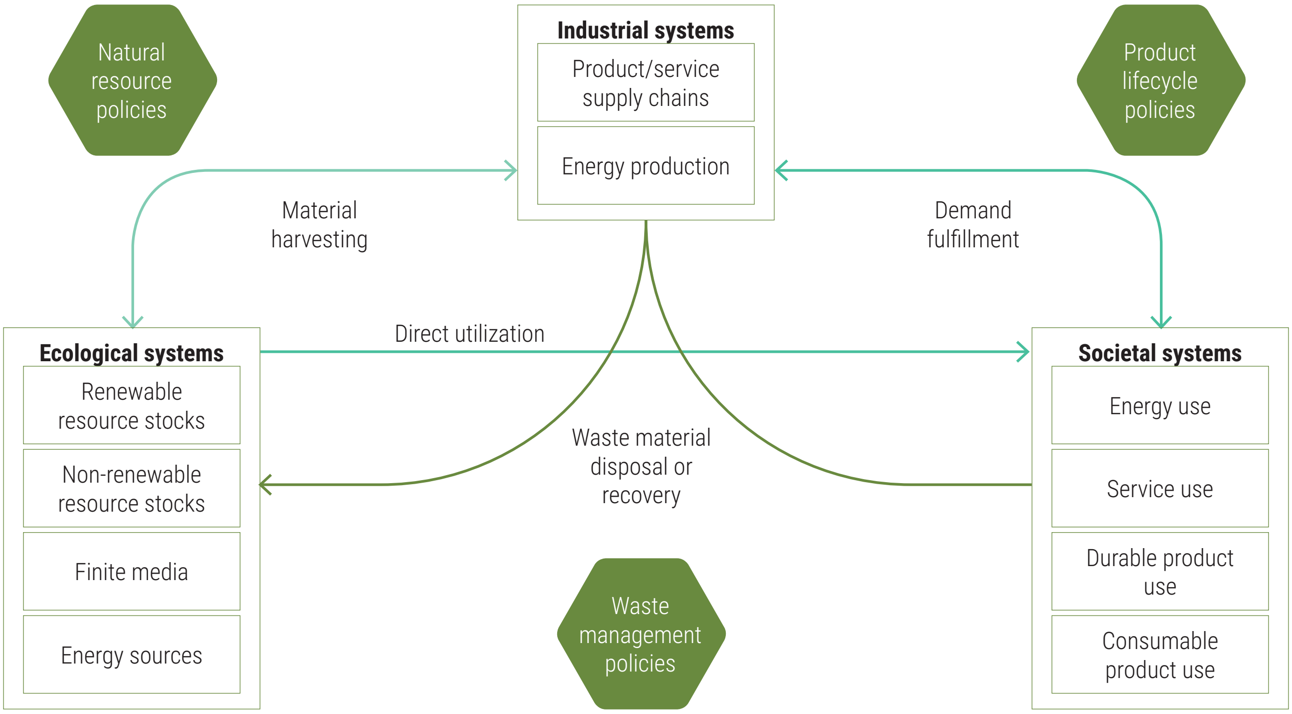
GCO-II concludes that the global goal to minimize adverse impacts of chemicals and waste will not be achieved by 2020. More ambitious and urgent worldwide action by all stakeholders is required and "Business as usual is not an option". Enhanced action needs to include immediate measures to minimize adverse impacts of existing chemicals, for example through bans and restrictions. Beyond these measures, the real opportunity in the 21st century resides in accelerating greener and more sustainable chemistry innovations. This can be achieved by scaling up innovation programmes, developing sustainable value chains that cover the entire lifecycle and commercializing chemicals and products that are sustainable.

Global material and product flows and their chemistry dimension

Since the year 2000, the global production capacity of the chemical industry almost doubled from 1.2 to 2.3 billion tonnes. Global sales of chemicals totalled United States (US) dollars 5.68 trillion in 2017 and is projected to almost double by 2030. Noticeably, growth was most rapid in emerging and developing economies, driven by industrialization, urbanization, and the rise of chemical-intensive industry sectors such as construction, agriculture-food processing, and electronics (UNEP 2019b). The projected growth creates opportunities, but also risks given the hazards and risks of many chemicals on the market and the lack of proper chemical management frameworks in many countries. GCO-II finds that these developments, driven by increased levels of consumption, are unsustainable and create vulnerabilities locally, and along the supply chains. Advanced manufacturing based on green and sustainable chemistry innovation offers novel options in the 21st century to help achieve sustainable consumption and production and product innovation, and a more balanced relationship with the earth.

The chemical industry plays a key role in turning raw materials and feedstocks into products and services, with materials flowing through ecological, industrial and societal systems. Chemistry is also the main science creating the new molecules and materials needed to achieve a number of SDGs. According to the OECD (2010), *Ecological Systems* provide the natural capital from which materials are extracted or derived. They include renewable resource stocks, such as forests, non-

Figure 2.2: **Systems View of Material Flow Cycles** (Organisation for Economic Co-operation and Development [OECD] 2010, p. 21)



renewable resource stocks (e.g. petroleum, metals), environmental media (i.e. air, water, and land) and physical renewable sources of energy (e.g. solar, geothermal, wind and tidal energy). *Industrial Systems* utilize ecosystem services and derive materials from natural capital, turning them into a finished product or service, and for a price. Some materials end up as stocks within infrastructures, like buildings. Finally, *Societal Systems* consume products, services, and energy supplied by industrial systems and generate waste that may be recycled back into *Industrial Systems* or is deposited into the Ecological System. *Societal Systems* many also consume ecosystem services and resource stocks directly, such as water (OECD 2010).

Complex global supply chains and product life cycles

Complex supply chains that span around the world, coupled with limitations in information about chemicals in production and products make it difficult for product manufacturers and retailers to know which chemicals are released throughout the product life cycle and in what quantities. These limitations create challenges for taking action across the product life cycle, such as minimizing chemical releases during production and exposure of workers during manufacturing; reducing consumer exposure; and reducing chemical emissions during recycling and final disposal. These knowledge gaps also create uncertainties for investors. The supply chain for an electronic product below illustrates the complexities of global supply chains in a specific economic sector and across geographic locations.

Multiple dimensions of the chemical enterprise affecting sustainability

The chemical enterprise – whether it is an individual facility, a brand, or the industry as a whole- has many interconnected dimensions that affect sustainability. Relevant topics include, for example, sourcing of sustainable raw materials and feedstocks, water and energy use, design toward function, use and reuse, safety management systems throughout the global supply chain, etc. Figure 2.4 provides an overview of relevant topics (Hill, Kumar and Verma 2013). Assessing the sustainability of the chemical industry, therefore, requires more than assessing hazards and risks of chemical products and production processes.

Another important question is how to deal with potential trade-offs across areas, for example, reducing CO2-emissions through composite materials that may not be recyclable, or using toxic heavy metals in devices used for generating

Figure 2.3: **The complexity of global supply chains: the case of an electronic product** (adapted from Sourcemap 2012)

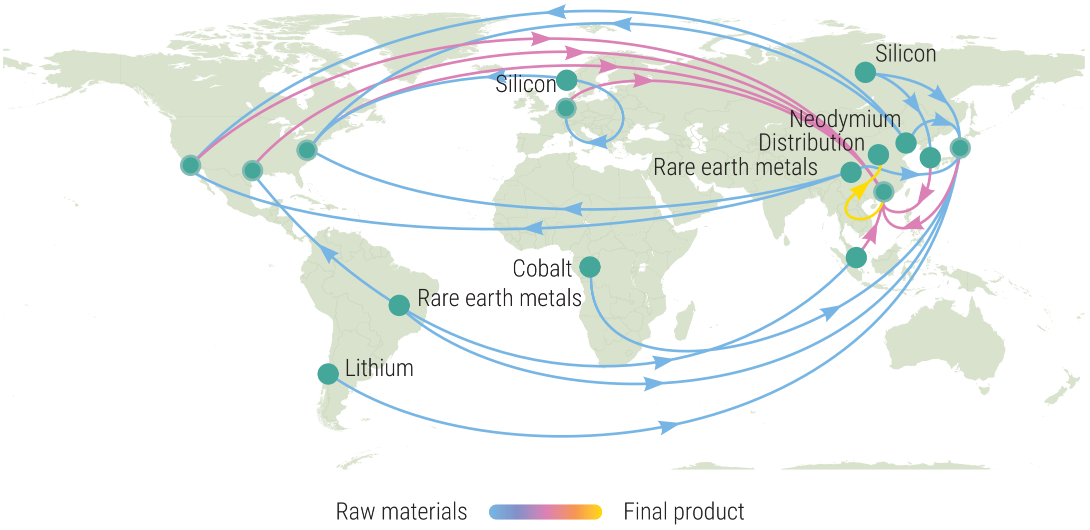
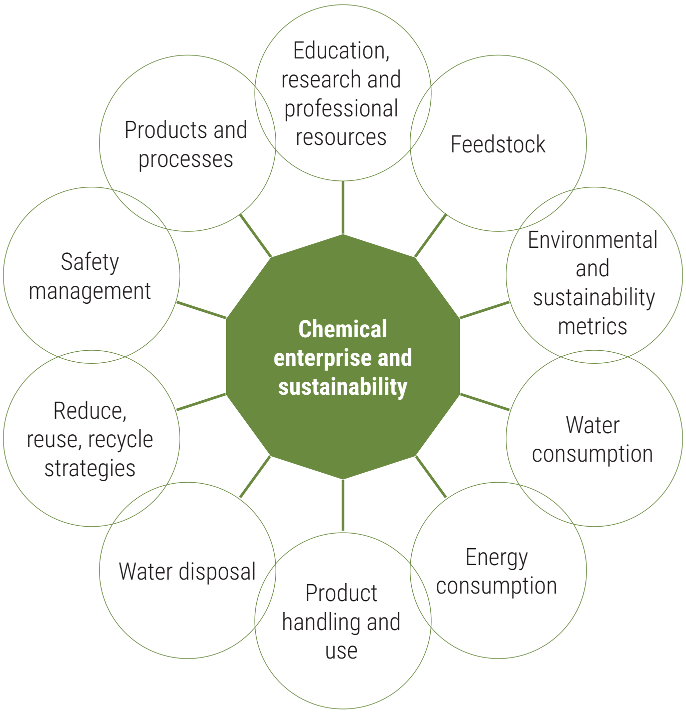


Figure 2.4: **Dimensions of a chemical enterprise: towards sustainability** (adapted from Hill, Kumar and Verma 2013, p. 27)



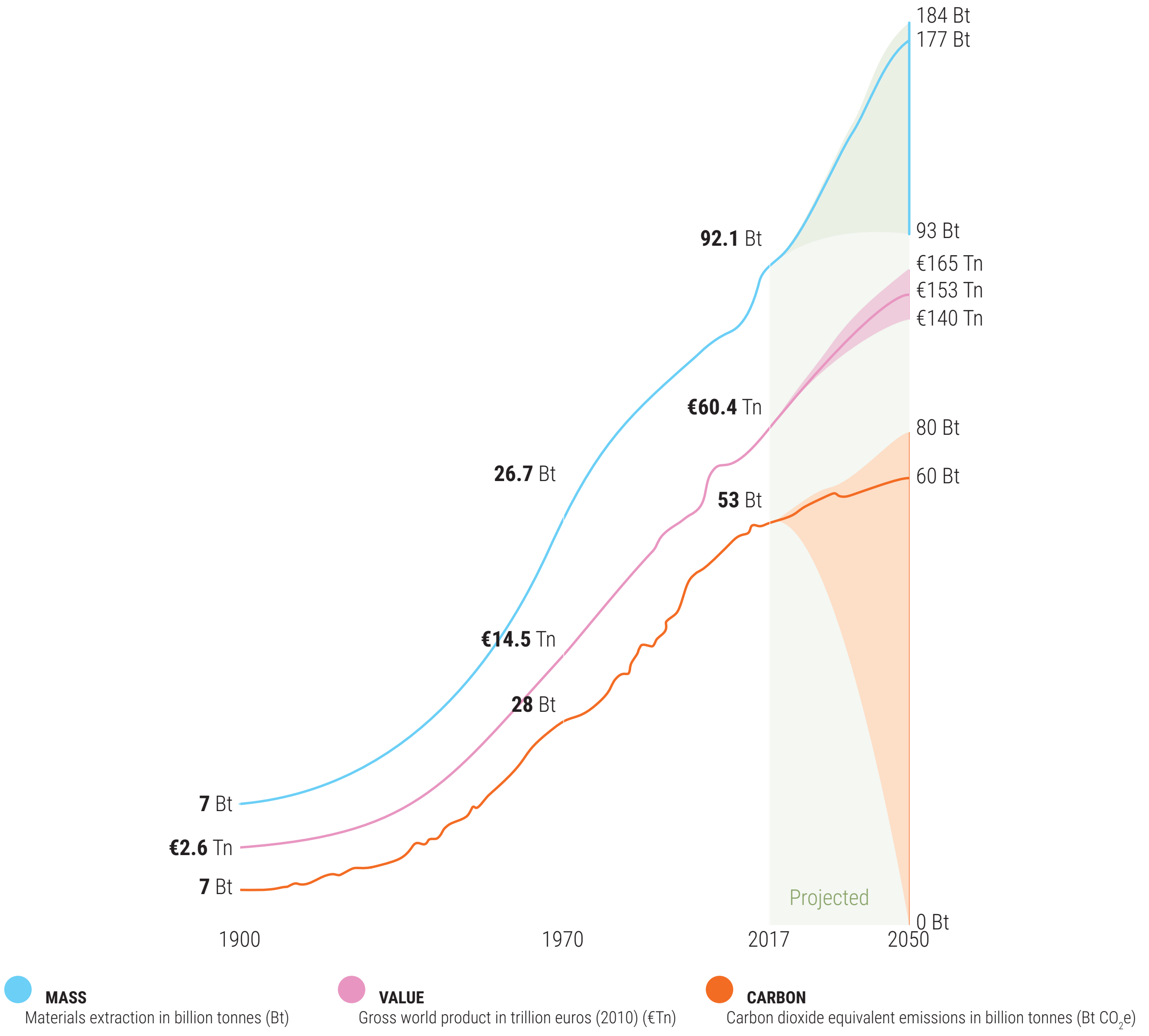
renewable energy. Potential trade-offs also extend into social dimensions. A more benign chemical may, for example, be produced under bad labour conditions, or use conflict minerals as a resource. For these types of questions, using tools such as a life cycle or social assessments may provide valuable insights (see chapter 5).

While discussions on green and sustainable chemistry often focus on the intrinsic properties of chemicals, processes and products (i.e. seeking to minimize their hazards properties and potential), broader considerations along the entire life cycle of chemicals and products (e.g. extrinsic manufacturing choices) are also of relevance in the context of achieving the Sustainable Development Goals. For example, non-hazardous chemicals designed following green chemistry principles may not necessarily support broader sustainability criteria, for instance, if they are used in the manufacture of unsustainable products (e.g. those contributing to climate change).

Sustainability challenges associated with materials, products and waste flows

The International Resources Panel's Global Resources Outlook 2019 (Oberle *et al.* 2019) presents data that approximately 92 billion tonnes of materials were extracted globally in 2017. It also projects that extraction will reach 190 billion tonnes by 2060 and highlights that less than 10% of resources extracted are currently recycled. The magnitude of the chemical sector's material resources flow is an important dimension of global material flows. In 2015, almost 1.7 billion tonnes of feedstocks and secondary reactants generated about 820 million metric tonnes (MMT) of chemical products, while also generating almost the same amount of by-products (e.g. organic solvents). Production processes associated with these material flows continue to generate significant chemical releases to air, water and soil as well as large amounts of waste, including hazardous waste. In the production of pharmaceuticals, for example, at least 25 kilograms (kg) of emissions and waste (and at times more than 100 kg) are generated for every kg of product, highlighting resource inefficiencies (Sheldon 2017).

Figure 2.5: **Trends in materials extraction, financial value creation and greenhouse gas emissions (1900-2050)** (adapted from de Wit *et al.* 2019, p. 11)

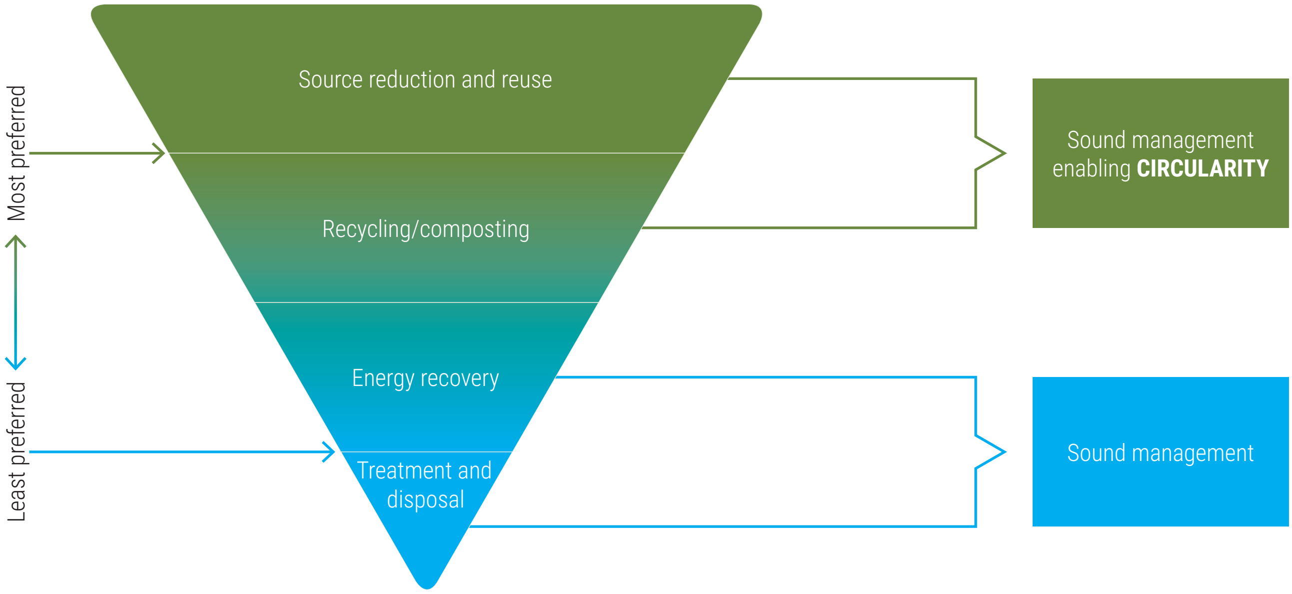


Many articles and products on the market contain hundreds of chemicals or chemical products with hazardous properties, creating concerns due to their emissions and releases and potential health or environmental effects. Examples cited in GCO-II include formaldehyde in shampoo, microbeads in toothpaste or lotions, phthalates in food packaging, certain flame retardants in televisions, and antimicrobials (e.g. triclosan) in soaps. The chemical contamination of products may also prevent circular use of materials and compliance with waste hierarchy principles, which emphasize, in the order of priority, source reduction, reuse and recycling. Green and sustainable chemistry innovations have the potential to help achieve these principles.

Meeting fundamental human needs, while protecting environment and human health

The increasing burden from chemical pollution and waste and the continued growth of the chemical industry (and failure to fully manage product life cycles sustainably) are interconnected issues that relate to consumption patterns of a growing

Figure 2.6: **The waste hierarchy: Potential driver for sustainable materials management and a circular economy** (adapted from United States Environmental Protection Agency [US EPA] 2017)



population that uses more materials as affluence increases. At the core of this issue is the need to assess how to meet fundamental human needs and protect environment and human health. Recognizing this can be an important step for promoting more sustainable consumption and production and lifestyle choices. The challenge is to explore and advance a system in which knowledge and use of green and sustainable chemistry can serve human needs in a more intentional, and sustainable way.

Chemistry and the 2030 Sustainable Development Agenda

The 2030 Agenda for Sustainable Development was adopted by the United Nations General Assembly in 2015. The 2030 Agenda emphasizes that development needs to be compatible with all three dimensions of sustainability: economic, social and environmental. Sustainable development is integrated and indivisible, meaning that it needs to be implemented as a whole, rather than through fragmented silos. At the same time, the recent COVID 19 pandemic is showing how fragile our global systems are, not least the supply chains, raising questions on how best to extend sustainability while maintaining resiliency. Figure 2.7 illustrates the three dimensions of sustainable development as three interdependent systems with the biosphere serving as a foundation for the development of societies and economies.

The sound management of chemicals and waste is integral to and cuts across the 17 SDGs, providing guidance for green and sustainable chemistry and serving as a universal concept. SDG Targets 12.4 and 3.9 are of direct relevance for a range of chemicals and waste management issues. Of similar importance is SDG 9 which fosters development of resilient infrastructure, inclusive and sustainable industrialization and innovation to generate employment and income. Other SDGs require safer chemistry, such as SDG Target 6.3 on improving water quality. Finally, some SDGs and targets are of direct relevance for chemical-intensive sectors, e.g. access to food, clean energy and safe housing. Common across all SDGs and targets is that they cannot be achieved without the sound management of chemicals and waste and sustainable innovations in chemistry. These SDGs thus provide a powerful reference and pave the way for advancing the green and sustainable chemistry agenda.

Figure 2.7: **The three dimensions of sustainability** (adapted from Stockholm Resilience Centre 2016)

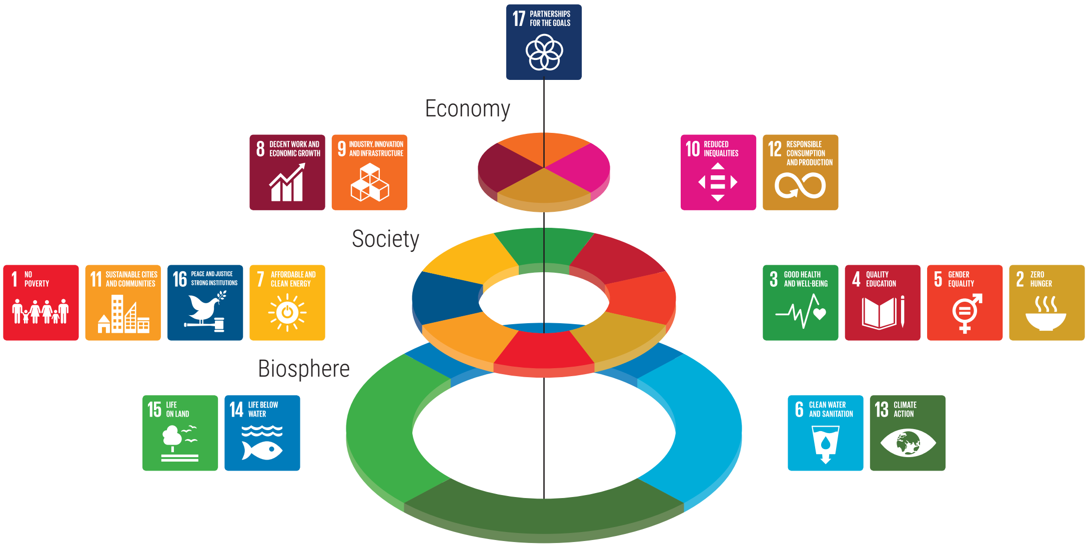


Figure 2.8: **Linkages between chemicals and waste and the SDGs** (adapted from Inter-Organization Programme for the Sound Management of Chemicals [IOMC] 2018, p. 3)

Ensuring that innovations meet sustainability criteria

Recent innovations in chemistry and advanced materials have created new opportunities throughout the value chain to advance sustainability. These include, for example: revolutionizing energy storage and battery development; creating sustainable building materials; improving the recyclability and biodegradability of a number of products; or turning carbon dioxide (CO_2) and wastes into chemical feedstocks and valuable products. Greener and more sustainable innovation at the interface of chemistry, biology and computer science is particularly promising (UNEP 2019b).

In order to ensure that chemistry innovations are fully compatible with the 2030 Sustainable Development Agenda, it is essential to develop and use robust sustainability criteria to assess specific innovations. Consistently applying such criteria would help reap the full potential of chemistry to advance sustainability and contribute towards the implementation of SDG 12 on sustainable consumption and production as well as a number of other SDGs and targets (see Table 2.1).

Table 2.1: **Selected SDGs and targets relevant for green and sustainable chemistry** (UNEP 2019b, p. 644)

Sectors		SDG targets	Examples of opportunities for management and innovation
Agriculture and food	2 ZERO HUNGER	Target 2.4: sustainable food production	Scale up Integrated Pest Management (IPM) and agroecological approaches, including development and use of non-chemical alternatives and other beneficial agricultural practices
Health	3 GOOD HEALTH AND WELL-BEING	Target 3.8: safe medicines and vaccines	Sound management of pharmaceuticals and disinfectants that contribute to antimicrobial resistance
Energy	7 AFFORDABLE AND CLEAN ENERGY	Target 7.a: clean energy research and technologies	Improve technologies using resource-efficient, sustainable materials when decarbonizing the energy sector
Infrastructure	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Target 9.1: sustainable infrastructures	Reduce raw material use and waste generation via advanced materials without creating future legacies
Industry	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Target 9.2: sustainable industrialization	Ensure that chemical-intensive industries rely on best available techniques and best environmental practices
Housing	11 SUSTAINABLE CITIES AND COMMUNITIES	Target 11.1: safe housing	Reduce indoor air pollution through safer insulation and replace building materials of concern (e.g. asbestos)
Transport	11 SUSTAINABLE CITIES AND COMMUNITIES	Target 11.2: sustainable transport systems	Advance clean mobility, for example based on sustainable chemistry solutions for batteries
Tourism	8 DECENT WORK AND ECONOMIC GROWTH	Target 8.9: sustainable tourism	Adopt practices to reduce the chemical footprint of tourism services
Mining	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Target 12.2: sustainable use of natural resources	While foremost ensuring sound management of mine tailings, tailings are reused and returned to the economy to the greatest possible extent possible
Labour	8 DECENT WORK AND ECONOMIC GROWTH	Target 8.8: safe working environments	Enhance risk assessment of chemicals of concern while promoting investment in green and sustainable chemistry to reduce hazardous occupational exposures
Education	4 QUALITY EDUCATION	Target 4.7: education for sustainable development	Mainstream green and sustainable chemistry into relevant curricula
Finance	17 PARTNERSHIPS FOR THE GOALS	Target 17.3: financial resources from multiple sources	Enhance use of green and sustainable chemistry metrics as criteria in investment

2.2 The evolving understanding of green and sustainable chemistry concepts

Green chemistry: an essential building block for sustainable chemistry

The term “green chemistry” was first used in the early 1990s. At the time, it gained momentum after it received recognition and support by the US EPA (Linthorst 2010) which included enhancing public-private information exchanges, encouraging innovations, creating visibility (annual awards), and building networks to bring innovative products to commerce. In a similar development in Europe, considerations compatible with “green chemistry” were included in the Council Directive on integrated pollution prevention and control (European Commission [EC] 1996). The 1993 European Communities Chemistry Council 1993 report on “Chemistry for a Clean World”, as well as conferences on the concept of Benign by Design (Linthorst 2010) were also instrumental. Other related concepts developed at the time include cleaner production, safer products, and the use of renewable feedstocks (Clark 2006; Mubofu 2016).

In 1998, 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” and elaborated the 12 Principles of Green Chemistry (Anastas and Warner 1998). In 2003, the 12 Green Chemistry Principles were complemented by the 12 Principles of Green Engineering (Anastas and

Box 2.1: **Twelve 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/deprotection, 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.

Zimmerman 2003). The American Chemical Society (ACS) provides a short explanation of each of the 12 Green Chemistry principles as well as guidance for making a greener chemical or reaction ACS 2020a). Meanwhile, many countries around the world have engaged the creation of green chemistry networks and adopted green chemistry policy statements.

Chemistry: the molecular basis for sustainable development

Chemists are “molecular architects”. They design molecules that provide the basis for materials and goods to meet human needs and demands. A sustainable society, however, depends on chemical products and processes designed to be “conducive to life” (Zimmerman *et al.* 2020), and not posing a potential threat to short- and long-term health of humans and ecosystems. The 12 green chemistry principles and 12 green engineering principles, therefore, challenge chemists and other scientists to consider inherent properties of chemical molecules at the design stage. The term “design” suggests that this task is purposeful and intentional (Anastas and Zimmerman 2016). It helps to assess early in the design “whether compounds and processes are, for example, depleting versus renewable, toxic versus benign, and persistent versus readily degradable” (Zimmerman *et al.* 2020).

An important aspect of green chemistry is the design of more benign chemicals and processes that mimic nature, and take place under conditions found in nature, i.e. not requiring heat and high pressure to catalyse reactions. For example, in contrast to substitution reactions with reactive organo-halides traditionally used in in industrial chemistry, nature often uses “geometric contortion” to cause reactivity on otherwise unreactive substrates with specificity, selectivity, and with little or no waste generation (Anastas and Zimmerman 2016). Table 2.2 provides some illustrations on how green chemistry approaches help move from traditional to green and biomimetic chemistry technologies.

Research in line with the green chemistry principles has enabled a wide range of developments in the fields of less-toxic design of chemicals and formulations, bio-based chemicals, renewable feedstocks, safer/less toxic solvents and reagents, atom economy, green polymers and other areas (Anastas and Warner 1998; Philp, Ritchie and Allan 2013). Some 25 years following the publication of the 12 Green Chemistry Principles, numerous scientific articles and reviews document how green chemistry enhances environmental health and safety (EHS) and provides economic and competitive advantages. These include, for example, the special ACS journal issue on “Building on 25 Years of Green Chemistry and Engineering for a Sustainable Future (Anastas and Allen 2016), the ACS publication “How Industrial Applications in Green Chemistry Are Changing Our World” (ACS 2015a), or various publication of the Green Chemistry & Commerce Council (n.d.).

While the 12 Principles of Green Chemistry are informative and precise, they do not intend to be prescriptive, nor do they have a strict order/weight toward fulfilment. Accordingly,

Table 2.2: **From traditional to green and biomimetic chemistry technologies** (Van Hamelen 2018, p. 6)

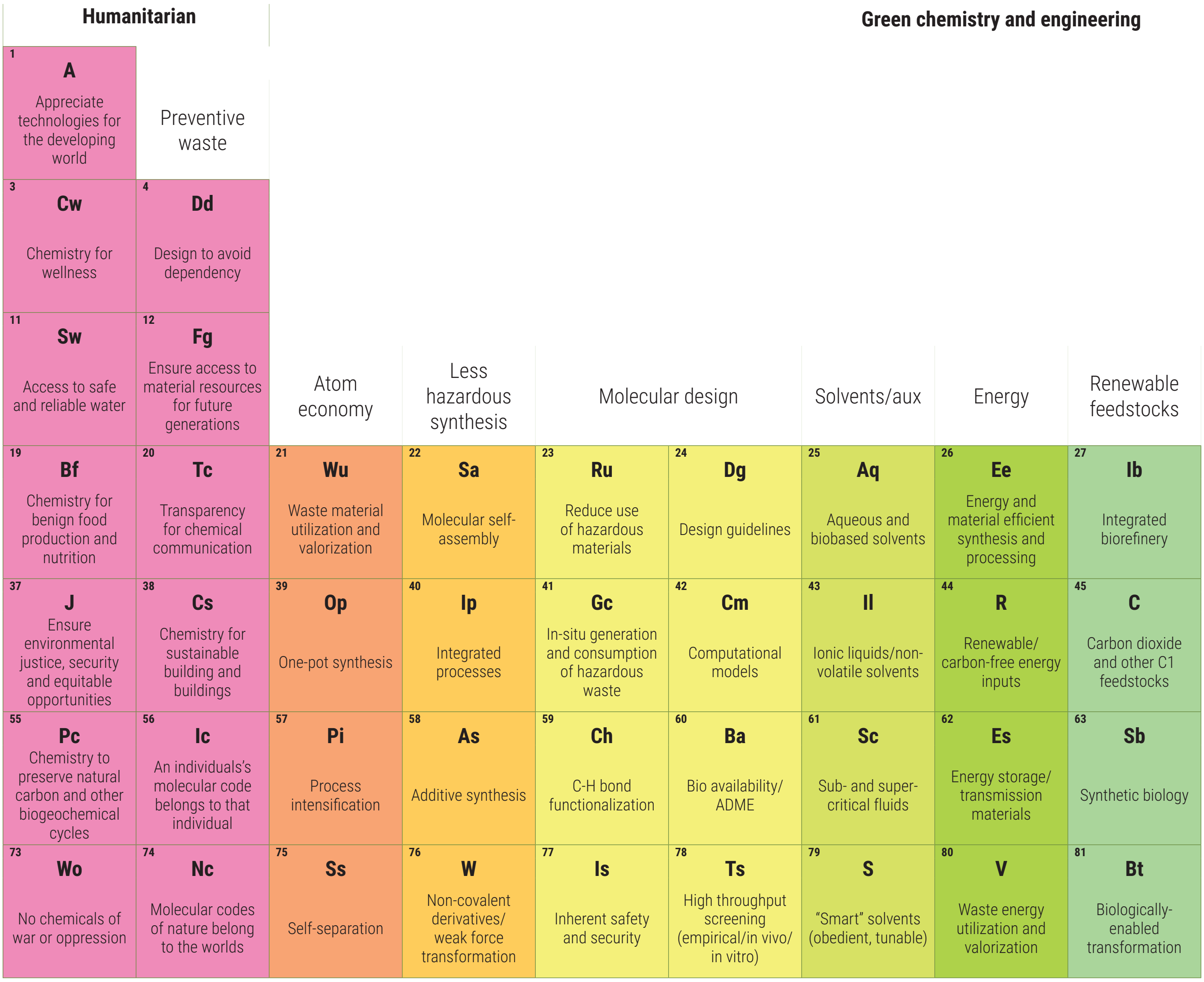
Traditional	Green and biomimetic
‣ “Heat, beat, treat”: chemical reactions under high temperature, high pressure and chemical treatment ‣ Organic solvents ‣ Fossil feedstock and fossil energy ‣ High purity of feedstock is imperative ‣ Use of the entire periodic system ‣ Resources sourced globally ‣ Controlling 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, hydrogen and nitrogen make up 96 percent of atoms in living systems; other elements are used in trace amounts ‣ Controlling risk by adopting the inherent properties of the materials

an agreement on how many of these principles must be fulfilled for a molecule or process to be qualified as “green” does not exist (Zuin 2016). Greener is the intention, and the principles are to be used a means toward the ends. Essentially, the green chemistry narrative encourages continuous performance improvements in innovation to protect human health and the environment, with the 12 Principles serving as a practical reference. It has created a flexible framework toward commitment to actions, and a learning process around these commitments. Using and complying with the 12 principles is a potent motivating factor for chemistry researchers and chemical enterprises alike by creating opportunities for reward. It is this approach of encouragement and flexibility which is one of the key factors for the global success of the green chemistry concept.

A broader and holistic perspective: sustainable chemistry

The notion of sustainable chemistry was advanced by the OECD in the late 1990s (OECD 2012) and early 2000s (German Environment Agency 2009). The OECD 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

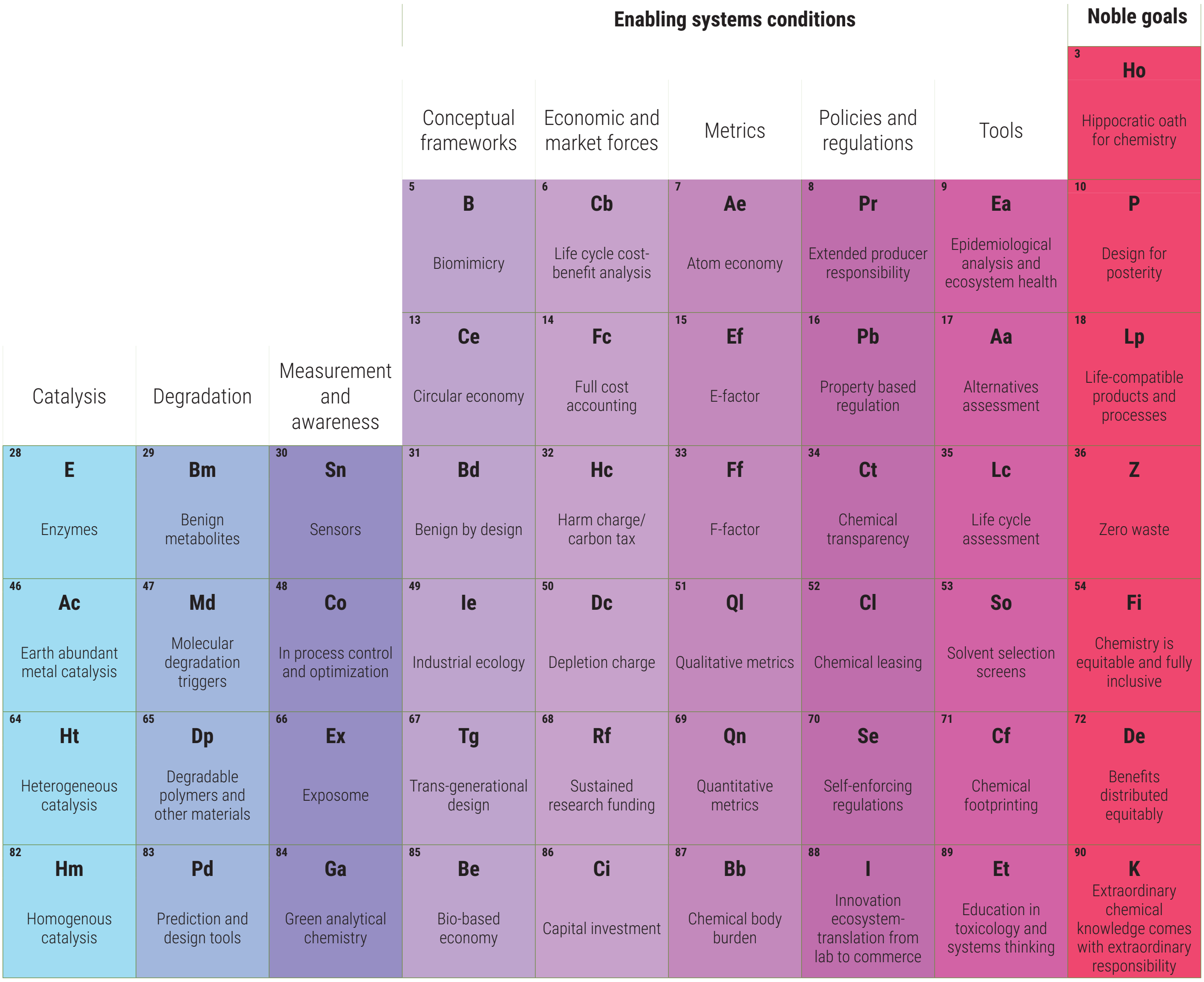
Figure 2.9: **The Periodic Table of the Elements of Green and Sustainable Chemistry** (Anastas and Zimmermann 2019, p. 6546)



Humanitarian		**Green chemistry and engineering**							
1 **A** Appreciate technologies for the developing world	Preventive waste								
3 **Cw** Chemistry for wellness	4 **Dd** Design to avoid dependency								
11 **Sw** Access to safe and reliable water	12 **Fg** Ensure access to material resources for future generations	Atom economy	Less hazardous synthesis	Molecular design		Solvents/aux	Energy	Renewable feedstocks	
19 **Bf** Chemistry for benign food production and nutrition	20 **Tc** Transparency for chemical communication	21 **Wu** Waste material utilization and valorization	22 **Sa** Molecular self-assembly	23 **Ru** Reduce use of hazardous materials	24 **Dg** Design guidelines	25 **Aq** Aqueous and biobased solvents	26 **Ee** Energy and material efficient synthesis and processing	27 **Ib** Integrated biorefinery	
37 **J** Ensure environmental justice, security and equitable opportunities	38 **Cs** Chemistry for sustainable building and buildings	39 **Op** One-pot synthesis	40 **Ip** Integrated processes	41 **Gc** In-situ generation and consumption of hazardous waste	42 **Cm** Computational models	43 **Il** Ionic liquids/non-volatile solvents	44 **R** Renewable/carbon-free energy inputs	45 **C** Carbon dioxide and other C1 feedstocks	
55 **Pc** Chemistry to preserve natural carbon and other biogeochemical cycles	56 **Ic** An individuals’s molecular code belongs to that individual	57 **Pi** Process intensification	58 **As** Additive synthesis	59 **Ch** C-H bond functionalization	60 **Ba** Bio availability/ ADME	61 **Sc** Sub- and super-critical fluids	62 **Es** Energy storage/ transmission materials	63 **Sb** Synthetic biology	
73 **Wo** No chemicals of war or oppression	74 **Nc** Molecular codes of nature belong to the worlds	75 **Ss** Self-separation	76 **W** Non-covalent derivatives/ weak force transformation	77 **Is** Inherent safety and security	78 **Ts** High throughput screening (empirical/in vivo/ in vitro)	79 **S** “Smart” solvents (obedient, tunable)	80 **V** Waste energy utilization and valorization	81 **Bt** Biologically-enabled transformation	

"the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. It 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". This scope has been enlarged over time by "additional aspects of sustainability, for example full life-cycle assessment, conservation of resources, promotion of reuse and recycling, application of corporate social responsibility (CSR), [and] inclusion of downstream users such as consumers" (Bazzanella, Friege and Zeschmar-Lahl 2017).

While green chemistry is characterized and guided by scientific principles that focus on chemistry innovation, recent discussions on sustainable chemistry suggest a broader concept and more holistic interpretation that takes into account economic, environmental and social dimensions. Recognizing the interdependence of nested systems (i.e. economy within society within the biosphere) sustainable chemistry covers a broader set of topics. These include, for example: advanced manufacturing, safe working conditions, local communities and human rights, consumption and disposal patterns, citizens and ethics, and new business and service models (Blum *et al.* 2017; Kümmerer 2017). Ensuring that chemicals are



			Enabling systems conditions					**Noble goals**
			Conceptual frameworks	Economic and market forces	Metrics	Policies and regulations	Tools	3 **Ho** Hippocratic oath for chemistry
			5 **B** Biomimicry	6 **Cb** Life cycle cost-benefit analysis	7 **Ae** Atom economy	8 **Pr** Extended producer responsibility	9 **Ea** Epidemiological analysis and ecosystem health	10 **P** Design for posterity
Catalysis	Degradation	Measurement and awareness	13 **Ce** Circular economy	14 **Fc** Full cost accounting	15 **Ef** E-factor	16 **Pb** Property based regulation	17 **Aa** Alternatives assessment	18 **Lp** Life-compatible products and processes
28 **E** Enzymes	29 **Bm** Benign metabolites	30 **Sn** Sensors	31 **Bd** Benign by design	32 **Hc** Harm charge/ carbon tax	33 **Ff** F-factor	34 **Ct** Chemical transparency	35 **Lc** Life cycle assessment	36 **Z** Zero waste
46 **Ac** Earth abundant metal catalysis	47 **Md** Molecular degradation triggers	48 **Co** In process control and optimization	49 **Ie** Industrial ecology	50 **Dc** Depletion charge	51 **Ql** Qualitative metrics	52 **Cl** Chemical leasing	53 **So** Solvent selection screens	54 **Fi** Chemistry is equitable and fully inclusive
64 **Ht** Heterogeneous catalysis	65 **Dp** Degradable polymers and other materials	66 **Ex** Exposome	67 **Tg** Trans-generational design	68 **Rf** Sustained research funding	69 **Qn** Quantitative metrics	70 **Se** Self-enforcing regulations	71 **Cf** Chemical footprinting	72 **De** Benefits distributed equitably
82 **Hm** Homogenous catalysis	83 **Pd** Prediction and design tools	84 **Ga** Green analytical chemistry	85 **Be** Bio-based economy	86 **Ci** Capital investment	87 **Bb** Chemical body burden	88 **I** Innovation ecosystem-translation from lab to commerce	89 **Et** Education in toxicology and systems thinking	90 **K** Extraordinary chemical knowledge comes with extraordinary responsibility

managed in a sound manner is a fundamental condition for sustainable chemistry.

As highlighted in GCO-II, a recent study by the United States Government Accountability Office (US GAO) on chemistry innovation identified common themes on "what sustainable chemistry strives to achieve," including the following:

- 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 [...];
- 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).

The recently developed "Periodic Table of the Elements of Green and Sustainable Chemistry" (Anastas and Zimmerman 2019) stands on the shoulders of green chemistry and places it into a broader sustainable chemistry and sustainability context. In the Periodic Table, green chemistry and green engineering provide the scientific and technological foundations of the Green and Sustainable Chemistry Elements of the Table. These are complemented by other Elements, such as humanitarian aims, enabling system conditions, or noble goals. The approach taken through the Periodic Table makes the case that achieving a sustainable future requires work at the intersection of science and technology with the human, societal, cultural, economic, policy, cultural, moral, and ethical ecosystem (Anastas and Zimmerman 2019).

Another recent initiative which seeks to facilitate an understanding of sustainable chemistry is the International Sustainable Chemistry Collaborative Centre (ISC3) stakeholder dialogue process. It has brought together different perspectives, expectations and criteria discussed in the context of sustainable chemistry and is compatible with a holistic interpretation of the sustainability concept (ISC3 2020a).

Opportunities for green and sustainable chemistry to advance circularity

In 2020, the weight of human-made materials on earth was estimated to exceed for the first time the earth's entire biomass (Elhacham *et al.* 2020). Coupled with an increasing scarcity of natural resources (e.g. metals), the quest for advancing towards circularity is growing.

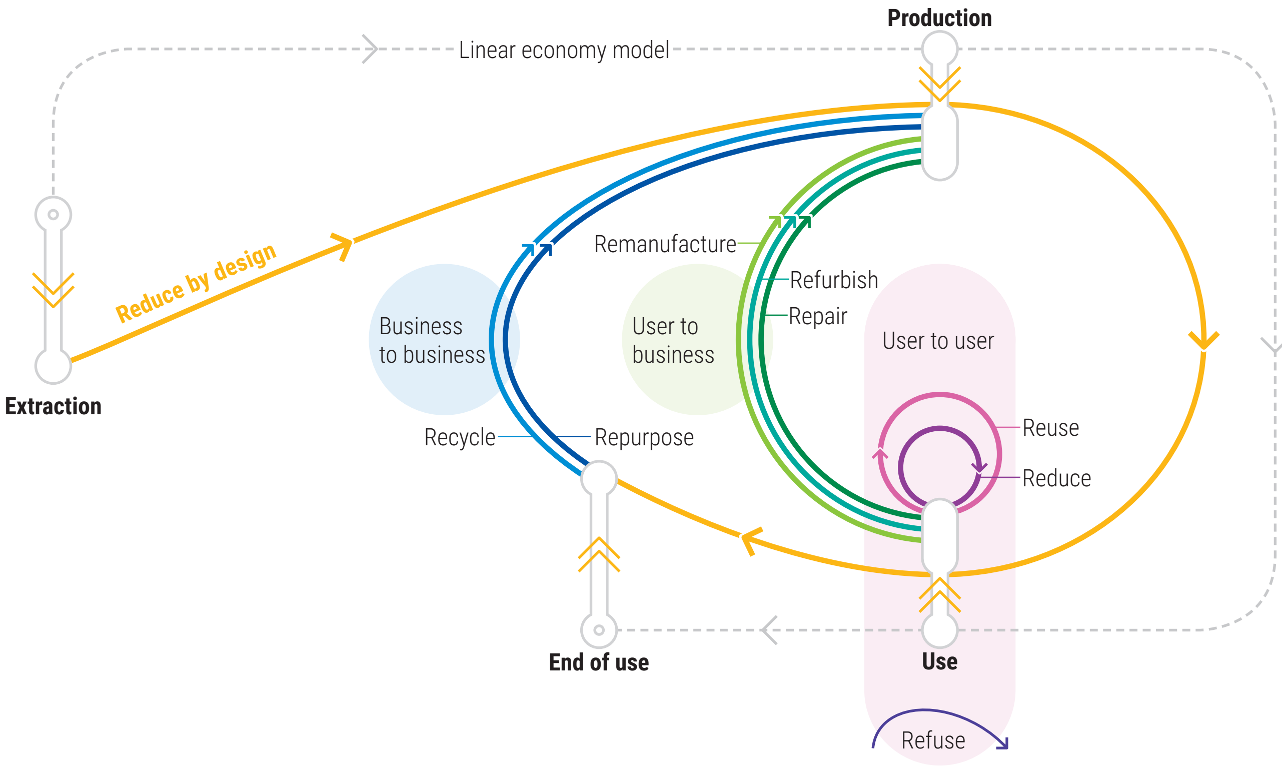
Circularity is presented by UNEP, in its circularity platform, as inclusive of the processes described in Figure 2.10.

Yet, many materials are complex, and difficult to recover and recycle. Plastics, for example, often contain additives (e.g. plasticizers), flame retardants, coloring agents or ultraviolet-light stabilizers that can be hazardous and difficult to separate (Kümmerer, Clark and Zuin 2020).

Green and sustainable chemistry innovation can play an important role in advancing a circular economy. It stimulates design of molecules, materials and products that can be more easily recycled and up-cycled than those currently on the market. This can be achieved, for example by eliminating chemicals of concern in products that currently prevent sound recovery and recycling (UNEP 2019b). For products that are intentionally released to the environment and have open-environmental applications (e.g. pesticides, cosmetics, biocides, or pharmaceuticals) green and sustainable chemistry innovation could help design molecules and materials that rapidly mineralize in the environment, while retaining desired functions (Kümmerer, Clark and Zuin 2020).

To nurture the integration of chemistry into a circular economy, Kümmerer, Clark and Zuin (2020) make 15 specific propositions. They include, amongst others: keeping molecular and product complexity to the minimum required for

Figure 2.10: **Understanding and visualizing Circularity** (UNEP 2019c)



the desired performance; designing products for recycling, including all additives and other components of the product; preventing raw materials from becoming critical through reduced use and efficient recovery and recycling (e.g., many metals); ensuring traceability and consider use of product digital passports (e.g., composition of products, components, and processes); and keeping processes as simple as possible with a minimal number of steps, auxiliaries, energy, and unit operations. These propositions are fully compatible with and support the 10 green and sustainable chemistry objectives presented in Chapter 3.

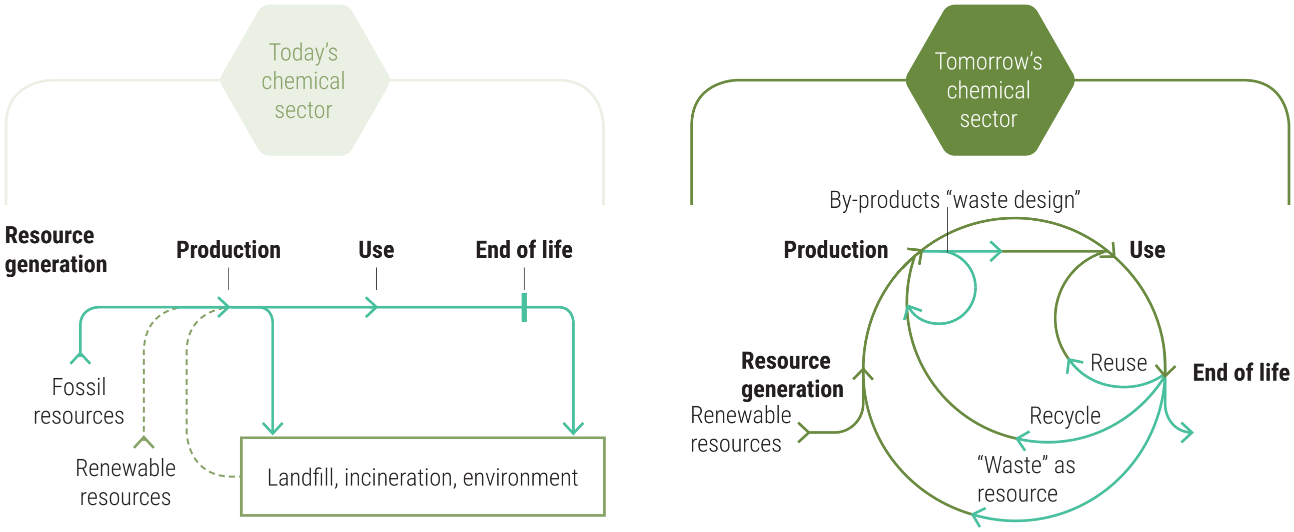
Towards an expanded definition of performance in the chemical industry

Momentum is growing to stimulate a transformation in the chemical industry that fully embraces what Zimmerman *et al.* (2020) refer to as an "expanded definition of performance that includes sustainability considerations" (Figure 2.11). This expanded notion starts with considering inherent properties of molecules, to ensuring that compounds, processes and products meet up to high sustainability standards. This transformation will require innovation beyond traditional chemistry innovation approaches and bring in "systems thinking and systems design that begins at the molecular level and results in a positive impact on the global scale" (Zimmerman *et al.* 2020).

The potential of green and sustainable chemistry for future industry sectors

The contribution of chemistry to many end markets of relevance for shaping the future of development and sustainable development is significant. Examples include the transportation industry, the construction industry, food and packaging, and waste management. Figure 2.12 provides selected examples on how chemistry contributes to industries that play a role in sustainable development in the future. Applying green and sustainable chemistry considerations in relevant innovations is essential.

Figure 2.11: **Characteristics of today's and tomorrow's chemical sector** (Zimmerman *et al.* 2020)



Mostly linear processes	Circular processes
Fossil feedstocks	Renewable feedstocks
Reactive, persistent, or toxic chemical reagents and products	Benign chemical reagents and products
Catalysis using rare metals	Catalysis using abundant metals, enzymes, photons, or electrons
Covalent bonds	Weak, noncovalent interactions
Conventional solvents	Low toxicity, recyclable, inert, abundant, easily separable green solvents or solventless
Material- and energy-consuming isolation and purification	Self-separating systems
Large "waste" volume	Atom-, step-, and solvent-economical processes
"Waste" treatment	"Waste" utilization
Design exclusively for use phase with reliance on circumstantial control	Intentional molecule design for full life cycle
Performance = maximize function	Performance = maximize function + minimize hazards
Maximum chemical production for increased profit	Maximum performance with minimal benign material use for increased profit

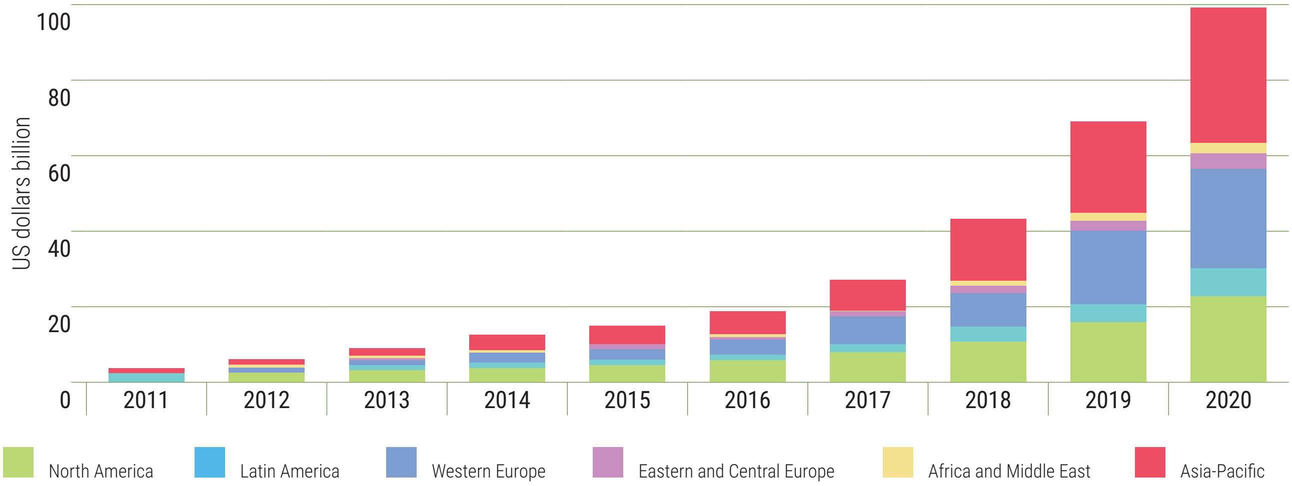
The market potential for green and sustainable chemistry

Although differences exist in the characterization of green and sustainable chemistry, available - albeit limited - data suggests that supply and demand for greener and more sustainable chemistry product is significantly growing. The global green chemistry industry was reported to have a market value of more than US dollars 50 billion in 2015 (BCC Research 2016) and projected to grow to US dollars 167.1 billion by 2027 (ReportLinker 2020). Asia and the Pacific, Western Europe and North America are the key market growth regions (Pike Research 2011) (Figure 2.13). More recent research suggests that the global green chemicals market size will grow by almost USD 50 billion during 2019-2023 at a CAGR close to 10% (Business Wire 2019).

Figure 2.12: **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

Figure 2.13: **Global green chemicals market by region (US dollars billion), 2011-2020** (Pike Research 2011)



The publisher for this copyrighted material is Mary Ann Liebert, Inc. publishers.

3

WHAT CAN GREEN AND SUSTAINABLE CHEMISTRY ACTION ACHIEVE?

OBJECTIVES AND GUIDING CONSIDERATIONS >

A vision for green and sustainable chemistry

This Framework Manual fosters a vision of green and sustainable chemistry which emphasizes the potential of chemistry to become fully compatible with the 2030 Agenda for Sustainable Development. In other words, chemistry and the global chemical industry must ultimately become fully aligned with the environmental, social and economic dimensions of sustainable development. The vision covers both greener and more sustainable chemistry innovations, while also addressing toxic and persistent legacies associated with past chemistries in order to minimize adverse impacts across the entire life-cycle of chemicals and products.

A large number of SDGs can benefit from the direct contributions of green and sustainable chemistry, including: zero hunger (SDG 2), good health and well-being (SGDG 3), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), sustainable consumption and production (SDG 12), and climate action (SDG 13). By reducing and/or eliminating chemical hazards, associated health and environmental impacts and pollution, green and sustainable chemistry also contribute to other SDGs, such as decent working conditions, and economic growth (SDG 8), innovation and infrastructure (SDG 9), life below water (SDG 14), and life on land (SDG 15).

Objectives and guiding considerations

The vision of green and sustainable chemistry can be achieved through new designs and innovations in chemistry that provide desirable functions and services of chemicals, materials, products, and production processes without causing harm to human health and the environment, while meeting broader development objectives. “Chemistry innovation”, in this context, includes innovation in chemistry (i.e. new molecules/ chemical compounds), innovations in chemical engineering sciences (i.e. chemical processes and sustainable production), as well as in related areas (e.g. product development).

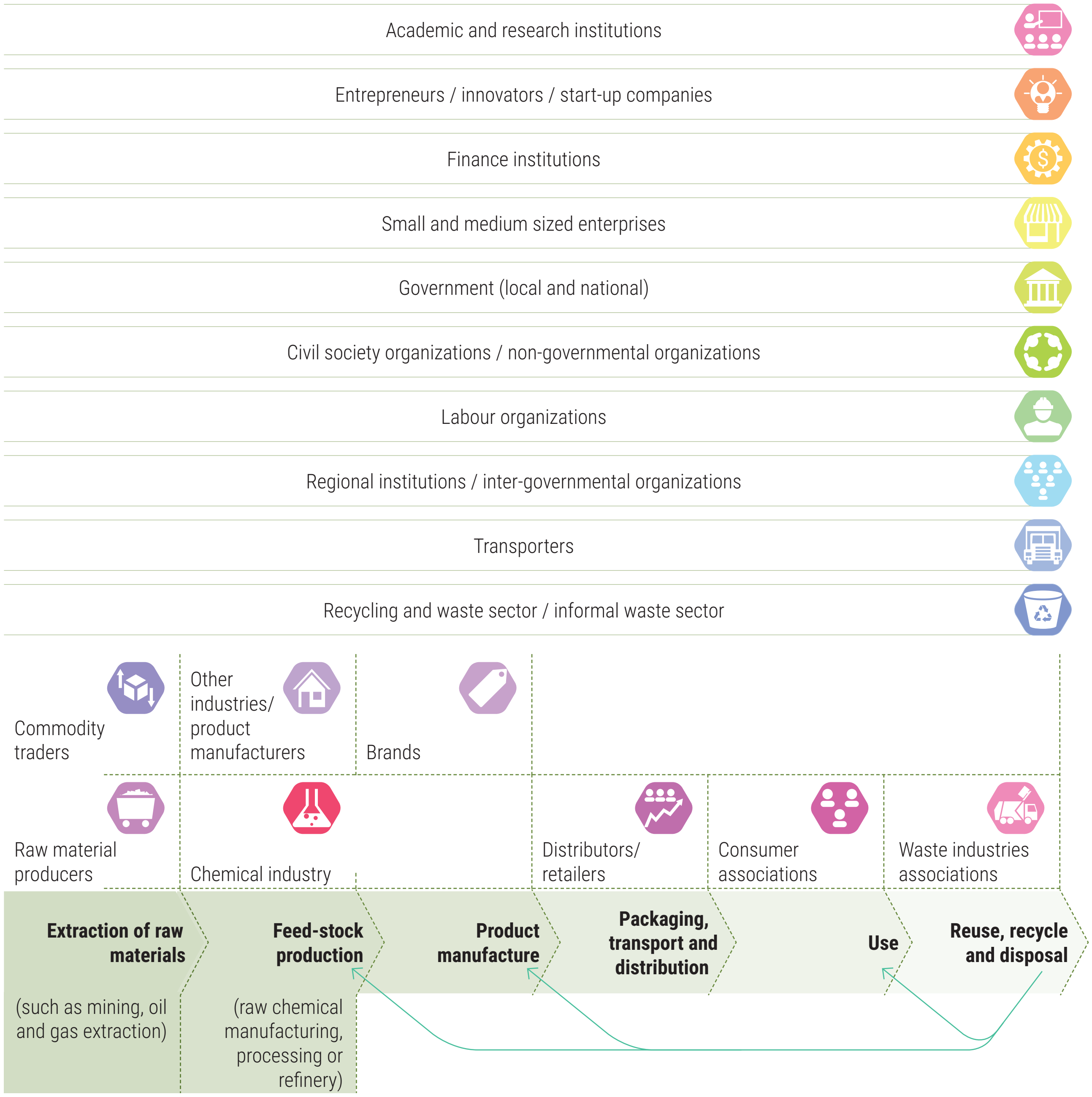
Apart from the 12 Principles of Green Chemistry and the 12 Principles of Green Engineering, a reference framework that helps better understand what comprises “green and sustainable chemistry” does not exist. Nor does an agreed set of criteria exist to determine how “green” or “sustainable” a chemical or an industrial process is (UNEP 2019b).

This Framework Manual aims to foster an enhanced understanding, by presenting 10 objectives and guiding considerations for what green and sustainable chemistry seeks to achieve Figure 3.1. The objectives encourage and seek to inspire actors to shift their chemistry innovations activities towards green and sustainable innovation. They are offered to stakeholders engaged in chemistry innovation, management, and policy development. These include, but are not limited to: chemists, chemical engineers, product designers, decision makers in the private sector, government and other stakeholder groups, as well as users and consumers. Figure 3.2 presents stakeholder and target audiences of green and sustainable chemistry in the value chain, building upon a similar mapping of the plastics value chain displayed in Ryberg, Laurent and Hauschild (2018).

Figure 3.1: **The 10 green and sustainable chemistry objectives**

1	**Minimizing chemical hazards**	Design of chemicals with minimized (or no) hazard properties for use in materials, products and production processes ("benign by design")
2	**Avoiding regrettable substitutions and alternatives**	Develop safe and sustainable alternatives for chemicals of concern through material and product innovations that do not create negative trade-offs
3	**Sustainable sourcing of resources and feedstocks**	Use of sustainably sourced resources, materials and feedstocks without creating negative trade-offs
4	**Advancing sustainability of production processes**	Use green and sustainable chemistry innovation to improve resource efficiency, pollution prevention, and waste minimization in industrial processes
5	**Advancing sustainability of products**	Use green and sustainable chemistry innovation to create sustainable products and consumption with minimized (or no) chemical hazard potential
6	**Minimizing chemical releases and pollution**	Reduce chemical releases throughout the life cycle of chemicals and products
7	**Enabling non-toxic circularity**	Use of chemistry innovations to enable non-toxic circular material flows and sustainable supply and value chains throughout the life cycle
8	**Maximizing social benefits**	Consider social factors, high standards of ethics, education and justice in chemistry innovation
9	**Protecting workers, consumers and vulnerable populations**	Safeguard the health of workers, consumers and vulnerable groups in formal and informal sectors
10	**Developing solutions for sustainability challenges**	Focus chemistry innovation to help address societal and sustainability challenges

Figure 3.2: **Stakeholder and targets audiences of green and sustainable chemistry in the value chain**
(Adapted from Ryberg, Laurent and Hauschild 2018, p.10)



A deeper look at the 10 green and sustainable chemistry objectives

The following sections introduce each of the 10 objectives and guiding considerations. They range from molecular design based on green chemistry principles, to ensuring that chemistry innovations address societal needs. For each objective, an explanatory line is offered, target groups for which the objective is relevant are mentioned, and a brief description of what it seeks to achieve is provided. While the objectives are distinct, some overlaps may occur, given the complexity and broad nature of the topic. Given the cross-cutting role of government decision makers in creating policies and an enabling environment, all 10 objectives and guiding considerations are relevant for this group.

Objective 1

Minimizing chemical hazards

Design of chemicals with minimized (or no) hazard properties for use in materials, products and production processes ("benign by design")

The first objective is directly relevant for chemists, chemical engineers, as well as material and product designers engaged in chemistry and chemical engineering innovation. It encourages the design and use of chemical molecules (or groups of molecules) with minimized (or no) human health and environment hazard properties , e.g. toxicity, persistence, mobility, etc. "Designing out hazards" helps create safer and sustainable materials, products and production processes, facilitates reuse and recycling; and addresses downstream challenges up front. This meets growing consumers' demand, strengthens competitiveness, and helps comply with regulatory frameworks, reuse, recycle, and safe disposal included. When determining chemical hazards, non-animal testing methods should be used whenever possible.

Objective 2

Avoiding regrettable substitutions and alternatives

Develop safe and sustainable alternatives for chemicals of concern through material and product innovations that do not create negative trade-offs

The second objective addresses material and product designers, as well as chemists. It encourages chemistry, material and/or product innovation to develop and apply alternatives for chemicals (or groups of chemicals) which currently cause concern for human health and the environment. The benchmark is to design and introduce alternatives that do not cause negative impacts, nor compromise other development objectives (e.g. mitigating climate change). Otherwise, they might be regrettable substitutions. Alternatives may provide desired functions through non-chemical approaches. Achieving the objective is facilitated through multi-disciplinary teams including manufacturers, regulators, and health and safety experts, and by using alternatives assessment to evaluate potential trade-offs.

Objective 3

Sustainable sourcing of resources and feedstocks

Use of sustainably sourced resources, materials and feedstocks without creating negative trade-offs

The third objective is relevant for stakeholders in mining, processing, farming, as well as chemists, engineers, and supply chain managers and engineers in the chemical industry. It encourages the use of sustainable and renewable resources, materials and feedstocks in the business of chemistry, including recycled chemical feedstock, as well as bio-based feedstocks, if broader sustainability criteria can be met. It also seeks to advance the sustainable use of rare resources, such as certain metals. For bio-based feedstocks, recognising the need for agricultural land to produce food, and limiting destructive impacts of feedstock on forests and ecosystems are among the sustainability criteria to be taken into account.

Objective
4

Advancing sustainability of production processes

Use green and sustainable chemistry innovation to improve resource efficiency, pollution prevention, and waste minimization in industrial processes

The fourth objective is relevant for chemists, chemical and industrial engineers, as well as waste management experts engaged in developing chemistry and chemical engineering solutions that can improve industrial production processes and encourage pollution prevention, as well as reuse and recycling of materials. It encourages chemistry innovation to enhance resource efficiency, minimize industrial waste, and foster reuse and recycling of chemicals and materials during production processes. This can be achieved through sustainable management of resources and cleaner production.

Objective
5

Advancing sustainability of products

Use green and sustainable chemistry innovation to create sustainable products and consumption with minimized (or no) chemical hazard potential

The fifth objective is relevant for brand managers, product and material designers, chemists and chemical engineers engaged in product design and production. It encourages chemistry innovations to design and produce sustainable products which are non-toxic and safe, have longevity (i.e. duration of shelf and service-life, repairability), and can be reused or recycled within a circular economy. This is an important dimension of advancing sustainable consumption.

Objective
6

Minimizing chemical releases and pollution

Reduce chemical releases throughout the life cycle of chemicals and products

The sixth objective is relevant for production managers, chemical engineers and chemists engaged in industrial processes and product development, as well as other stakeholders across the product life cycle including the waste sector. It encourages chemistry innovations to minimize intended and un-intended releases of chemicals to indoor and outdoor environments during manufacturing processes, use of products, and disposal. This can be achieved, for example by creating new designs that minimize or eliminate hazardous chemicals in products; maximizing the use of closed production systems; ensuring reuse and recycle of materials; using life cycle assessments; and through information transparency. Communicating among stakeholders across the value chain is critical to achieve this objective.

Objective
7

Enabling non-toxic circularity

Use of chemistry innovations to enable non-toxic circular material flows and sustainable supply and value chains throughout the life cycle

The seventh objective is relevant for all stakeholders. This includes citizens, consumers, decisions makers, investors, as well as scientists and innovators engaged in and concerned with product development and industrial processes. It encourages green and sustainable chemistry innovation to foster sustainable material management, including maintaining value of materials during the life cycle of a product. It goes beyond minimising releases into the environment by encouraging elimination of toxic compounds in products to allow re-use and recycling, thus minimizing waste.

Objective
8

Maximizing social benefits

Consider social factors, high standards of ethics, education and justice in chemistry innovation

The eighth objective is relevant for all stakeholders, including citizens, consumers, policy makers, managers and scientists engaged in the sound management of chemicals and waste. It recognizes the benefits of chemical products and processes, while recognizing that such benefits are often not distributed equally. It encourages that chemistry innovation be fully compatible with broader social sustainability objectives, including, but not limited to ethics, education, and socio-economic-justice. Specific considerations include, but are not limited to: protecting workers and disadvantaged communities; making products of sustainable chemistry accessible to everyone; challenging financial and technical support so that every country and entrepreneur can succeed; fostering education that address disproportionate impacts; and ensuring that everyone can enjoy the benefits of sustainable chemistry.

Objective
9

Protecting workers, consumers and vulnerable populations

Safeguard the health of workers, consumers and vulnerable groups in formal and informal sectors

The ninth objective is relevant for all stakeholders, including citizens, consumers, workers, policy makers, managers and scientists engaged in the sound management of chemicals and waste. It emphasizes that green and sustainable chemistry must go hand-in-hand with broader management and protection measures to ensure the sound management of chemicals and waste, such as implementation of the Globally Harmonized System for Classification and Labelling of Chemicals (GHS). It recognises that workers, marginalized communities and consumers are among the most affected by environmental pollution and should be explicitly considered when advancing green and sustainable chemistry priorities and solutions (Alcántar *et al.* 2017). It also encourages access to knowledge, education, and participation (citizens, consumers, public and private) to protect human health and the environment from hazardous chemicals.

Objective
10

Developing solutions for sustainability challenges

Focus chemistry innovation to help address societal and sustainability challenges

The tenth objective is relevant for all managers and scientists engaged in a broader dialogue in society about the role of the chemical industry in meeting societal needs, while strengthening and fostering sustainable development. It encourages to engage, prioritize, and create certainty to focus chemistry innovation on developing solutions that address sustainability challenges, including, but not limited to food security, human wellbeing, climate change, biodiversity, pollution, and supply chain resiliency (locally and globally). It also encourages consideration of broader drivers, such as the impact of software development on increasing electric waste, or the sustainability impacts of short innovation cycles in the textile industry (fast fashion).

Determinants for effective implementation

The implementation of the 10 objectives and guiding considerations for green and sustainable chemistry will require fundamental shifts in raising awareness, creating new knowledge, and innovation practices. The following chapter 4 introduces technology and innovation areas and topics considered particularly important in advancing green and sustainable chemistry. Chapters 5, 6 and 7 introduce relevant enabling tools, measures and metrics, and chapter 8 calls for scaling-up action by all stakeholder. The important cross-cutting topic of education and learning to advance green and sustainable chemistry will be further covered in a specialized manual which is also set to be published this year.

4

CHEMISTRY AND TECHNOLOGY INNOVATION TO ADVANCE GREEN AND SUSTAINABLE CHEMISTRY >

4.1 Elements of a research and innovation framework for green and sustainable chemistry

A growing number of international scientific journals and conferences are featuring research topics and innovation initiatives under the green and sustainable chemistry heading. While these efforts provide a rich set of topics, a global framework which structures green and sustainable chemistry research and innovation topics does not exist. This chapter aims to contribute to this discussion by introducing chemistry and technology topics which are considered relevant for advancing green and sustainable chemistry innovation. It thereby seeks to inform the development of an international research agenda for green and sustainable chemistry.

The topics featured in this chapter have been identified following a review of green and sustainable chemistry publications (e.g. Bazzanella, Friege and Zeschmar-Lahl 2017; Zimmerman *et al.* 2020) as well as conference agendas that use the green and sustainable chemistry narrative. The latter include, for example, the ACS Green Chemistry Engineering Conference series (ACS 2020b), or the annual Elsevier Green & Sustainable Chemistry Conference (Elsevier 2020a). The topics range from developing more benign molecules for selected chemicals (or chemical groups causing concern), to using chemistry innovations to improve resource efficiency in production processes. A number of these topics and chemicals of concern are addressed through global conventions, such as the Stockholm Convention or the Basel Convention. The chapter also features the energy sector as one (of many possible) examples how green and sustainable chemistry innovation may contribute to sustainable development at the sectoral level.

The topics and examples featured have not been assessed from a sustainability perspective. In order to determine if they are "greener" and/or "more sustainable" than current practices, a life cycle assessment and social assessment may be needed that clarifies assumptions, estimates emissions, and assesses impacts. Furthermore, qualitative assessments may be valuable to spot potential trade-offs. For example, a biodegradable plastic does not necessarily advance sustainability, unless conditions are in place to ensure that it degrades fully (e.g. in an industrial composting plant). Achieving zero trade-offs or impacts is, in any case a challenge and unlikely. Further details of life cycle assessment are provided in chapter 5 and in GCO-II.

4.2 Biobased and renewable chemical feedstocks

Biobased feedstocks

For more than a century, the chemical industry has used fossil resources (mainly oil, coal and gas) to produce basic chemicals such as ammonia, methanol, ethylene, and propylene. These chemicals provide the platform for a wide range of other chemicals, materials and products in the chemical industry value chain. Given the depletion (and ultimate scarcity) of fossil resources, their contribution to greenhouse gas emissions, and uncertainties in global supply chains, opportunities are being explored to use new bio-based sources for producing chemical feedstocks. This is consistent with the 7th principle of green chemistry which postulates that "a raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable" (Anastas and Warner 1998).

Biomass is derived from living organisms, usually plants. Biorefinery technologies have the potential to yield a range of basic chemicals traditionally produced through energy intensive and polluting petrochemical refinery technology (Kohli, Prajapati and Sharma 2019). Examples include biofuels, chemical building blocks, bio-ethylene and bio-propylene (as a replacement of fossil-derived ethylene and propylene), or biodegradable polymers. Biomass may therefore

Box 4.1: Biomass and bio-based feedstocks are not necessarily more sustainable

Using biomass and renewable feedstocks in the chemical industry has some promise, but raises important sustainability questions and concerns at the same time.

One important consideration is the sourcing of biomass. For example, using biomass that results from clearing of forests for plantations and/or from land occupation may lead to destruction of habitats, emission of greenhouse gases and erosion of arable lands with negative impacts on communities. Similarly, the use of pesticides and fertilizers in producing biomass through industrial agriculture may cause adverse human health and environmental impacts.

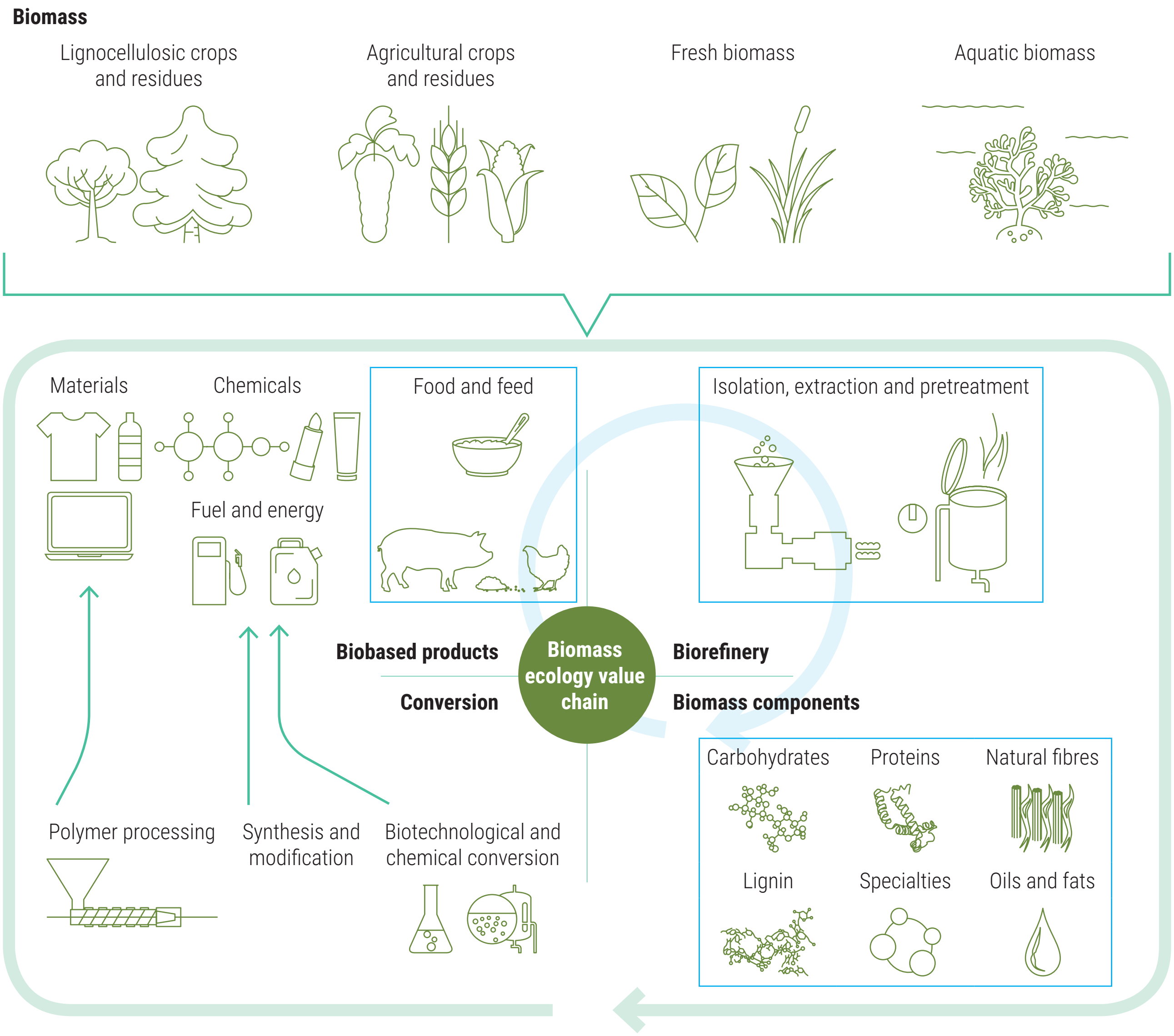
Sourcing biomass and feedstocks in a sustainable way is therefore essential. Microalgae-based biomass can, for example, be grown on nonarable land, helping to reverse desertification, and converting CO_2 into feedstocks through photosynthesis (Karan *et al.* 2019). Using agricultural waste, rather than crops as biomass, may, under certain conditions advance resource efficiency and circularity.

A second consideration is the nature of chemicals, materials and products produced with biomass. While biorefineries reduce energy needs, need for fossil resources and emission of certain hazardous chemicals, the chemicals produced (e.g. ammonia) may be the same as those produced through petrochemical processes. These chemicals then have the same hazard potential and the products they help to produce as intermediates are not more benign.

In the case of bioplastics, for example, a recent study has found that most bioplastics and plant-based materials contain toxic chemicals, and that bio-based/biodegradable materials and conventional plastics are similarly toxic (Zimmermann *et al.* 2020). A case in point is the development of PVC from a bio-based feedstock, which does not address potential problems of dioxin formation during unsound PVC disposal.

In summary, replacing the fossil feedstocks with feedstocks from renewable sources does not necessarily advance sustainability. It is therefore important to consider pros and cons of using various feedstock sources and chemistry processes. Life cycle approaches may provide valuable guidance for such assessments.

Figure 4.1: **Biobased Value Chain** (Wageningen University & Research [WUR] n.d a)



provide the foundation for a range of products and applications, including food, energy, materials, and pharmaceuticals.

Carbon dioxide as resource and feedstock

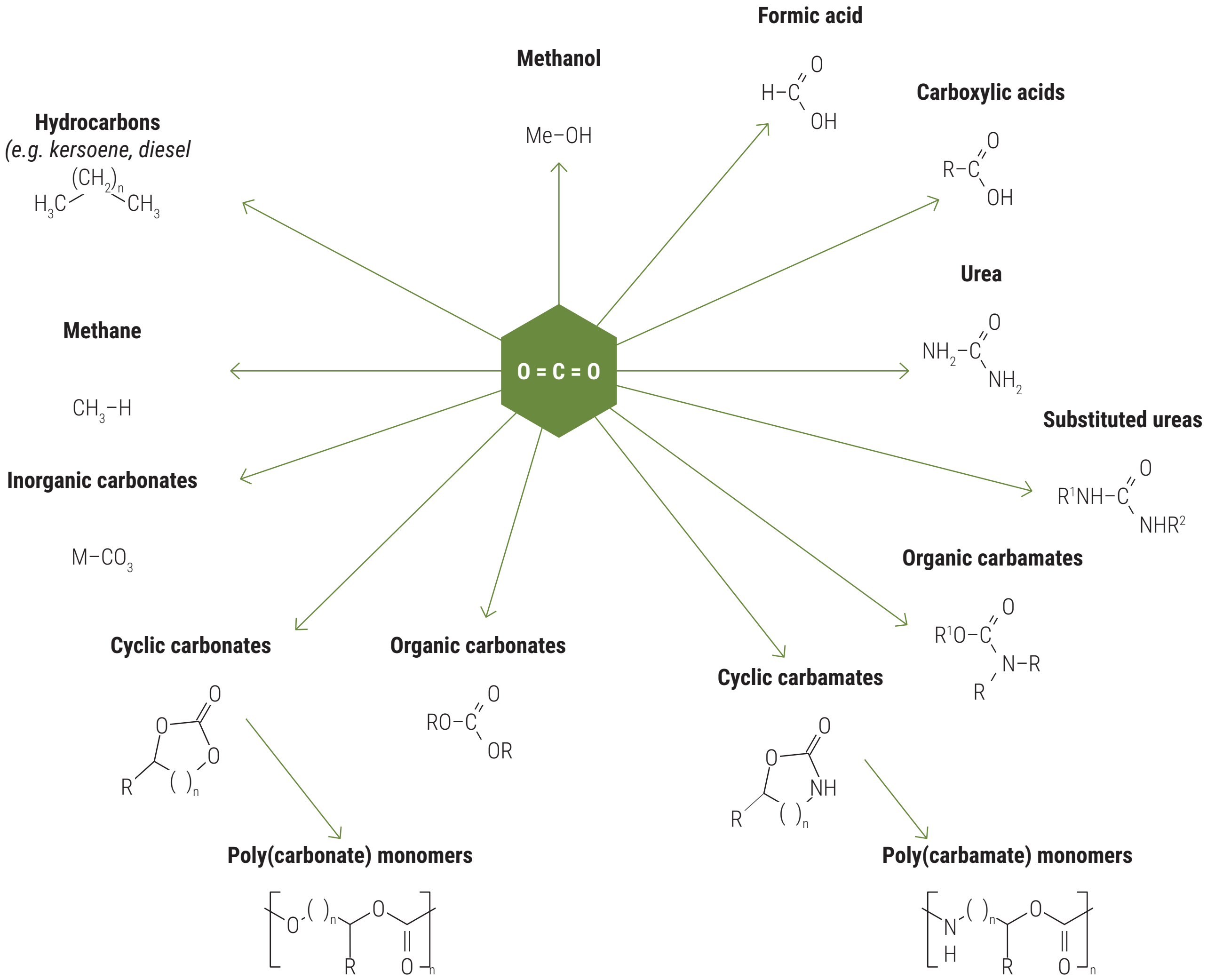
Several pathways exist to utilize CO_2, a potent greenhouse gas, as a resource. These include the conversion of CO_2 into fuels, the use of CO_2 as a feedstock for the chemical industry, and non-conversion uses of CO_2 (International Energy Agency [IEA] 2019). These technologies have the potential to absorb CO_2 from the atmosphere, and thus may help mitigate climate change. However, since they require significant amounts of energy, using renewable energy is essential to meet sustainability criteria. Figure 4.2 provides an overview of opportunities to use carbon dioxide as a resource and feedstock in the chemical industry. While some of the technologies are at the stage of basic research, others have already matured, but have not yet achieved commercial breakthrough.

As a resource to produce fuel, CO_2 can be converted via chemical and electrochemical processes to other energy storage chemicals. Such gases include syngas, formic acid, methane, ethylene, methanol, or dimethyl ether (DME). Since significant amounts of energy are needed for this type of conversion, use of renewable energy in these processes is particularly essential.

As a feedstock chemical, CO_2 has the potential to replace a range of fossil feedstock in producing basic chemicals that are used to produce commodity chemicals. Other feedstock uses of CO_2 include insertion of CO_2 into epoxides for manufacturing polymeric materials or converting CO_2 into inorganic minerals for building materials. This stores CO_2 in the product. As for CO_2 conversion to fuel, it is important to use renewable energy sources.

Non-conversion usage of CO_2 does not involve chemical reactions to convert CO_2 to other chemicals. Examples include injection of supercritical (fluid) CO_2 into oil wells to enhance the recovery of oil, or recuperation of methane from unmined coal seams. Supercritical CO_2 can also be used as a solvent in processing chemicals (e.g., flavour extraction) and is being explored as a heat transfer fluid for certain geothermal applications. Again, recognising energy needs and implications associated with supercritical (fluid) CO_2 is important.

Figure 4.2: **Overview of chemicals derived from Carbon Dioxide** (Styring *et al.* 2012, p. 11)

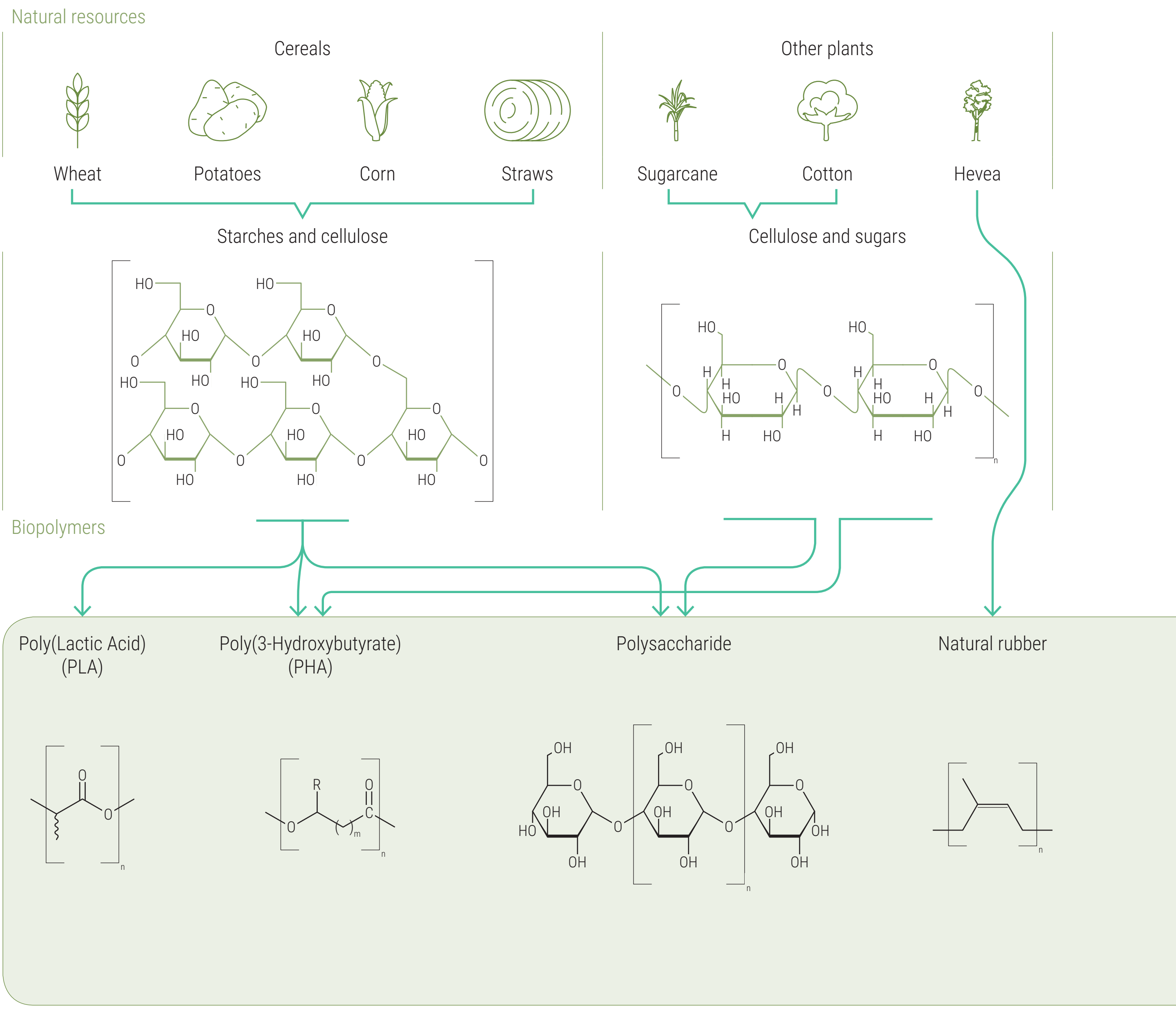


4.3 Chemical innovation opportunities

Plastics

Plastics are organic polymers, which include a wide range of synthetic or semi-synthetic materials used in applications such as clothes, cars, toys, televisions, computers, etc. They are commonly derived from crude oil, coal, or natural gas. However, significant amounts of plastics are disposed into the environment and accumulate in ecosystems, including in freshwater systems and oceans. Furthermore, chemicals are added to plastics as additives, such as plasticizers, some of

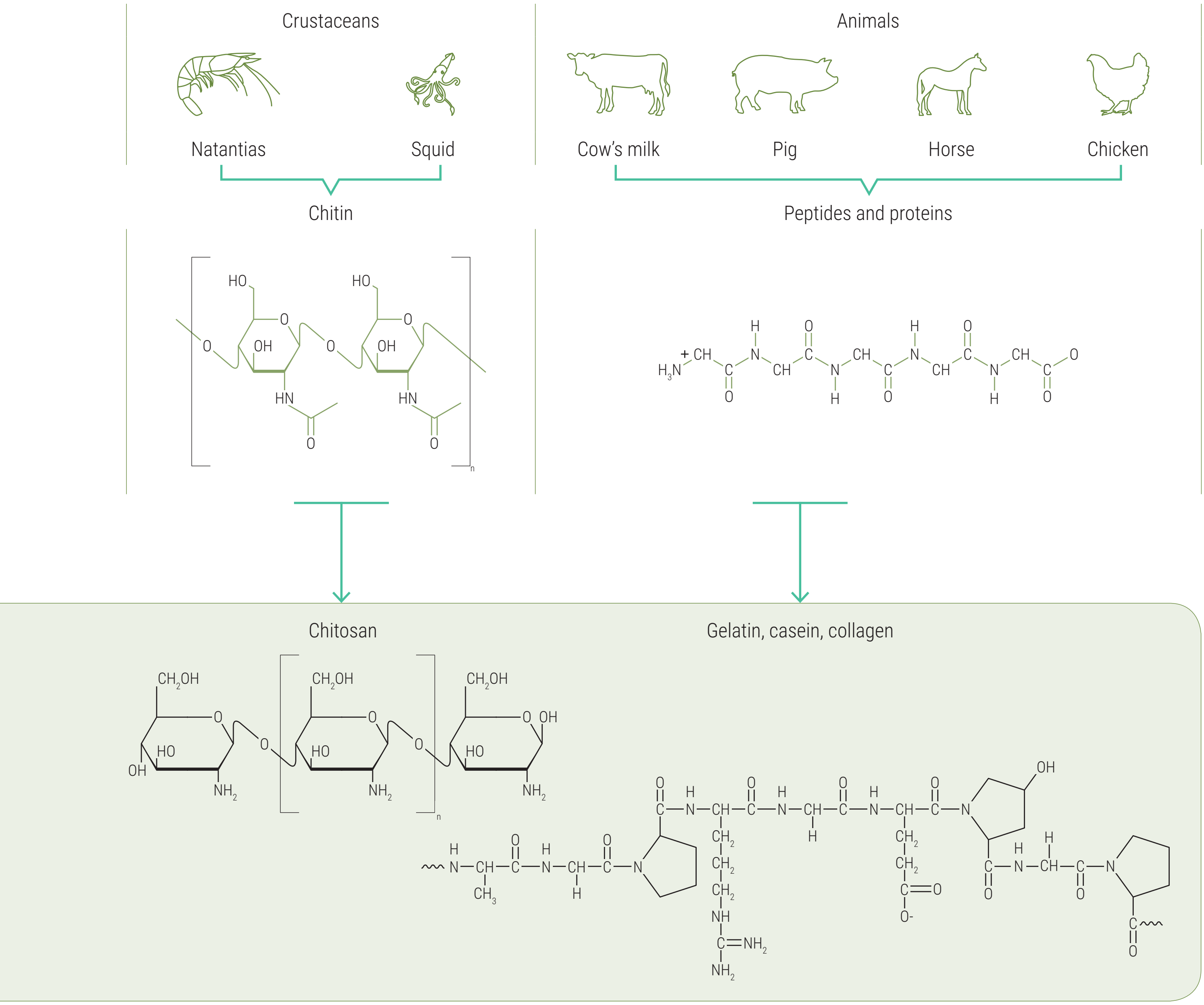
Figure 4.3: **Overview of biopolymers and their natural origin** (Bocqué *et al.* 2015, p. 15)



which cause concern (see below) and may hinder recycling.

Bioplastics are plastics materials produced from renewable biomass sources, including agricultural and food waste. Sources include cereals (e.g. wheat, corn, straws), other plants (cotton, woodchips, sawdust, algae, etc) or animal biomass. Currently produced bio-based plastics include plastics based on starch, polyhydroxyalkanoates (PHAs), polylactic acid (PLA), cellulose, or protein-based polymers (Karan *et al.* 2019). Polylactic Acid (PLA), for example, is a biodegradable, thermoplastic, aliphatic polyester derived from sugar through fermentation which can replace polyethylene in several applications, including packaging.

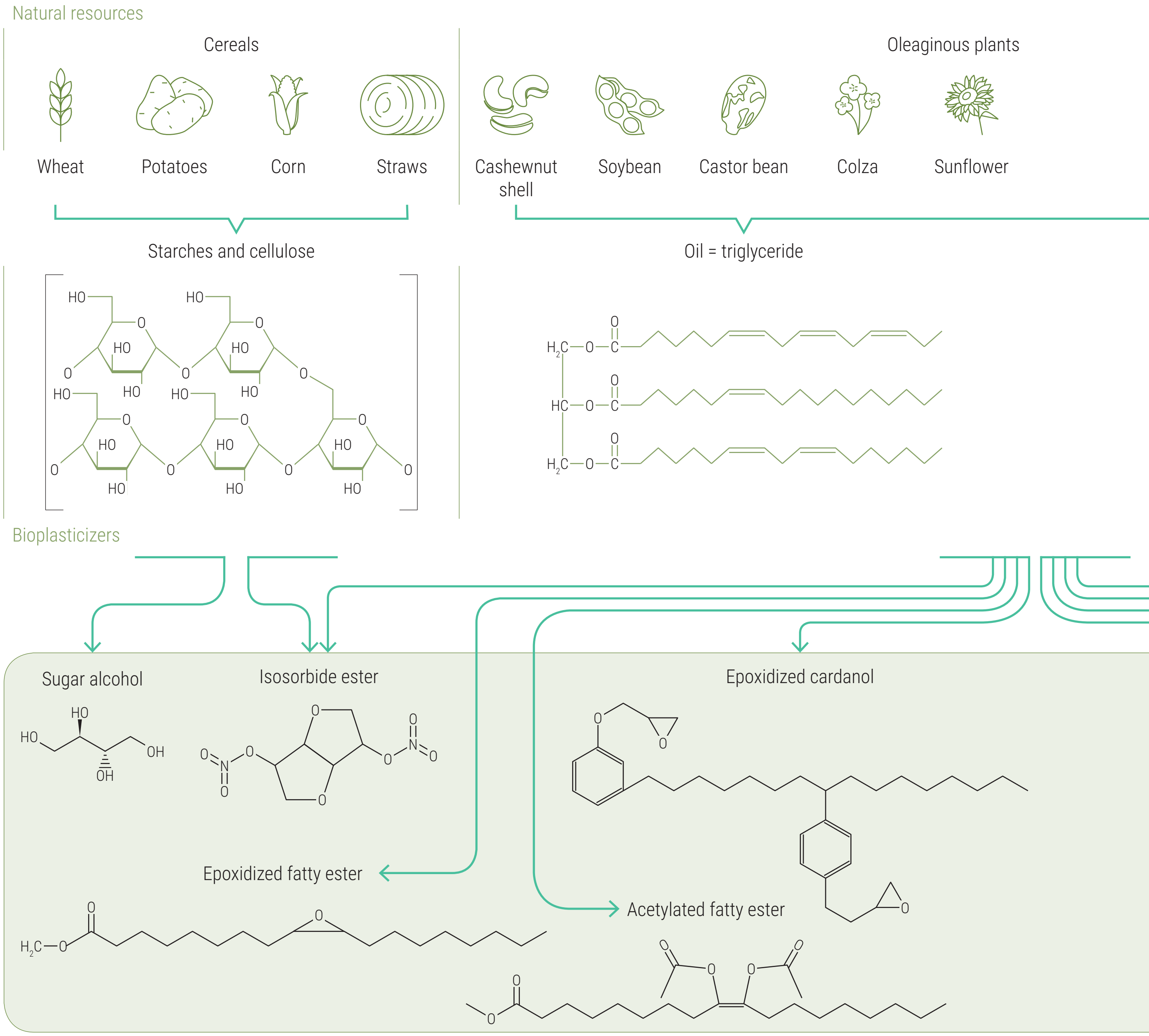
Bioplastics include both nondegradable and biodegradable plastics, with both having a potential role in advancing sustainability, if certain conditions are met. Nondegradable bioplastics can, for example, play a role in sustainable infrastructure



development (e.g., sewer piping, building, roofing materials, road surfaces, etc.) and serve as long-term carbon sinks. An important sustainability condition is that when these materials reach end of life, sound recycling is ensured (which is often not the case).

Degradable bioplastics are sometimes used for products that have a short-to-medium shelf life, and their durability can be tailored to the product purpose (Karan *et al.* 2019). However, unless specific and proper conditions for biodegradation are met (e.g. in a composting plant), biodegradable plastics do not advance sustainability either. An example is biodegradable plastics ending up in the marine environment where they do not degrade rapidly. A thorough discussion of this issue is featured in the UNEP publication, Biodegradable Plastics and Marine Litter: Misconceptions, concerns and impacts on marine environments (Kershaw 2015).

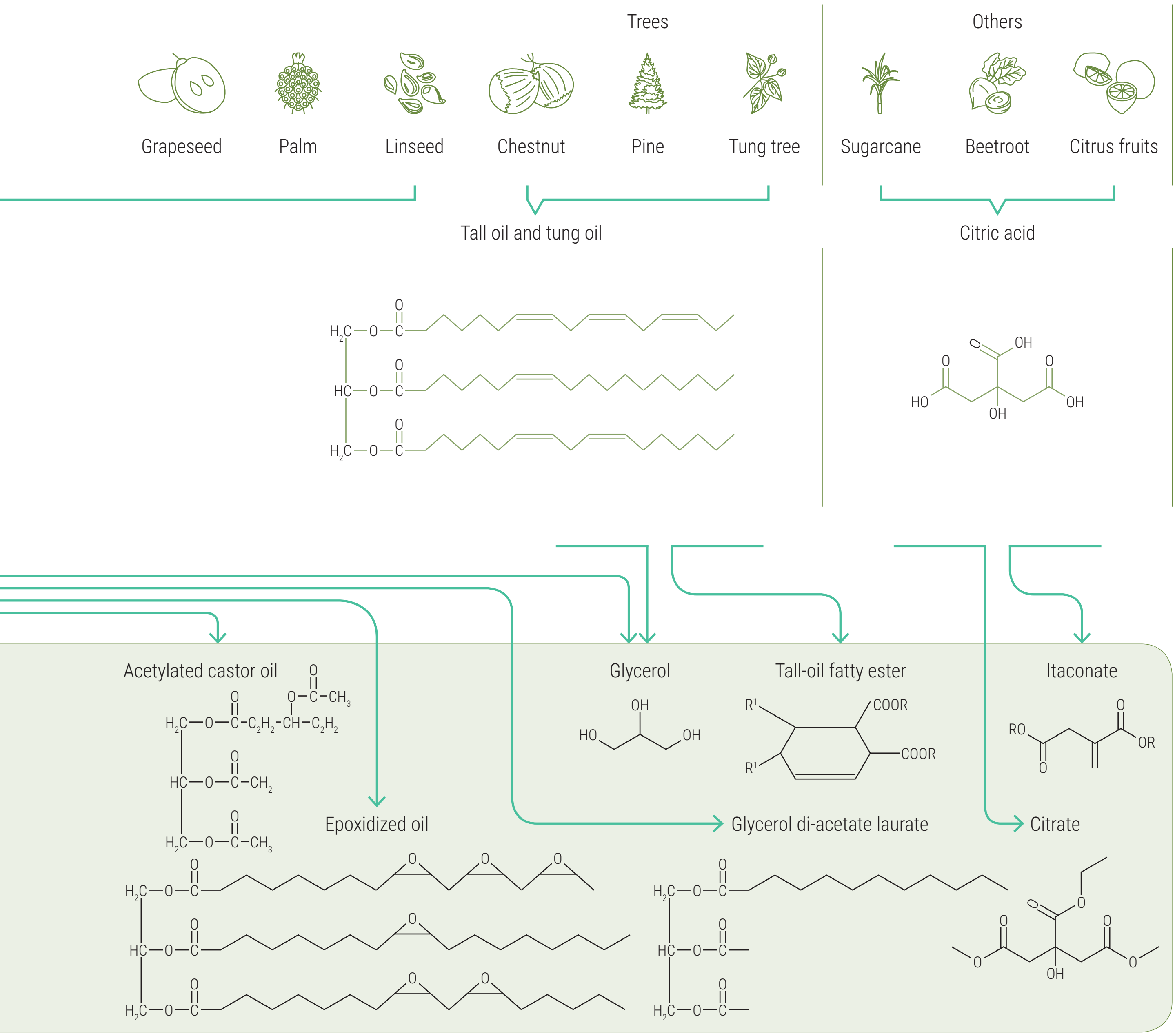
Figure 4.4: **Overview of biopolymers and their natural origin** (Bocqué *et al.* 2015, p. 21)



Plasticizers

Plasticizers are chemicals added to plastics to enhance flexibility of polymer blends and improve their processability. Many plasticizers typically do not have covalent bonds with the polymers and therefore may leach, resulting in potential human exposure and environmental contamination (Jamarani *et al.* 2018). An example are certain plasticizers created from phthalate esters, which can leach from products during use and are considered to be of concern due to the potential for adverse health effects (e.g. endocrine disruption). Their ubiquity in the environment is an additional source of concern (Benjamin *et al.* 2017).

Innovations to advance sustainability of plasticizers include the design of plasticizers with low migration rates, low volatility, no adverse health effects, and biodegradability. Alkyl diol



dibenzoate compounds, for example, provide many of the functions of DEHP (diethylhexyl phthalate) a plasticizer of concern. According to Erythropel *et al.* (2018), they degrade rapidly in soil and have a low toxicity profile.

Like other functional molecules, bio-based plasticizers can be derived from agricultural resources, such as cereals, oleaginous plants, trees, fruits, and vegetables or their wastes. From a chemistry perspective, these resources provide suitable structures (polyol and polyester), functionality (di-, tri-, tetra-, and pentafunctional molecules) and molecular weight (molecular, oligomer, and polymer) (Bocque et. al 2015). However, despite the potential of bio-based plasticizers, their cost, availability, toxicity and impact need to be further researched (Harmon and Otter 2017). Since bio-based does not necessarily mean non-toxic, generating more complete knowledge would provide a better understanding about potential sustainability opportunities and trade-offs.

Solvents

Solvents act to dissolve a solid, liquid, or gaseous solute. While water is the most well-known solvent, many solvents are organic chemicals, including alcohols and glycols, DMSO, (di)ethyl ether, hexane, tetrachloroethane, toluene, or xylene. They are used, for example, as stripping agents, in extraction processes, as degreasing agents, or as additives and diluents. Many organic solvents have hazardous properties and are released to the environment in significant quantities. Depending on the nature of the solvent, possible health effects may include irritation of the skin, eyes and lungs, headache, nausea, dizziness and light- headedness, while high exposure can cause unconsciousness and even death (Health and Safety Executive 2003).

To address the impact of solvents, the development of green and more sustainable solvents has received significant attention (Freire and Countinho 2019; Sheldon 2019). Innovation areas include for example: development of non-toxic solvents from biotic waste; use of water as a solvent in the production of pharmaceuticals and other chemicals instead of organic solvents; replacing toluene with safer alternatives that perform the same function; or designing materials and processes so that they do not require solvents (e.g. new building materials not requiring paints and coatings) (van der Waals *et al.* 2018).

Water, grease and dirt repellents

Water, grease and dirt repellents are chemicals affecting the resistance to the absorption or passage of water, oil or dirt resulting from the application of surface coating treatment. Most of these treatments are based on fluorochemicals. Per- and polyfluoroalkyl substances (PFAS) have been extensively used for their repellence of water, grease and dirt, and their temperature resistance in various applications. Many PFASs are hazardous to human health, persistent in the environment, and longer chain versions bio-accumulate in living organisms. Shorter chain PFAS are mobile in the environment and persistent (UNEP 2019b). These properties of PFAS cause concern, creating opportunities for green and sustainable chemistry innovation.

A range of innovations have been developed to advance the sustainability of water, grease and dirt repellents. Chromatogeny, for example, is a solvent-free green chemistry process that imparts hydrophobicity to papers and boards, by applying fatty chloride acids in a liquid state onto paper. Potential applications include packaging, textiles, medical devices, or technical films. In the textile industry, innovation efforts focus on the development of sustainable water repellents for fabrics that are biocarbon-based and PFC-free (Inno4sd.net 2019) (Innovation for Sustainable Development Network 2019).

Flame retardants

Flame retardants include a diverse group of chemicals which are added to manufactured materials, such as plastics, textiles, surface finishes or coatings to make them resistant to fire. A number of halogenated flame-retardants, i.e. brominated and chlorinated flame retardants, cause concern because of their persistence, bioaccumulation, long-range transport and toxicity. This has increased the use of halogen-free alternatives, such as organo-phosphorous compounds, although some of these alternatives may pose similar risks.

Flame retardants generated from biological sources have a significant potential. They tend to be low cost, may be nontoxic, and are independent of petrochemical market fluctuations (Howell *et al.* 2018a). Bio-based flame retardants are derived, for example, from tartaric acid (a by-product of the wine industry), chitosan (a by-product of the fishing industry), castor oil (a non-edible plant oil), and isosorbide (a diether diol produced from starch) (Howell, Daniel and Ostrander 2018). A recent innovation is the use of gallic acid, commonly found in fruits, nuts and leaves; and 3,5-dihydroxybenzoic acid from buckwheat to produce flame retardants. Hydroxyl groups on these compounds are converted to flame-retardant phosphorous esters. They can then be added to an epoxy resin, a polymer used in electronics, automobiles and aircraft (Howell, Oberdorfer and Ostrander 2018). Another promising area of innovation is the development of novel bio-based flame-retardant systems from tannic acid (Laoutid *et al.* 2018).

Surfactants

Surfactants are chemicals which are added to a liquid to reduce surface tension, thereby increasing spreading and wetting properties of the product. These amphiphilic organic molecules adsorb at the interface and self-aggregate or self-assemble into different phases in aqueous or non-aqueous solution. Surfactants are key components, for example, of household detergents (e.g. washing powder) and home cleaning supplies (e.g. floor cleaner), or personal toiletries (e.g. shampoo). Surfactants may irritate eyes, skin, and lungs, and some are known or suspected EDC, are toxic in the aquatic environment, and bioaccumulate (van der Waals *et al.*).

Chemistry innovation to advance the sustainability of surfactants is referred to as 'green surfactants', 'oleo-chemical based surfactants', 'renewable surfactants', 'bio-surfactants', or 'natural surfactants' (Bhadani *et al.* 2020). The spectrum of green alternative surfactants on the market is diverse and includes, for example alkypolyglucosides, plant-based saponins, amino acid derivatives, and betaines (SpecialChem 2015). Often, more eco-friendly surfactant molecules are derived from renewable biomass building blocks (Bhadani *et al.* 2020). The surfactant algal betaine, for example, is made through controlled fermentation from renewable microalgae (Business Wire 2015). It is used in products that need foams, such as shampoos, liquid soaps, or dishwashing liquids.

Further innovation opportunities exist through modifying technologies and microbial strain improvement methods (Kandasamy *et al.* 2019). For, example, a new surfactant recently developed through biotech methods consists of sophorolipids. It shows good cleaning properties, is gentle on the skin, and rapidly degrades in the environment (Bhadani *et al.* 2020).

Chemical preservatives

Chemical preservatives are chemicals added to products to prevent decay of a product by microbial growth or unwanted chemical changes. They are widely used in food products, beverages, pharmaceutical drugs, paints, cosmetics, wood, etc. Depending on their chemistry, preservatives may have potential adverse effects on human health and the environment. For example, some parabens, i.e. butylparaben and propyl paraben, have been shown to have potential endocrine effects and oestrogenic properties (EC 2011). Formaldehyde and formaldehyde-releasing preservatives used in shampoos and liquid baby soaps are of concern because of their carcinogenic and allergenic properties (van der Waals *et al.* 2018).

Given the direct contact that many chemical preservatives have with the human body, chemistry innovation to develop safer chemical preservatives is important. However, since chemical preservatives are inherently antimicrobial, finding a chemical preservative that prevents microbial growth, but shows no toxicity is challenging. Efforts focus on identifying and developing chemical preservatives which are less toxic, in comparison to those on the market.

A review recently undertaken from a green chemistry perspective compares chemicals preservatives for a range of product categories (Buckley *et al.* 2017). It concludes, for example, that octyl gallate, a food preservative has better antimicrobial activity and lower chemical hazards compared to currently used preservatives. Equally important, opportunities exist to make use of natural preservatives (e.g. rosemary and oregano extract, hops, salt, sugar, vinegar, alcohol, etc). In some cases, and for certain products, alternative preservation strategies may reduce the need for chemical preservatives.

Box 4.2: **Green and sustainable chemistry in agriculture** (Peabody O'brien *et al*. 2009)

Growing populations and demand for food have led to an increased use of pesticides and fertilizers world-wide. In particular, highly hazardous pesticides are causing concerns for human health and the environment. Similarly, runoffs of fertilizers are causing significant environmental problems, in particular in freshwater and ocean ecosystems (UNEP 2019b). Green and sustainable chemistry therefore has an important role to place in advancing the sustainability of agriculture.

Peabody O'brien *et al*. (2009) propose that green chemistry and sustainable agriculture are inherently intertwined in at least three ways. First, green and sustainable chemistry is a consumer of agricultural inputs, such as bio-feedstocks. Green chemists therefore need farmers to practice sustainable agriculture to provide truly "green" bio-based raw materials. Second, green chemistry alternatives can play an important role in producing agricultural goods without toxic pesticides and other chemicals of concern. Lastly, green chemistry innovations can help to remediate land, by eliminating chemical soil pollution associated with traditional farming practices.

4.4 Process innovation opportunities

Catalysis

Catalysis is the process of increasing the rate of a chemical reaction by adding a substance referred to as a "catalyst". The catalyst is not consumed in the reaction and therefore can continue to act. Catalysts lower the activation energy (e.g. heat) required for a reaction to occur, and thus ensure the raw material reacts more completely and is used more effectively. In most cases, only small amounts of catalyst are required to alter the reaction rate.

Problems with the use of catalysts arise when toxic materials are used in reactions, or the catalyzed reactions requires extreme conditions which lessen the overall benefit of the catalyst. Some organic transformations have, for example, used rare transition-metal catalysts based on palladium, rhodium, ruthenium, and iridium. While being highly efficient, these metals have restricted availability, are costly, and have toxic properties. Furthermore, some catalytic processes require energy-intensive reaction conditions, such as high heat or high pressure. Identifying more sustainable catalysts or catalytic processes could address a range of sustainability challenges and help unlock the potential of many innovations. Approaches towards more sustainable catalysis include the development of low-toxicity catalysts, processes requiring less energy-intensive reaction conditions, or catalysts which can harvest renewable energy sources for reactions.

Earth abundant metal catalysis

Earth abundant metals, which include first row transition metal elements such as manganese, iron, cobalt, nickel, vanadium, or chromium (Chirik and Morris 2015) have a potential to enhance sustainable use of catalysts in chemical reactions (ACS 2015b). This has led to research efforts towards the development of homogeneous catalysts based on earth-abundant, low-toxicity metal complexes. According to the ACS, earth-abundant metal catalysis "is touted for its inherent sustainability, and the advantages of low toxicity and minimal environmental impact" (ACS 2020b). Complexes based on the first-row metals Fe, Co, Ni and Mn are particularly appealing (Chakraborty, Leitus and Milstein 2016).

Earth abundant metals also have the potential to support a greater variety of chemical transformations than traditionally used catalysts. Recent innovation efforts include, for example, the use of abundant earth metals in the synthesis of well-defined nanomaterials for enhanced activity, using earth abundant catalysts to reduce the amount of noble metals needed in a reaction, or for photoactivation (Kaushik and Moores 2017). Another promising application is the use of the iron-based catalyst Fe-TAML® to convert harmful pollutants into less toxic or harmless substances, including harmful pesticides in soil (Platt 2004).

Organocatalysis

Organocatalysis uses small organic molecules consisting of carbon, hydrogen, sulphur and other non-metal elements as catalysts. Those include amines, urea, acids, alcohols, halogenated species and carbenes, among others (Vitale *et al.* 2016). Organocatalysts may be produced from waste, thereby satisfying the principles of a green and more sustainable chemistry (Meninno 2020). Advantages are their availability, low cost, and low toxicity. Organocatalysts are also able to work under milder and less hazardous reaction conditions than many other catalysts.

Areas of application include, for example, organic synthesis and polymer synthesis, as well as biomass conversion to produce a range of chemicals, materials, and biofuels. Examples in the area of biomass conversion include the conversion of cellulose, glucose and fructose, upgrading of furaldehydes, and organocatalytic polymerization of biomass feedstocks (Liu and Chen 2014).

Bio-catalysis

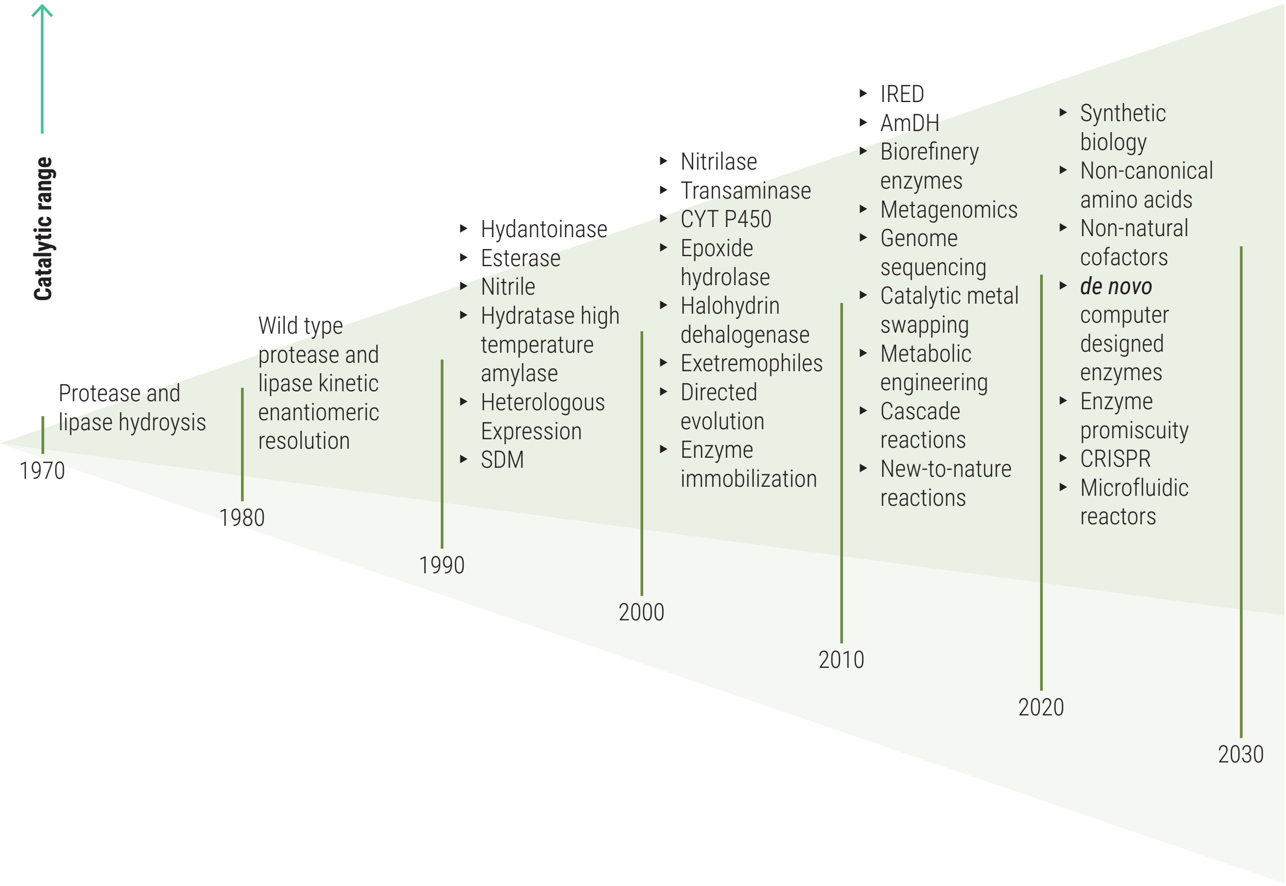
Enzymes are proteinaceous catalysts. They catalyse highly specific reactions and can be modified to catalyse a desired reaction. Bio-catalysis uses enzymes for reactions under mild conditions, e.g. ambient temperature, which requires little external addition of energy. Another advantage is that most enzymes used industrially are non-hazardous and biodegradable. The catalytic properties of enzymes allow development of new technologies, such as the production of chiral molecules, specialty chemicals, and commodity chemicals. Enzymes are produced from inexpensive renewable resources and their costs are stable.

Expanded application of bio-catalysis is possible thanks to the sequencing of large numbers of microbial genomes, coupled with advances in gene synthesis, allowing access to a broad range of wild-type enzymes (Sheldon and Woodley 2018). The properties of potentially interesting enzymes can then, with the aid of directed evolution tools, be fine-tuned to fit seamlessly into a predefined process. For example, the biocatalytic production of certain pharmaceutical intermediates, (e.g. enantiopure alcohols and amines) has become state of the art organic synthesis. Another promising innovation area is the use of enzymes in the production of polymers (Kobayashi, Uyama and Kadokawa 2019).

Photo-catalysis

Photocatalysis involves the absorption of light by one or more reacting species in the presence of a catalyst. It converts photonic energy (e.g. solar radiation) to chemical energy with the help of semiconducting catalytic materials, such as TiO_2 and other photocatalysts. Photocatalysis can be used in diverse applications, such as water hydrolysis for producing hydrogen as fuel, organic synthesis, and the recovery of polluted effluents (Ravelli *et al.* 2009). Specific applications include technologies to advance artificial photosynthesis (where radiation is used to convert CO_2 to energy rich organic chemicals), or water treatment (where radiation is used to convert toxic pollutants to non-toxic chemicals).

Figure 4.5: **Scope of Biocatalysis in Sustainable Organic Synthesis** (Sheldon and Brady 2019, p. 2859)



Batch vs. continuous processing

Batch processing involves the processing of bulk material in groups in distinctive step of the production process. An alternative to batch processing is continuous processing, in which materials react as they flow along a system of channels, pipes, or tubes. According to the US Government Accountability Office (2018), continuous processing uses materials more efficiently than batch processing, has lower energy consumption, less waste production, less consumption of solvents, safer processes, and creates less exposure to chemicals. The technology therefore meets many of the 12 Principles of Green Chemistry.

Biorefineries

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and value-added chemicals from biomass. The International Energy Agency (IEA) defines biorefineries as "the sustainable processing of biomass into a spectrum of bio-based products (food, feed, chemicals, materials) and bioenergy (biofuels, power and/or heat) (Bell *et al*. 2014). Biorefineries can develop multiple chemicals by fractioning biomass into intermediates (carbohydrates, proteins, triglycerides) that can be further converted into valuable products.

Innovation areas and examples to use biorefineries to advance green and sustainable chemistry include (WUR n.d. b):

- Fermentation of glucose to succinic acid replacing petroleum feedstock and using

Table 4.1: **Comparison of chemical engineering reactor and a bioreactor** (Verster *et al.* 2014, p. 95)

Chemical engineering reactor	Typical Bioreactor	Implication for bioreactor engineering
Simple reaction mixture	Complexity of reaction mixture	Affects downstream processing & purification, can affect catalytic functionality (catalyst 'poisoning' or feedback inhibition)
High concentration of reactants and products	Low concentration of reactants and products	Inefficient mass and heat transfer
Increase of product with decrease of substrate	Increase in biomass simultaneously with progress of biochemical transformation	Affects downstream processing & purification, non-linear productivity optimization
Catalyst needs to be added to the system, could have limited catalytic life span	Microorganisms synthesise their own catalysts (enzymes) –'regeneration' of catalyst	In a well-designed system the progress can be self-seeding / self-organising
Extreme reaction conditions	Mild reaction conditions (temperature, pH)	Potential to be a safer process, demanding less energy. Establishing a cooling gradient may be a challenge

significantly less energy than tradition production methods, with applications in polyurethanes, paints, coatings, adhesives, pharmaceuticals, etc.

- Conversion of components from low-cost substrates and side streams into energy sources such as hydrogen

- Development of micro-algae that use sunlight and CO_2 as energy and carbon sources to produce high-quality oils and biodiesel, among other products

Microreactors

Microreactors - also referred to as a micro-structured reactors or microchannel reactors - are devices in which flow chemistry reactions take place in a confinement with dimensions often below 1 mm. Microreactor technology and flow chemistry have the potential to play an important role in the development of green and sustainable synthesis. The technology preserves atom economy, uses safer solvents and auxiliaries, creates less waste and allows for real-time analysis for pollution prevention, essentially providing inherently safer chemistry (Fanelli *et al.* 2017).

4.5 Opportunities of digitization to advance green and sustainable chemistry

Digitization and modern information technologies have a significant potential in advancing green and sustainable chemistry innovation, when robust sustainability assessments are conducted. In chemical manufacturing for example, the generation and analysis of large data sets allows to generate higher yields and throughputs, lower energy consumption, reduce pollution and foster effective maintenance (Fermeglia, Longo and Toma 2009). For many chemical operations, these benefits can be achieved by using and upgrading existing information technology and process control systems (UNEP 2019b).

Digitization also enables more rapid experimentation and discovery of new molecules at lower cost than laboratories can achieve (Davies *et al.* 2016). Advanced software allows to screen chemical molecules for a number of hazard properties resulting in a significant reduction of animal testing (Pradeep, Friedman and Judson 2020). Innovations in software, coupled with modern computer technology, also help screen the chemicals space – about 1060 molecules in total (Kirkpatrick and Ellis 2004) – and create molecules with desired properties relevant for sustainable material development and achieving sustainability objectives.

Agriculture is one important sector where IT based solutions have a particular potential to advance sustainability (King 2017). Robots and drones can detect pests at an early stage of their outbreaks, allowing precision use of pesticides and significantly minimizing their use. These technologies also collect other data relevant for advancing sustainability, including for the efficient use of fertilizers (minimizing their losses to the environment) and minimizing the use of scarce water resources.

4.6 Potential of green and sustainable chemistry innovation in a sector: The example of energy

Green and sustainable chemistry opportunities in key sectors

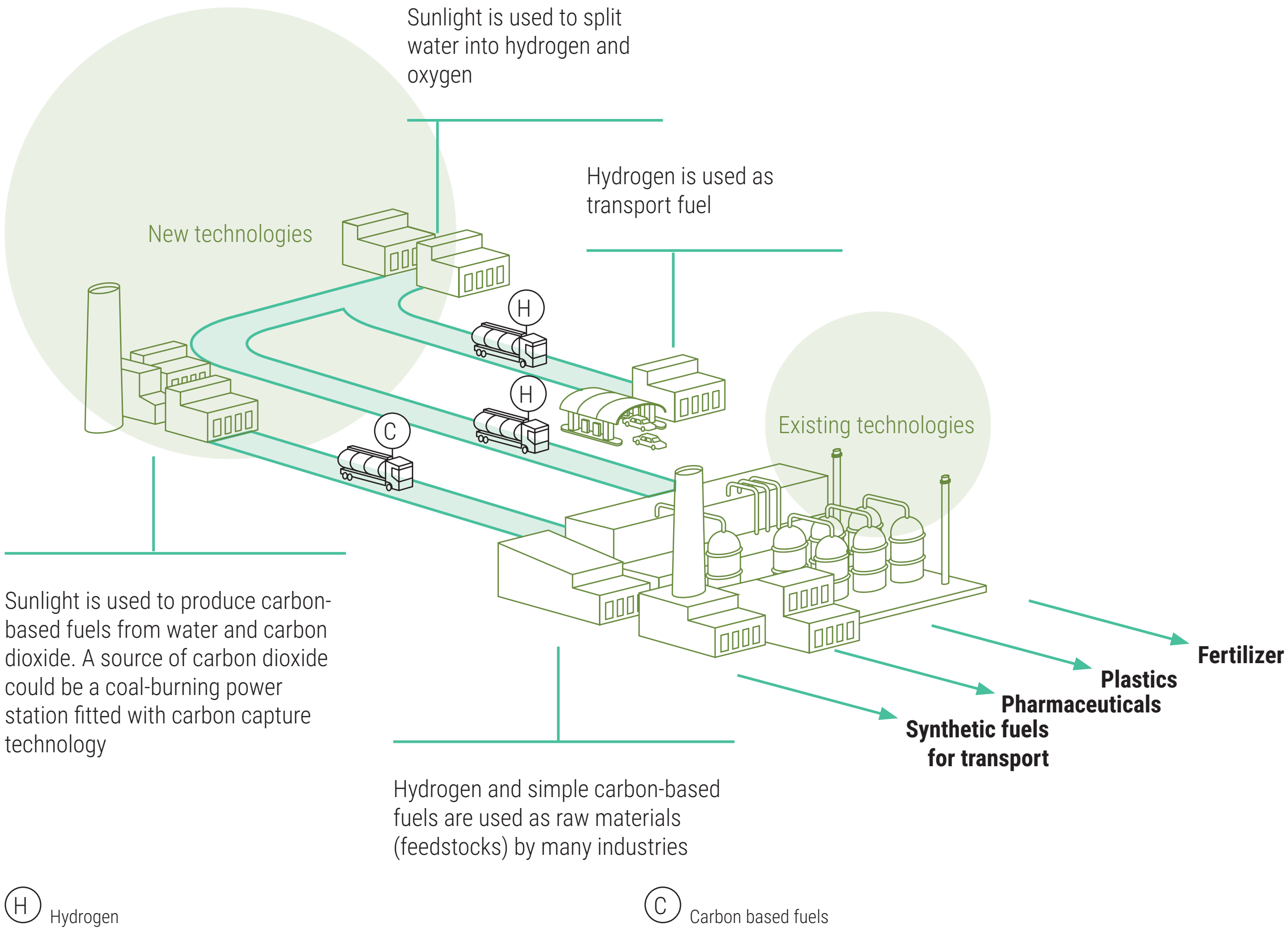
Green and sustainable chemistry innovation has the potential to drive sustainability in important sectors of the economy. This includes, but is not limited to the energy, transport, agriculture, textile, tourism sectors. Given the importance of the energy sector in addressing climate change, the sector is briefly introduced to illustrate how green and sustainable chemistry is relevant for and how it can make a difference in shaping a sustainable transformation at the sectoral level.

Enhancing energy efficiency through chemistry innovation

The 6th principle of green chemistry states that energy requirements should be recognized for their environmental and economic impacts and be minimized. Synthetic methods should, if possible, be conducted at ambient temperature and pressure (Anastas and Warner 1998). While significant steps have been taken by the chemical industry to save energy in producing chemicals, it is challenging to make further significant gains through process efficiency measures, pointing to the need for technology disruption, based in green chemistry reactions which are less energy intensive. Disruptive concepts such as electrochemical synthesis and other innovative catalysis techniques are being researched to replace thermochemical methods with milder, less energetically demanding processes. Passive separation techniques using membranes have already begun to outpace demanding traditional separation methods in cost effectiveness and performance. New sustainable technological concepts in which energy and chemical products are produced simultaneously are on the horizon. Continued incentivization and development of these technologies will be necessary to market these innovations and achieve an energetically efficient, safe and resilient chemical industry.

Beyond process innovations, chemistry innovation has a significant potential to increase energy

Figure 4.6: **What could the production of solar fuels look like** (Royal Society of Chemistry 2020)



Sunlight is used to split water into hydrogen and oxygen

Hydrogen is used as transport fuel

Sunlight is used to produce carbon-based fuels from water and carbon dioxide. A source of carbon dioxide could be a coal-burning power station fitted with carbon capture technology

Hydrogen and simple carbon-based fuels are used as raw materials (feedstocks) by many industries

efficiency and reduce greenhouse gas emissions through the development of novel products and materials. Examples are lightweight and recyclable composite materials that contribute to reduced energy consumption because of their reduced weight. Their applications are manifold and include mobility (airplanes, cars), energy generation through windmills, etc.

Another area is the development of energy efficient building materials. For example, cellulose aerogel (CA) isolated from tea stem wastes (TSW) is a good heat insulator and fire retardant. It is environmentally friendly, thermally stable and can be produced at low cost (Kaya and Tabak 2020). The green and sustainable chemistry challenge is to develop high-performing materials and ensure they are non-toxic and recyclable. Therefore, “green materials” promoted for their energy saving potential need to be screened for green and sustainability chemistry criteria, before they can be considered more sustainable.

Developing solar fuels through chemistry innovation

Solar fuels include technologies that use sunlight to produce valuable molecules such as hydrogen and methanol from water and carbon dioxide. The novelty of this approach is the direct use of solar energy to produce already known and widely used chemicals from water and carbon dioxide. The concept covers fuels for transport and electricity generation, as well as chemical feedstocks to produce petrochemicals, fertilisers, plastics and pharmaceuticals. Commercial prototypes are expected to be available within 10–15 years (Royal Society of Chemistry 2020).

Artificial photosynthesis is a chemical process that bio-mimics the natural process of photosynthesis to convert sunlight, water, and carbon dioxide into carbohydrates and oxygen. This creates the potential to use excess carbon dioxide to store solar energy in the form of chemical bonds. Chemists already have already been successful in producing fuels through artificial photosynthesis (ScienceDaily 2019).

Innovation areas to convert sun radiation and CO_2 into valuable organic molecules include: photocatalytic water splitting converting water into hydrogen and oxygen, (electrolysis), a major research topic is artificial photosynthesis; light-driven CO_2 absorption that replicates natural carbon fixation; design and assembly of devices for the direct production of solar fuels, photo electrochemistry and its application in fuel cells; and the engineering of enzymes and photoautotrophic microorganisms for biofuel and hydrogen production from sunlight.

Improving photo-voltaic energy generation through chemistry innovation

Chemistry innovation also plays a role in advancing solar photovoltaics in a number of ways; organic and dye-sensitised solar photovoltaic technologies offer the possibility of developing lightweight, flexible, coloured and inexpensive solar panels; new materials for solar shingles both protect homes, while also generating electricity; new silicon inks can increase the efficiency of solar cells; or, alternative materials and materials recovery techniques (e.g. for silicon photovoltaics) help reduce dependence on critical raw materials such as rare metals (European Technology Platform for Sustainable Chemistry [SusChem] 2019).

Improving energy storage through chemistry innovation

Batteries have the potential to provide society with a consistent supply of energy generated from renewable sources. However, many batteries still contain toxic metals such as Aluminium, Cadmium, Mercury, Nickel, Lead, Iron, Zinc, Calcium, Magnesium, and Lithium. In the case of Lithium, which plays a key role in expanding electric vehicle and grid applications, there are risks of possible supply shortages as well as recycling and disposal challenges

Innovations in chemistry have the potential to improve battery safety, reliability, durability, and recyclability. Innovation topics include, for example: new materials for lithium-ion batteries; redox flow batteries; metal-air batteries; organic batteries; and materials for large capacity thermo-solar and heat energy storage. One promising area are new chemistries dealing with monovalent (K_+, Na_+) or divalent (Mg_{2+} and Ca_{2+}) cations, as well as technologies to efficiently recycle lithium. From a sustainability perspective, an appealing alternative to lithium metal is sodium and its sodium salts (PF6–, TFSI–, FSI–) which are less toxic than their lithium counterparts (Larcher and Tarascon 2015).

5

ENABLING POLICIES, TOOLS AND INSTRUMENTS TO ADVANCE GREEN AND SUSTAINABLE CHEMISTRY >

5.1 The role of enabling policies, tools and instruments in advancing green and sustainable chemistry

Although the market for green and sustainable chemistry is growing, relevant innovation needs to be nurtured to increase its market shares. This chapter introduces policies, tools and instruments which can help to create the necessary enabling conditions. They range from regulatory action and standard setting, to assessment tools and approaches, strengthening corporate governance, as well as knowledge-sharing and award programmes. An important question relevant across all policies, tools and instruments is how green and sustainable chemistry considerations can be fully and systematically considered in their development and application. Chapter 6 will address more strategic enabling sectors and programmes. Together, both chapters offer a suite of enabling measures to accelerate green and sustainable chemistry innovation and their market performance.

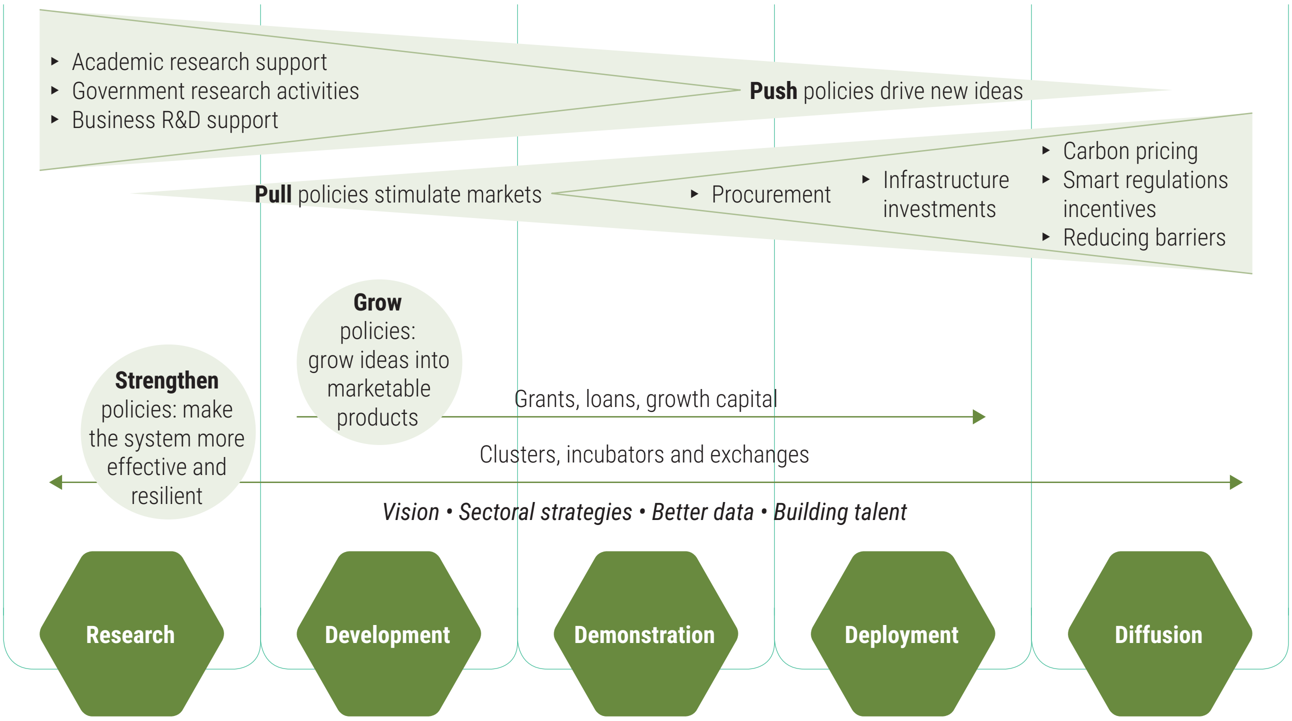
5.2 Policies, regulatory action and standard setting

Push and pull policies

Policy approaches or interventions to advance innovation may fall 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 (Elgie and Brownlee 2017). Other characteristics of policy instruments that play a role include stringency, predictability, and flexibility.

While these are general categorizations, this framing illustrates how consistent and informed public interventions that are cognizant of the culture they operate in may be structured to shape different elements of the innovation system in a direction which support green and sustainable chemistry innovation. The German National Bioeconomy Strategy is an example of a strategy which features a wide range of policy approaches including both push and pull measures. It lists measures for implementation, building on the National Research Strategy BioEconomy 2030 and the National Policy Strategy on Bioeconomy to pool the various political strands together into a coherent framework (German Ministry of Education and Research and German Ministry of Food and Agriculture 2020).

Figure 5.1: **Policy interventions that foster technology innovation** (adapted from Elgie and Brownlee 2017, p. 15)



Government policies to stimulate substitution and green and sustainable chemistry innovation

Identifying chemicals, or groups of chemicals of concern, setting explicit limits on selected uses and defining substitution goals by public authorities can drive voluntary frontrunner innovation. In Europe, the listing of substances of very high concern (SVHC) on the Candidate list for inclusion of substances for authorization under Annex XIV of REACH conveyed the intention of the regulator to take risk management action (European Chemicals Agency 2011). This action incentivizes industry to prioritize replacement activities. Hoffman-La Roche, for example, has implemented a substitution action programme to comply with REACH in advance of regulatory timelines by evaluating and testing alternatives (Buxton 2016).

At the global level, the Stockholm Convention provides a stimulus for innovation by listing persistent organic chemicals and pollutants for which global agreement exists to phase them out. The same applies for the Minamata Convention covering mercury. These global agreements cover, however, only a limited number of chemicals of concern. To expand and deepen its innovation-driving policy framework, the European Commission published a Chemicals Strategy for Sustainability in October 2020 that is part of the EU's zero pollution ambition, a key commitment of the European Green Deal. The Strategy aims to better protect citizens and the environment and boost innovation for the development of safe and sustainable alternatives (EC 2019).

Government policies may also be of enabling nature. In the US, the Sustainable Chemistry Research and Development Act of 2019 which passed in July 2020 in the US Senate, envisages convening of an interagency entity under the National Science and Technology Council to coordinate federal programs and activities in support of sustainable chemistry. Parties participating in the entity carry out specified activities in support of sustainable chemistry, including incorporating sustainable chemistry into existing research, development, demonstration, technology transfer, commercialization, education, and training programs (Lipinski 2019). The entity is required to create a roadmap for sustainable chemistry within two years from the date of enactment. As a first step the entity will consult with relevant stakeholders, including international stakeholders, to develop a definition for the term sustainable chemistry.

Access to information: Labelling, certification and transparency

Providing access to different types of information to workers, citizen, consumers and other interested stakeholders not only helps them to take protective measures, as necessary. It also shapes demand for safer and more sustainable chemicals and products.

Labels and certification systems, as well as a requirement for listing of ingredients, are useful for the public to identify safer and sustainable chemicals and products, as long as the information is presented in a transparent, reliable and clear manner, as well as relevant and accessible. Implementation of the Globally Harmonized System for Classification and Labelling of Chemicals (GHS) is an important measure to communicate chemical hazards and required protection measures to workers and consumers. Of importance is that information is readily accessible at the time and location the consumer needs it, during research into buying options, and at the point of purchase and use (UNEP 2017a).

New information tools, such as smartphone apps that link to regulatory initiatives and consumer report publications are also emerging as valuable tools to bring information to consumers. The apps ToxFox and AskReach, for example, draw attention to chemicals on the REACH candidate list, helping users to make informed decisions and creating demand for nontoxic and sustainable product purchase.

Enabling policies, such as right-to-know for workers, consumers and communities, public participation, and access to justice, coupled with innovative technologies, can be driving forces to advance green and sustainable chemistry. Examples include the Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters, or the Regional Agreement on Access to Information, Public Participation and Justice in Environmental Matters in Latin America and the Caribbean.

For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapter 8.

Public participation and stakeholder engagement

Effective public participation in chemicals- and product – related decision-making remains crucial to ensure environmental protection, safe management of chemicals and wastes and sustainable consumption and production. Public participation in decision-making related to chemicals should be ensured with regard to projects, plans, programmes and policies and legislation. For example, business operators of project activities are encouraged to identify the public concerned (not only local communities but also non-governmental organizations promoting environmental protection), to involve them in decision-making, and to provide information regarding the objectives of their application before applying for a permit. This also applies when the industry operator wishes to change or update the operating conditions for the activity.

5.3 Life cycle assessment and sustainable design approaches

Life cycle assessment methods and thinking

Life cycle approaches help scientists, product developers and managers to understand the potential impacts of a product during the many stages of its production, use, and end of life. Life cycle assessment (LCA) is defined by the International Organization for Standardization (ISO) as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2016). Assessing and managing chemicals along entire chemical and product life cycles allows to benchmark environmental performance of products against pollution and exposure reduction targets (Fantke and Illner 2019). LCA also helps to avoid shifting the burden from one stage of the life cycle to another (e.g. decreased raw material extraction through recycling at the expense of increased residues of contaminants in recirculates) (Hellweg and Milà i Canals 2014).

LCA covers human health impacts, such as those arising from toxicity and pollution linked to the product (Arvidsson *et al.* 2018). To assess social impacts in more depth, Social Life Cycle Assessment (SLCA) may be used (Andrews *et al.* 2009), while Life Cycle Sustainability Assessment cover all three dimensions of sustainable development - environmental, social and economic (Guinée 2016; UNEP 2020)

Life cycle assessment methods provide valuable insights for decision-making, but can be resource intensive and may require data sets difficult to obtain. LCAs also face challenges in assessing chemical risks and impacts on human health and the environment during the various stages of a product life cycle, as well as assessing recyclability of materials. The ISO 14000 standard series provides a broadly accepted set of principles for conducting life cycle assessments. However, some parts are subject to interpretation, such as the definition of the study boundaries. As a result, different LCA studies can yield different results, making comparison challenging.

Taking some of the above limitations into account, the concept of lifecycle thinking has been promoted and used, for example by the US National Research Council in its guide on the selection of chemical alternatives (US National Research Council 2014). Life cycle thinking is a flexible approach that includes qualitative analysis to help spot potential trade-offs, without the quantitative assessment done through an LCA.

Box 5.1: **The Life Cycle Initiative** (UNEP 2020)

The Life Cycle Initiative is a public-private, multi-stakeholder partnership enabling the global use of credible life cycle knowledge by private and public decision makers. Hosted by UN Environment, the Life Cycle Initiative is at the interface between users and experts of Life Cycle approaches. It provides a global forum to ensure a science-based, consensus-building process to support decisions and policies towards the shared vision of sustainability as a public good. It delivers authoritative opinion on sound tools and approaches by engaging its multi-stakeholder partnership (including governments, businesses, scientific and civil society organizations). The Initiative facilitates the application of life cycle knowledge in the global sustainable development agenda in order to achieve global goals faster and more efficiently.

Alternatives assessment for chemicals of concern

Alternatives assessment provides a systematic approach to the evaluation of chemical, process and design alternatives to chemicals of concern. By being systematic, it guides the transition to safer, more sustainable chemicals, materials, and products and minimizes the potential for unintended consequences (UNEP 2019b). The knowledge and skillsets needed in alternatives assessment – toxicology, engineering, health and safety – are complimentary to those needed for green and sustainable chemistry and can be built into new chemical design.

The interdisciplinary approach involved in alternatives assessment guides thorough consideration of changes and potential trade-offs between alternatives to a chemical of concern at the manufacturing, use, and end-of-life stages of alternatives and identifies opportunities to reduce impacts as well as unmet needs that green and sustainable chemistry can solve. For example, Mycelium, the vegetative root structure of a mushroom, is a green chemistry solution used to make innovative green packaging and other materials. While enhancing sustainability, exposure to live Mycelium during production (making packaging molds) may result in exposure to potential allergens if exposure is not controlled (Żukiewicz-Sobczak 2013).

The lack of understanding of environment, health and safety considerations among chemists and designers in the development of new technologies, particularly in academia and small start-ups, may inadvertently result in problematic exposures. To support alternative assessments that are compatible with green and sustainable chemistry, a wealth of guidance and resources are available (UNEP 2019b). One example is the U.S. Occupational Safety and Health Administration's Transitioning to Safer Alternatives Website which provides approaches small companies can use in identifying and evaluating potential trade-offs associated with alternatives.

Sustainable material management

Sustainable Materials Management is a "systemic approach to using and reusing materials more productively over their entire lifecycles". By looking at a product's entire lifecycle, opportunities can be identified to reduce environmental impacts, conserve resources, and reduce costs (US EPA 2020a). Sustainable Materials Management assesses, amongst other criteria, hazardous substances in materials and products throughout their life cycle, by demanding full material disclosure and enhanced knowledge-sharing throughout the supply chain (including recyclers). This helps minimize chemical releases from material stocks and products and generate safe and sustainable secondary raw materials in a circular economy. Packaging is an illustration of how green and sustainable chemistry innovation has a significant potential to develop non-toxic and more sustainable materials (Sustainable Packaging Coalition 2020).

Design Thinking and sustainable product design

Design Thinking is an approach to solve complex problems, including sustainability challenges (Buhl *et al.* 2019). In contrast to conventional approaches that start with, and assume technical solvability, Design Thinking puts customer needs (as well as user-centered inventions) at the heart of the process, requiring steady back-coupling between the innovator and the customer. Design Thinking is also a means of increasing problem-solving competencies of the user, or of the companies using it, for all kinds of product and service innovation. The method is therefore used in revising internal company processes in areas such as finance and accounting, supply chain management, personnel administration and client management (Waerder, Stinnes and Erdenberger 2017). For an assessment, why and how design thinking can foster the development of sustainability-oriented innovation see Buhl *et al.* (2019).

Including non-toxic considerations into the product design process can be a driver for green and sustainable chemistry innovation. For example, the European Commission has proposed an initiative in September 2020 to revise the existing EcoDesign Directive and suggest additional legislative measures to make products placed on the EU market more sustainable. The initiative addresses, amongst others, harmful chemicals in sectors including electronics, IT, textiles, furniture, steel, and cement (EC n.d.).

Sustainable supply chain management and procurement

Sustainable supply chain management helps to ensure that purchasing and procurement decisions comply with sustainability criteria, creating a force for upstream suppliers to participate in growing markets for sustainable products. The concept covers product design and development, material selection (including raw material extraction or agricultural production), manufacturing, packaging, transportation, warehousing, distribution, consumption, return and disposal (Sarkis 2019).

Adopting sustainable (and resilient) supply chain management practices can assist organizations and companies, via purchasing decisions, to reduce their environmental and human health impacts. It also assists in optimizing end-to-end operations, creates cost savings, and enhances profitability and sustainability at the same time. “Together for Sustainability” is an example of a sustainable supply chain management programme in the chemical sector. It is a joint initiative of 26 chemical companies which use a single standard of auditing and assessment, creating a driving force for innovation across companies to address identified sustainability challenges (Together for Sustainability 2020).

5.4 Knowledge-sharing and award programs

Public and private knowledge sharing is an essential instrument to ensure that knowledge is shared widely and in an organized way. Scaling-up knowledge management platforms at different levels, therefore has the potential to support public and private sectors stakeholders in their efforts to advance green and sustainable chemistry innovation. Government to government information exchanges could help create cooperation, resolve issues, and may lead toward harmonized approaches and practices. They could cover, for example, knowledge on chemicals, sustainable innovative solutions, products and alternatives. Furthermore, they could foster sharing of best practices, policies, as well as enabling conditions and their impacts. From an international perspective, low and middle income countries could benefit from a more fluid and organized flow of information adapted to meet their needs for green and sustainable chemistry knowledge.

Award programs may provide credible recognition to green and sustainable chemistry innovations, when expert judgement is used during the selection process. For example, for more than 20 years the US EPA Green Chemistry Challenge Awards has promoted novel green chemistry innovations. Awards recognize technologies that incorporate the principles of green chemistry into chemical design, manufacture, and use (US EPA 2020b). The Elsevier Foundation Green and Sustainable Chemistry Challenge, launched in 2015, is a thematic challenge focusing on chemistry innovations which have a positive impact on sustainable development (Elsevier 2020b). The ISC3 Innovation Challenge, launched in 2018, awards pioneering start-ups in thematic topics that change annually (ISC3 2020b). Finally, featuring promising green and sustainable chemistry research initiatives in open access journals can foster recognition.


PLASTIC FREE
COMPOSTABLE
RECYCLED
BIO DEGRADABLE

5.5 Supporting policy approaches and principles

Precautionary approach

The precautionary approach informs decision-making, when robust knowledge about possible impacts is uncertain and negative implications are potentially significant. A well-known definition of a "precautionary approach" is embedded in the 1992 Rio Declaration on Environment and Development. It states that: "Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". Examples, how the precautionary approach has been used in fostering innovation and substitution for chemicals of concern are provided in Gee *et al*. (2013). The approach therefore can become an important driver in advancing green and sustainable chemistry innovation.

Product stewardship

Product Stewardship is a product management strategy that takes responsibility for minimizing the product's impact throughout all stages of its life cycle, including end of life management. It is relevant to scientists, engineers and toxicologists along with all those who design, produce, sell, or use a product. Whoever has the ability to affect life cycle environmental impacts of the product has a particular responsibility. This is normally the producer, albeit other actors, including citizens, consumers, and those responsible for disposal also have a responsibility to act (Northwest Product Stewardship Council n.d.). Identifying environmental and human health impacts of chemicals during all stages of the value chain (e.g. unsound disposal of electronic products containing toxic chemicals) creates an opportunity for chemical companies and downstream companies to work together to foster sustainable product design that takes into account green and sustainable chemistry considerations.

Extended producer responsibility

Extended producer responsibility (EPR) is a policy approach, voluntary or legally mandated, which compels producers to take responsibility for a product during sub-sequent stages of the value chain, including disposal. Some countries use pollutant release and transfer registry systems to facilitate companies' reporting related to EPR. Responsibilities may be financial and/or physical. This creates incentives and innovative business models that prevent wastes at the source and promote sustainable and non-toxic product design for a circular economy. Whether EPR is voluntary depends on specific regulatory approaches of countries.

EPR is particularly relevant for new product development and product groups, such as electrical appliances and electronics (OECD n.d.) or packaging materials. For example, Coop Denmark proactively commissioned innovation research to a supplier to replace certain fluorinated chemicals in food packaging products with a (non-chemical) sustainable alternative (Green Science Policy Institute 2013), based on consumer safety concerns. In addition to designing out chemicals of concerns in product development and preventing waste at the source, EPR incentivises proper treatment and recycling of hazardous chemicals, when products have reached the end of their life span.

Extended consumer responsibility

The concept of "Extended consumer responsibility" complements EPR, but should not replace it. It stimulates sustainable consumer market choices, for example, through trade-in-for upgrade (TIFU) programs in the consumer electronics markets (Sheu and Choi 2019). TIFU type of business models target consumers to upgrade their old devices and to shape more sustainable consumption patterns and decrease waste generation. As consumers are offered and take up these opportunities, private sector actors may be motivated to design more sustainable product and circular business models.

Corporate social responsibility (CSR)

Corporate Social Responsibility is a concept used by companies to integrate social and environmental consideration into business operations and communicate with their stakeholders and with communities in which they operate. It aims at helping companies to achieve a balance of economic, environmental and social imperatives (“Triple-Bottom-Line-Approach”) (United Nations Industrial Development Organization [UNIDO] 2020). Corporate Social Responsibility policies could be used to further drive company business model towards more sustainability, including through specific provisions to advance green and sustainable chemistry objectives throughout the company.

Considering gender equity and vulnerable groups

Women, children, groups with low income, and people of color are among vulnerable groups who are disproportionally exposed to hazardous chemicals (Temper *et al.* 2018; UNEP 2019b; Woo *et al.* 2019; Johnston and Cushing 2020). This calls for specific intervention and innovation measures to protect their health from toxic chemicals. Applying green and sustainable chemistry objectives in identifying relevant measures can be an important element to achieve adequate protection and ensure “fairness of treatment for women and men, according to their respective needs” (International Labour Office 2000).

Human rights and the rule of law

International human rights instruments place duties on countries and businesses to respect human rights, including those threatened by hazardous chemicals and waste. 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. Some companies in the chemical industry, such as BASF and Merck, have signed up the UN’s Guiding Principles on Business and Human Rights.

For a detailed discussion of this topic, pleases refer to GCO-II, Part IV, Chapter 8.

5.6 Integrating green and sustainable chemistry into corporate governance

SDG 12.6 specifically encourages companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle (Government of the US n.d.). An indicators framework has been developed to measure progress (United Nations Conference on Trade and Development 2019). Consistent with SDG 12.6, a growing number of retailers, product manufacturers and chemical companies have integrated sustainability objectives and measures, such as sustainable supply chain management or extended producer responsibility into their corporate governance frameworks.

Corporate sustainability measures of particular relevance for advancing green and sustainable chemistry innovation include: scaling up voluntary standard-setting for chemicals of emissions of concern beyond compliance; harmonizing chemical management protocols across industry sectors (e.g. on full material disclosure and labelling of products); using LCA tools, metrics and reporting to address the toxicity and sustainability of products throughout their life cycle; and systematically mandating the design of safer and more sustainable products and production processes. Government entities, for example those dealing with industry innovation, competitiveness and commerce, could bring visibility to these initiatives through their existing programs and structures, as well as through enabling sectoral policies and programmes presented in chapter 6.

6

ENABLING SECTORS AND PROGRAMMES TO ADVANCE GREEN AND SUSTAINABLE CHEMISTRY >

6.1 The role of enabling sectors and programmes in advancing green and sustainable chemistry

While chapter 5 presented tools, instruments and policy opportunities relevant for advancing green and sustainable chemistry, Chapter 6 takes the discussion to more strategically enabling sectors and programmes and approaches. It covers, foremost green and sustainable chemistry education; research and innovation; as well as enabling business models and financing. Many of these areas have traditionally not directly addressed the green and sustainable chemistry agenda. The challenge, therefore, is to identify relevant linkages and initiate action in order to ensure that relevant sectors and programmes can play a conducive role in advancing green and sustainable chemistry.

6.2 Green and sustainable chemistry education

Scaling-up chemistry research, innovation and sustainable product development requires a new generation of chemists and engineers capacitated to do so. Formal, informal, and non-formal means of education, as well as educating a broader range of stakeholders and the public at large, can help achieve this. A specialized manual addressing this topic will be published by UNEP later in 2021.

Opportunities for green and sustainable chemistry reform includes most of all, integrating toxicology, green and sustainable chemistry, as well as relevant topics of the 2030 Agenda for Sustainable Development into curricula of primary, secondary and tertiary education and professional schools. The Indian Ministry of Education, for example, is piloting a programme in which all chemists take a one-year course in green chemistry (UNEP 2019b). The Global Green Chemistry Initiative by UNIDO and the Center for Green Chemistry and Green Engineering at Yale University comprises an educational program to increase global awareness and capacities on green chemistry worldwide which makes materials available for free. Pilot activities have been conducted in Brazil, Colombia, Egypt Serbia, South Africa, and Sri Lanka (Yale University n.d.). Examples of professional courses on green and sustainable chemistry include an online course offered by the Universidade Federal de São Carlos, Brazil and a summer school offered by Leuphana University, Germany. Such efforts may inspire other countries and organizations to scale-up their efforts.

As a result of these and other activities, educational tools and materials on green and sustainable chemistry are available for use at primary, secondary, tertiary and professional levels. Further action is needed, however, to disseminate best practices and overcome barriers in academia and the private sector to embrace green and sustainable chemistry. Existing national, regional and global networks can be used to disseminate best practices and exchange lessons learned. Green and sustainable chemistry should also be embedded within broader efforts to integrate sustainability into education, such as the United Nations Educational, Scientific and Cultural Organization's initiative on sustainable education.

For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapter 2.

Box 6.1: **Green chemistry and sustainability in profession education and training course: a case study from Brazil** (UNEP 2019b)

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 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 (Yale University n.d.).

6.3 Green and sustainable chemistry research and innovation

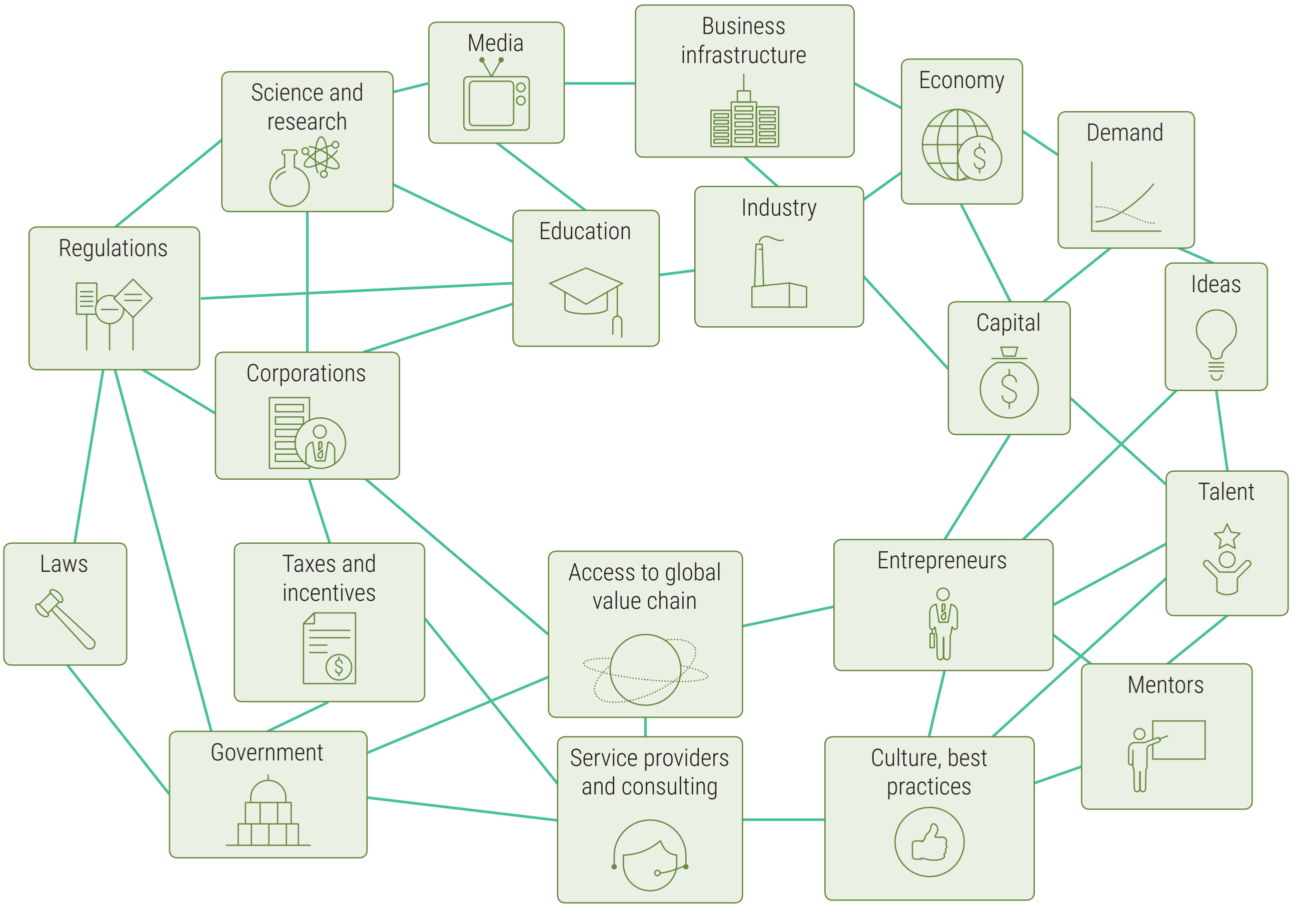
The ecosystem for chemistry innovation and its key actors

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 contribute to the 2030 Sustainable Development Agenda. Relevant chemistry research and innovation takes place in a broader innovation ecosystem that includes diverse actors and complex relationships (Jackson 2011) as presented in Figure 6.1. National research and technology institutes, economic development agencies, and trade promotion programmes may support relevant national and international collaborative activities.

Universities

Universities traditionally have focused on teaching and basic research but given pressure to produce purpose-driven or applied research, are increasingly engaging in entrepreneurial and business activities (Etzkowitz *et al*. 2008). This means that they become not only problem-solvers, inventors and entrepreneurs (EC and OECD 2012) but also important stakeholders in the innovation landscape of green and sustainable chemistry. Examples of relevant university activities include patenting or licensing of innovations, and the establishment of start-up support systems, including spin-off venture formation (Klofsten and Jones-Evans 2000). Training young researchers is key to ensure the feasibility of start-ups in the long term. To overcome constraints in curricula to generate conditions that favour the development of new businesses, creating linkages between

Figure 6.1: **Innovation ecosystem model** (adapted from Ryzhonkov 2013)



research groups, curricula, and the industry are key elements to nurture the development of green and sustainable chemistry-oriented ventures (Ocampo-López *et al.* 2019)..

Start-up companies

Start-up initiatives and young entrepreneurs are becoming important players in reaping the full potential of green and sustainable chemistry. Start-up companies contribute significantly to innovation and the creation of jobs and wealth (WEF 2018). They invest significant resources in R&D and foster technology transfer across regions and value chains through international cooperation (Oviatt and McDougall 2005). Start-ups in developing and emerging economies face, however, particular challenges, including a lack of basic laboratory infrastructure and of access to capital (UNEP 2017b).

To achieve their full potential, it is important to support start-ups through various measures, ranging from university-based technology innovation offices, to providing conducive environments for start-ups in incubators and accelerators, to integrating sustainable chemistry considerations into green bonds, including those covering climate change mitigation. These initiatives could help ensure that chemistry start-up research meets green and sustainable chemistry objectives, by encouraging chemistry start-ups to take into account green and sustainable chemistry guiding considerations in their selection process.

Small and Medium Sized Enterprises (SMEs)

Small and Medium Enterprises (SMEs) play a major role in most economies, particularly in developing countries. SMEs account for the majority of businesses worldwide and are important contributors to job creation and global economic development. They represent about 90% of businesses and more than 50% of employment worldwide (World Bank Group 2020). SMEs are particularly responsive to eco-innovation due to their adaptability and flexibility and are potentially a key driver of a resource efficient economy (Bisgaard and Tuck 2014). Since many SMEs face resource constraints, in particular for research and innovation, supporting measures, such as those suggested for start-ups are important to advance their engagement in green and sustainable chemistry innovation. Furthermore, practical support programmes to encourage use of safer chemicals could be established. The United States Occupational Safety and Health Administration (US OSHA), for example, created a "Transitioning to Safer Chemicals" website and capacity development programme to support SMEs in making informed choices about chemical alternatives (US OSHA n.d.).

The chemical industry

Chemical companies carry out significant capital- and engineering-intensive research and development (Whitesides 2015). Given the high costs of research and innovation, a close collaboration between industry and academia is evolving. Over the past years, important chemistry innovations have been co-invented or developed, such as heterogeneous catalysis, the synthesis of monomers for small-molecule pharmaceutical chemistry, organometallic chemistry, electrochemistry and energy storage (Whitesides 2015). Direct support for universities by the private sector is also valuable. It may include, for example, research funding, training partnerships and technical service contracts (Malairaja and Zawdie 2008).

The financial services industry

Actors in the financing sectors with a potential to shape the sustainability of chemistry innovation include both public and private finance entities. The former includes national, as well as regional or multilateral development banks, export credit agencies, or government enterprises and utilities. Private finance entities and sources include, for example, pension funds, sovereign funds, mutual funds, insurance companies, hedge funds, banks, and company capital expenditures. The insurance sector, as a major investor, can also help to ensure that its investments contribute to green and sustainable chemistry innovation. In the banking sector, lending decisions can direct investments towards sustainable projects and technologies. Institutional investors can exert influence towards more sustainable practices of companies and as shareholders to demand that companies act sustainably (UNEP 2019b).

Government

Governments play an important enabling role in fostering chemistry innovation, helping to correct market failures to produce innovation (United Nations Economic Commission for Europe [UNECE] 2012). Governments may provide, for example, financial incentives, finance infrastructure, or directly finance innovation projects (Lopes da Silva, Baptista Narcizo and Cardoso 2012). They may also ensure that barriers to innovation are removed (UNIDO 2017). Government also plays a key role in bring key sectors and stakeholders together in advancing the public interest.

Enabling strategies that could be led by governments include development of national industrial policies or programmes that foster green and sustainable chemistry innovation. Such initiatives are in line with the role of government to create enabling instruments and favourable conditions, rather than making specific choices (UNECE 2012). The Government of Ontario, Canada for example, has invested more than $16 million to help establish GreenCentre, which supports pre-commercial R&D in green chemistry to support sustainable, prosperous, and healthy communities, high-quality jobs, and better lives for all Ontarians (GreenCentre Canada 2020).

Other important actors

NGOs, workers and employers' associations, as well as the general public usually do not conduct chemistry research, yet they play an important role in in the innovation process. For example, innovation-focused dialogues among stakeholders may be undertaken in developing innovation friendly regulatory frameworks. This approach requires new interaction channels but has a significant potential in advancing green and sustainable chemistry innovation to implement the SDGs (WEF 2018). NGOs and workers associations a play a particularly key role in helping to hold companies accountable for their actions. Utilizing market-based campaigns in conjunction with regulatory action can serve as an important driver to promote green and sustainable chemistry innovation.

Other conducive measures and considerations

Linking research to development needs

The 2030 Agenda for Sustainable Development provides a valuable framework for guiding future research on green and sustainable chemistry and shaping the research agendas of public and private actors, ideally developed together. 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 2019). To advance innovations for sustainability, actors engaged in chemistry innovation may consider the guiding objectives and considerations for green and sustainable chemistry presented in Chapter 3. For example, start-up incubators and accelerators and funding mechanisms could integrate green and sustainable chemistry objectives into their selection process, especially if research is co-financed by public entities.

Strengthening collaborative innovation

Collaborative innovation mechanisms have shown to be effective in shaping research and innovation in a way that engages, and meets the needs of, a range of stakeholders and sustainability considerations. New and innovative forms of collaboration are being created within chemical companies, as well as between chemical companies and external entities, such as academia, customers and consumers, regulators and civil society organizations. One example which has generated valuable lessons learned is the Green Chemistry & Commerce Council's collaborative innovation challenge for safe and effective preservatives for consumer products (Becker and Tickner 2020).

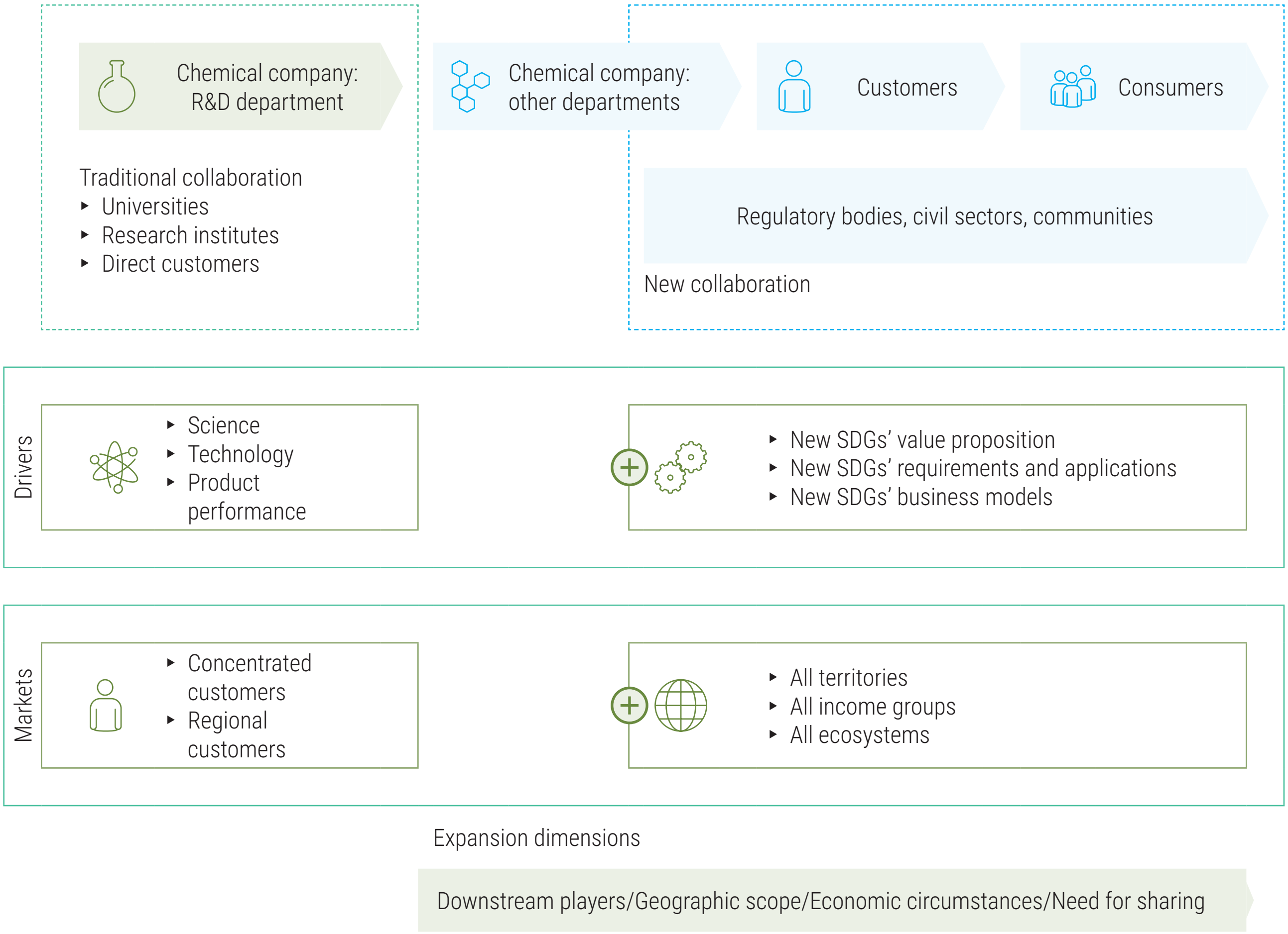
Partnerships are often driven by the SDGs, and are implemented with cross-sectoral, global and diverse markets in mind (WEF 2018). In the textile sector, for example, collaborative innovation may include the chemical industry, chemistry start-up companies, designers, potential end-users, research institutes, and potential investors. Governments and other stakeholders can enable such collaboration and encourage development of consortia through relevant innovation policies, subsidy schemes or technology programmes.

For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapter 4.

Strengthening science policy bodies

A number of national and international bodies and mechanisms have been established that bring together scientists and policymakers to ensure that policymaking is informed by the latest scientific evidence. These bodies can serve as important drivers to stimulate green and sustainable chemistry innovation. At the international level, the Persistent Organic Pollutants Review Committee (PORC) of the Stockholm Convention reviews Parties' proposals for listing new chemicals, evaluates possible control measures, taking into account socio-economic considerations, and makes recommendations for listing. Another example is the Rotterdam Convention's Chemical Review Committee which, amongst other functions, reviews proposals for listing severely hazardous pesticide formulations.

Figure 6.2: **New collaboration approaches in the chemical industry** (adapted from WEF 2018)



6.4 Financial incentives and business models

Markets-based instruments

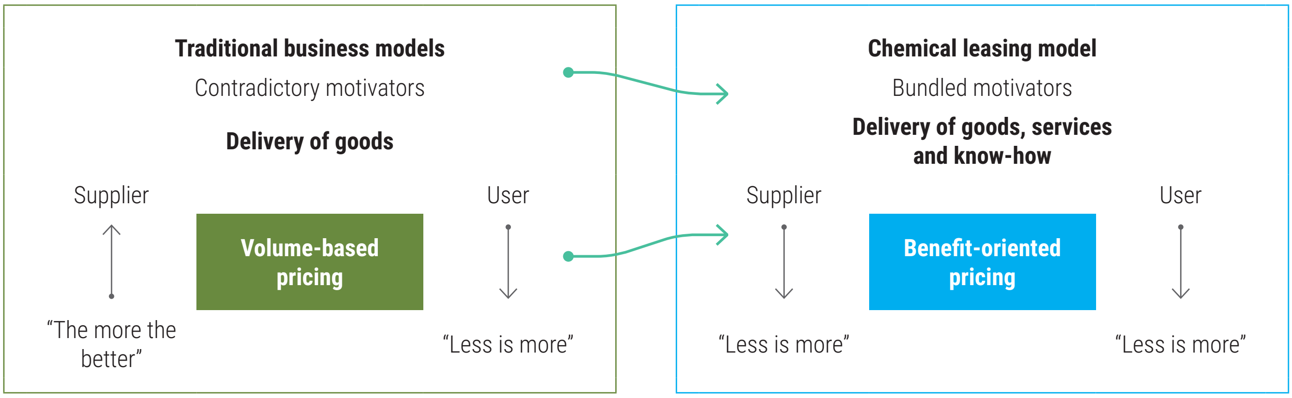
The use of market-based instruments has the potential to effectively complement regulatory approaches to advance green and sustainable chemistry innovation. Possible measures include the use of differential taxation of hazardous chemicals, based on lessons learned from recent hazard- and risk-based taxation, or the use of charges to speed up the phasing out of substances of very high concern.

Financing programmes are equally important. Green bonds, for example, are a "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). Green bonds designed to encourage sustainability come with tax incentives such as tax exemption and tax credits making them more attractive than a comparable taxable bond. While green bonds currently focus on climate change (Ernst & Young 2016), their potential to advance sustainable chemistry investment and innovation could also be explored.

Table 6.1: **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)

Figure 6.3: **Traditional business models vs. Chemical Leasing** (adapted from Joas *et al.* 2018, p. 398)



Replicated with permission of Springer Nature: permission conveyed through Copyright Clearance Center, Inc.
For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapters 5 and 6.

]

Sustainable business models

Business models with a strong focus on sustainability and circularity require a company to re-think its products and processes. This includes opportunities to improve resource efficiency, reduce the use of chemicals of concern, and lower the impact of its products and processes, including at the end of life (e.g. reducing waste). Opening up product design process and engaging stakeholders across the entire value chain can help to address sustainability concerns from the outset.

Eco-innovation, based on a lifecycle thinking, helps companies, in particular SMEs, to adopt sustainable business models. As a result, they can access new and expanding markets, increase profitability across the value chain, and stay ahead of regulations and standards, while improving resource efficiency, including the use of chemicals of concern (Bisgaard and Tuck 2014). It can lead to innovative sustainable products, improved processes, waste regeneration systems and service-based models, such as Chemical Leasing.

Under the service-oriented Chemical Leasing Scheme, suppliers sell services (e.g. number of cars painted) rather than chemicals, which creates incentives to minimize the use of chemicals and maximize resource efficiency (UNIDO 2017). A successful example was implemented in Colombia, where the introduction of a chemical leasing scheme in the petroleum industry in the field of water treatment resulted in a 20 per cent reduction in chemical consumption, while at the same time reducing water treatment costs by 80 per cent. At the international level, the 2016 Declaration of Intent on Chemical Leasing has been signed by Austria, Germany and Switzerland, El Salvador, Sri Lanka and Serbia.

For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapters 5 and 6.

7

METRICS AND REPORTING TO ADVANCE GREEN AND SUSTAINABLE CHEMISTRY >

7.1 The role of metrics and reporting in advancing green and sustainable chemistry

A frequently cited quote in the management literature is the observation of Peter Ducker that “If you can’t measure it, you can’t improve it”. The rationale behind this concept is that unless robust metrics are available, it is difficult to quantify progress and to make adjustments to produce the desired outcome. This chapter features metrics and reporting schemes which support the objective of advancing green and sustainable chemistry. While some of them are directly relevant to green and sustainable chemistry, others cover broader sustainability topics. In the latter case, adjusting these metrics and reporting schemes to advance green and sustainable chemistry innovation, could be further explored.

7.2 Green and sustainable chemistry metrics

Hazard assessment and screening

Chemical hazard refers to the intrinsic property of a chemical to cause adverse effects on human health and the environment. Examples of chemical hazard properties include acute toxicity; corrosive properties; the ability to bring about allergies; long-term effects on reproduction, development and other systems in the human body; or persistence in environmental media (UNEP 2019b). The Globally Harmonized System for the Classification and Labeling of Chemicals provides a set of criteria to help conduct a chemical hazard assessment. Many tools exist to assist companies in identifying chemical hazard and finding safer and greener chemicals. GreenScreen®, for example, is a tool that identifies hazardous chemicals and safer alternatives (GreenScreen 2020). Providing an understanding how these tools work, as well the criteria they use to screen and identify hazardous chemicals and safer alternatives, is important in ensuring that they are truly reliable. An overview and review of relevant tools is provided in Gauthier *et al.* (2014) and Panko *et al.* (2017).

For a detailed discussion on this topic, pleases refer to GCO-II, Part III, Chapter 1.

E-factor

The “E-factor” is a metric allowing to calculate the ratio of waste generated per weight unit of product (Sheldon 2017). An e-factor of 10 means that 10 kg of waste is generated for 1 kg of product. The lower the E-factor, the more a process is environmentally benign. In pharmaceutical companies, the E-factor for a drug product is generally in the range of about 25 to 100. This means that up to 100 kg of waste may be generate for one kg of product synthesized, creating significant opportunity for green and sustainable chemistry innovation.

Process mass intensity index (PMI)

The process mass intensity index is another metrics which allows evaluating and benchmarking progress towards more sustainable manufacturing. It is defined as the total mass of materials needed and used to produce a specified mass of product. Materials which are taken into account include reactants, reagents, solvents used for reaction and purification, as well as catalysts. Ideally all materials are incorporated into the product and no waste is produced. For discussion on the advantages of PMI vis-a-vis other metrices, such as the E-factor and atom energy (see Jimenez Gonzalez *et al.* (2011).

Chemical footprint metrics

The Chemical Footprint method provides a quantitative metric which manufacturers, brands and retailers can use to measure progress in reducing the use of chemicals of high concern. It is essentially a hazard-based metric which is used in the Chemical Footprint Project (CFP), an initiative of investors, retailers, government agencies, non-governmental organizations (NGOs) and health care organizations that aspire to support healthy lives, clean water and air, and sustainable consumption and production through the effective management of chemicals in products and supply chains. Participation is voluntary and the results are made publicly available (Rossi *et al.* 2017).

Table 7.1: **Resource efficiency in the chemical industry: ratio of products and waste generated** (Sheldon and Brady 2019)

Industry segment	Tonnes per year	e-factor (kg waste per kg product)
Oil refining	10^6-10^8	< 0.1
Bulk chemicals	10^4-10^6	< 1-5
Fine chemicals	10^2-10^4	5-50
Pharmaceuticals	10-10^3	25->100

7.3 Sustainability assessment and reporting

The use of metrics to assess and report on the sustainability performance of companies and producers in the chemical industry and downstream sectors is gaining momentum. Sustainability metrics have been developed by range of actors, including public institutions, the private sector and NGOs. Reporting under relevant chemicals and waste multilateral environmental agreements (MEAs) also plays some role in measuring progress towards objectives in line with green and sustainable chemistry.

Existing metrics and reporting schemes usually contain a range of criteria and indicators but have to date not yet systematically integrated with chemical specific issues (UNEP 2019b). Yet, progress is being made. The Chemie3 initiative for example, was established in 2013 as a partnership of the German Chemical Association (VCI) with key social partners to underpin sustainability as a guiding principle of the chemical industry in Germany. At the center of these measures is a variety of information and support services designed to put 12 Sustainability Guidelines for the Chemical Industry into business practices and measure its implementation (Chemie3 n.d.). Furthermore, existing datasets such as Pollutant Release and Transfer Registries (PRTR) and the Zero Discharge of Hazardous Chemical Gateway data platform can be repurposed to identify targets guiding green and sustainable chemistry implementation as well as tracking and assessing the impact of current initiatives.

The inclusion of green and sustainable chemistry as well as broader chemical management indicators in sustainability and reporting frameworks allows for an overall understanding of the activities of companies, their impacts, and for measuring progress towards smaller environmental impact and less pollution. As an illustration, investor interest in chemicals-related corporate sustainability performance is also growing. Under the Dow Jones Sustainability Index, for example, chemical suppliers and downstream companies are requested to provide information on the percentage of their products that contain certain hazardous substances. These types of initiatives call for the use of green and sustainable chemistry. They should be further encouraged.

Box 7.1: Pollutant Release and Transfer Registries

PRTRs are powerful systems for the collection and dissemination of data related to the release of hazardous substances from industrial zones and other facilities as well as diffuse emission sources. Various PRTRs have been established such as the European pollutant release and transfer registry (E-PRTR), the Registro de emisiones y transferencia de contaminantes (RETC) in Mexico and the Toxic Release Inventory (TRI) in the United States. These systems work to build trust between communities and industry while allowing facility owners to showcase pollution prevention initiatives. Countries that have implemented PRTRs have reported the positive effect they have had to promote public participation which will be key driver in building awareness of green and sustainable chemistry. Additionally, the wealth of data generated by these instruments can be further used to systematically identify specific pollutant hotspots where solutions based on green and sustainable chemistry could have the greatest possible immediate effect. PRTRs can also serve to aid in the continual assessment of the impact which sustainable chemical processes have in terms of hazardous releases to nearby communities. The TRI in particular is an encouraging case study on how PRTR systems can evolve to meet the needs of green and sustainable chemistry by identifying and evaluating the progress of relevant initiatives (Gaona 2017).

A further area of exploration is how overarching sustainability frameworks, such as the Framework for Strategic Sustainable Development, could be applied to the domain of chemicals, materials and product life cycles (Broman and Robèrt 2017). The core methodology of back casting from sustainability principles uses systems thinking and a future-oriented process to assess and plan steps to close the gap between today's current situation and a desired (sustainable) future state. The sustainability principles define basic conditions that a sustainable society needs to respect in order to safeguard the health of social and ecological systems. As these are based on the scientific study of natural and social systems, they offer useful criteria serving as a common language at the chemical, material, product, organization, value chain and overarching global systems levels (The Natural Step 2020a).

Self-assessments and reporting are also taking place in downstream sectors, such as under the ZDHC initiative, where compliance rates are being made publicly available. To help create credibility, some companies choose to engage with external bodies, such as the Cradle-to-Cradle Product Standard and the Chemical Footprint Project. Furthermore, independent external assessments are undertaken, for example through the NGO-founded Mind the Store initiative.

For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapter 7.

Box 7.2: **NSI/ACS Greener Chemical Products & Processes Information Standard** (NSF International n.d.)

The Greener Chemical Products and Processes Information Standard (NSF/GCI 355), published in 2010 established criteria for comparing chemicals and processes. Developed by NSI and the American Chemical Society Green Chemistry Institute (ACS GCI), it provides a framework for chemical manufacturers to develop a comprehensive, standardized report to provide information to their customers throughout the supply chain. The report is used to evaluate chemical products and their associated manufacturing processes in several key categories, including: ***Chemical Characteristics*** (i.e. physical chemical properties, human health effects and ecological effects); ***Chemical Processes*** (i.e. chemical efficiency and waste prevention, water, energy, bio-based carbon content, innovative manufacturing processes and technology and process safety) and ***Social Responsibility*** (i.e. child labor, forced and compulsory labor and compliance with laws and regulations). It was informed by green chemistry principles, green engineering principles, ISO 14000, the global reporting initiatives and many other existing programs.

8

DEVELOPING GREEN AND SUSTAINABLE CHEMISTRY

ROAD MAPS BY STAKEHOLDERS ›

The road map concept: a powerful planning tool

The road map approach to support strategic planning and decision-making has been used for many years, including applications in technology innovation (see, for example, Phaal, Farrukh and Probert 2004). Road mapping is a technique which brings actors and stakeholders together to develop a common vision and long-term planning to achieve it. Beyond identifying a common vision, roadmaps help to identify existing resources, describe gaps, define action, and obtain adequate funding to fill gaps. They are often used in the private sector, but are equally relevant for other stakeholder groups, including public bodies. Road maps also provide a structured approach to identify, assess and promulgate interventions to advance technology solutions. Road maps have for example, been a powerful instrument to drive innovation in the semiconductor industry (Voorhees and Hutchison 2015).

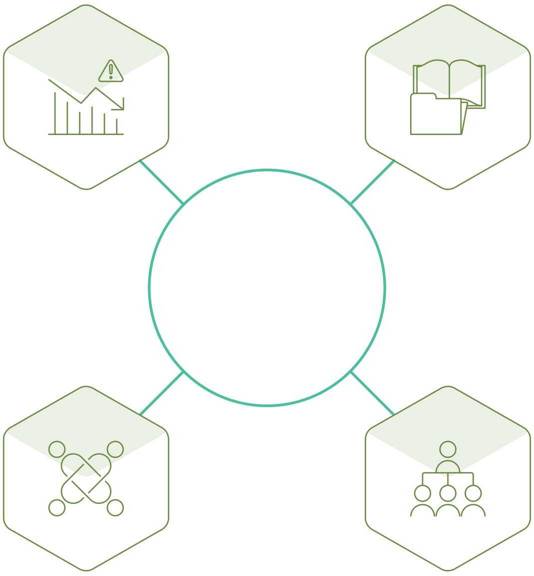
Road maps in the chemical sector and across value chains

The road map approach has been used by several actors in the chemical sector and value chain to advance action to achieve the sound management of chemicals and waste. One example is, the roadmap developed by chemical companies and industry associations, under the auspices of the World Business Council for Sustainable Development (WBCSD), exploring how the chemical sector can contribute to achieving various SDGs and targets (WBCSD 2018). Another example is the WHO Chemical Road Map, adopted in May 2017 by the World Health Assembly, identifying actions where the health sector has either a lead or important supporting role to play in advancing the sound management of chemicals and waste. The WHO road map is complemented by a series of practical workbooks (WHO 2020).

Road maps have also been developed taking a value chain approach which brings together different actors across the life cycle of chemicals and products. For example, the EU Roadmap for the chemical industry in Europe towards a Bioeconomy (RoadToBio 2020) applies a value chain approach for a variety of products, with the goal of increasing the use of bio-based feedstocks. The example of the European PVC industry and its voluntary sustainability commitment VinylPlus (Smith and Jarisch 2019) highlights how a roadmap can foster a structured dialogue and systematic steps to address issues through engagement of key stakeholders to address issues such as closing the loop with a dedicated recycling network; optimizing additive formulations with circularity in mind etc. The road map “Addressing Marine Plastics. A Roadmap to a Circular Economy” features an action-oriented strategy by identifying a core set of priority solutions to be implemented by stakeholders from the plastics value chain under different time horizons, and at different geographical scales (Wang, Talaue McManus and Xie 2019).

Figure 8.1: **Chemical Sector Road Map** (WBCSD 2018)

Figure 8.2: **WHO Chemicals Road Map: Action areas and interlinkages** (WHO 2018b, p.3)



Risk reduction
Reduced risk is an outcome of all the road map activities. Some activities, directly reduce risk, and all activities contribute to reduced risk in the long term.

Knowledge and evidence
Knowledge and evidence, on chemicals, health vulnerabilities, which interventions work best, on current gaps and priorities etc., is needed to guide all the other interventions.

Institutional capacity
Institutional capacity develops around a base of evidence and knowledge and strong leadership. It includes legislative frameworks and proper enforcement, strong policies, guidelines, laboratories, poison centres, emergency response systems and an educated workforce.

Leadership and coordination
is required to ensure road map actions are part of the policy/political agenda, are adequately funded, include the contribution of multiple sectors and deliver on national and international targets.

Opportunities to develop Green and Sustainable Chemistry Road Maps by stakeholders

Given the potential benefits of road maps, GCO-II encouraged the development of country- and stakeholder-driven roadmaps on specific topics and by different stakeholder groups to support the implementation of the sound management of chemicals and waste beyond 2020 and help monitor progress at all levels, including at the global level (UNEP 2019b). Consistent with this suggestion, Green and Sustainable Chemistry Road Maps could be developed by diverse stakeholder groups, as important components of concerted national and global results-oriented action to achieve the sound management of chemicals and waste. These road maps could be developed at different levels and through different stakeholders, including individual governments (national, sub-national or local); chemicals and downstream sector companies; university and research institutes; and other concerned actors. They may also be developed around a singular issue like the case of the solvent management plans (SMP) formulated in the UNECE region. What they require is leadership within relevant organizations. Such leadership can come from the top through senior management, or from bottom-up, through interested and committed individuals.

Identifying action through Green and Sustainable Chemistry Road Maps

As a starting point, stakeholders may want to take stock of their current sustainability performance and opportunities taking into account the 10 objectives and guiding considerations for green and sustainable chemistry offered in Chapter 3. This analysis could help to create a green and sustainable chemistry vision for the organization and inform identifying possible measures of action. For example:

- governments could provide dedicated support to green and sustainable research programmes in industry and the research community and drive innovation through regulatory action;
- universities could systematically introduce green and sustainable chemistry into teaching curricula, research operations, and start-up support;
- chemical companies could systematically introduce life cycle assessment, set innovation targets for replacing chemicals of concerns and ensure communication within the supply chain; or

Box 8.1: ACS green chemistry education road map project

An example of a road map process focusing on green and sustainable chemistry is the ACS green chemistry education road map project. It articulates an aspirational vision for green chemistry education: "Chemistry education that equips and inspires chemists to solve the grand challenges of sustainability." This vision aligns with the UN sustainable development goals, whose implementation depends significantly on chemistry (Carroll 2019). To engage stakeholders in the development of the roadmap, ACS sent a survey to some 17,000 educators.

Questions addressed in the road map process include, for example (Voorhees and Hutchison 2015):

- How can educators replace existing course material with material that integrates sustainable and green chemistry lessons and principles into chemistry education?
- How can chemists and non-chemists who take chemistry courses as part of their education be trained to think about the discipline holistically and sustainably without creating more work for already strained educators?
- What resources are already out there and what needs must be met?

- civil society organizations could act to bring knowledge to consumers and share feedback with other stakeholder groups to help create demand for green and sustainable chemicals and products.

Developing a technology road map: Methodological considerations

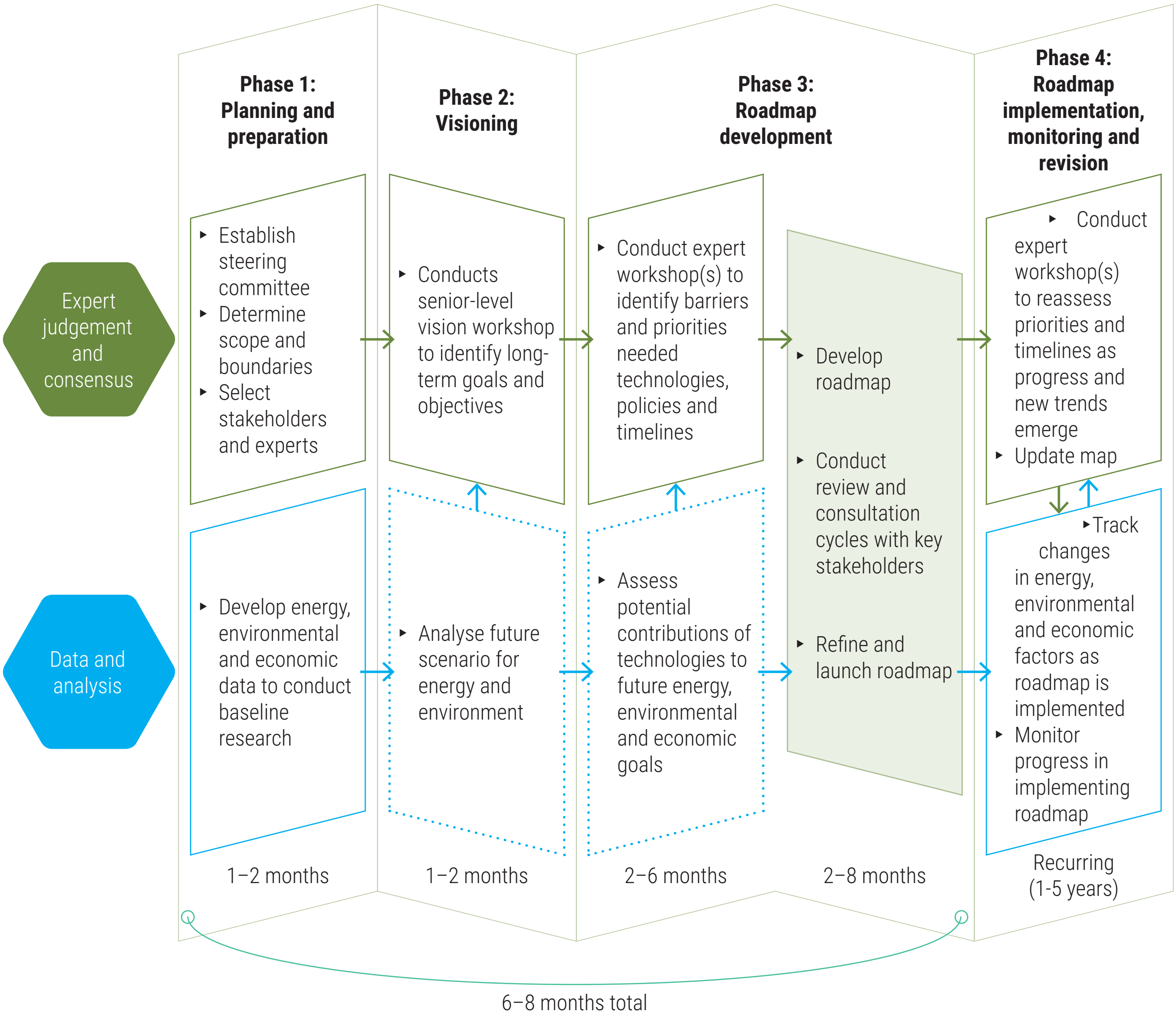
A range of methodological approaches exist to support the development of technology innovation road maps. Following a review of various road map approaches and considering that the energy and chemical sector both face strategic sustainability and technology challenges, guidance developed by International Energy Agency may provide insights and inspiration. The publication "Energy Technology Roadmaps: A Guide to Development and Implementation" aims at "providing countries and companies with the context, information and tools needed to design, manage and implement an effective energy technology roadmap process relevant to their own local circumstances and objectives" (IEA 2014). It features guidance on identifying stakeholders, developing a technology baseline, and crafting indicators to help track progress against milestones. The ultimate aim of the guidance is to help stakeholders allocate limited resources to identify priorities and high impact action in the short term, while laying the groundwork and taking action for longer-term improvement.

Figure 8.3: **Logic of a road map process** (IEA 2014, p. 5)

An effective road map process starts by addressing a set of important up-front questions. These include, for example (based on IEA 2014):

- What are the boundaries of the road map effort?
- Which green and sustainable chemistry topics will the roadmap consider?
- Which external experts and stakeholders need to be engaged in the process?

Figure 8.4: **Process for developing an energy technology road map** (IEA 2014, p. 6)



Note: Dotted lines indicate optional steps, based on analysis capabilities an resources.

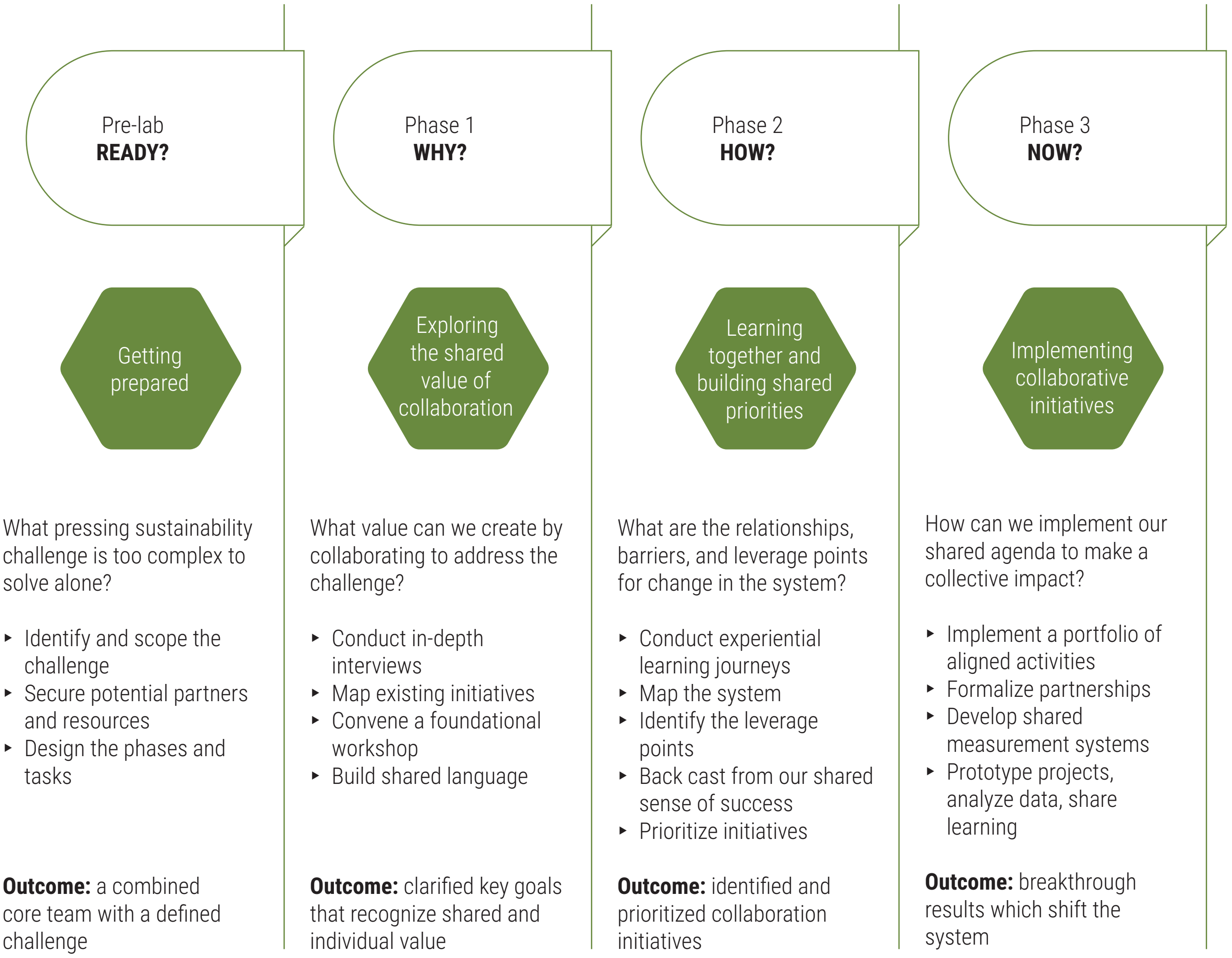
- What is the time frame for developing the road map?
- What technology opportunities are under consideration?
- How will the leading organization use and implement the roadmap?

Figure 8.4 provides an illustrative road map process in the area of energy technology. It includes four stages as well as cross-cutting interface of Data and analysis and Expert judgment and consensus. The four phases include: Phase 1: Planning and preparation; Phase 2: Visioning; Phase 3: Roadmap development; and Phase 4: Road map implementation, monitoring and revision. Stakeholder interested in developing a green and sustainable chemistry road map may want to consider and adapt this guidance, as appropriate.

Sustainability Labs to support road map development

One option to organize a green and sustainability road map process is to organize a Sustainability Lab, a concept which brings together key actors

Figure 8.5: **Natural Step "Sustainability Transition Labs"** (The Natural Step Canada n.d.)



Pre-lab **READY?**	Phase 1 **WHY?**	Phase 2 **HOW?**	Phase 3 **NOW?**
Getting prepared	Exploring the shared value of collaboration	Learning together and building shared priorities	Implementing collaborative initiatives
What pressing sustainability challenge is too complex to solve alone?	What value can we create by collaborating to address the challenge?	What are the relationships, barriers, and leverage points for change in the system?	How can we implement our shared agenda to make a collective impact?
‣ Identify and scope the challenge ‣ Secure potential partners and resources ‣ Design the phases and tasks	‣ Conduct in-depth interviews ‣ Map existing initiatives ‣ Convene a foundational workshop ‣ Build shared language	‣ Conduct experiential learning journeys ‣ Map the system ‣ Identify the leverage points ‣ Back cast from our shared sense of success ‣ Prioritize initiatives	‣ Implement a portfolio of aligned activities ‣ Formalize partnerships ‣ Develop shared measurement systems ‣ Prototype projects, analyze data, share learning
Outcome: a combined core team with a defined challenge	**Outcome:** clarified key goals that recognize shared and individual value	**Outcome:** identified and prioritized collaboration initiatives	**Outcome:** breakthrough results which shift the system

and stakeholders in addressing a complex issue (McCrory *et al.* 2020). The focus of Sustainability Labs is to put the issue at the centre and recognize that addressing complex sustainability challenges requires unprecedented collaboration and new ways of working across sectors and across scales. One example is the global Programme Sustainability Transition Labs coordinated by The Natural Step which blends expertise in designing and facilitating transformational change towards sustainability with approaches to multi-stakeholder collaboration (The Natural Step 2020b).

The time is ripe for strategic action to advance green and sustainable chemistry

The trends and opportunities presented in this framework manual all point into one direction. Advancing green and sustainable chemistry offers many benefits, environmental, social and economic. However, leadership at all levels is still not sufficient and must improve in order to reap the full potential of green and sustainable chemistry. Ensuring that the topic is brought to the instrument being discussed under the Strategic Approach and the sound management of chemicals and waste beyond 2020 process can support this objective, as deemed necessary.

In addition, all actors and decision-makers, from public officials to company CEOs and heads of chemistry laboratories, are encouraged to consider the analysis and guidance provided in this framework manual and consider the initiation of a "Green and Sustainable Chemistry Road Map" within their organizations. UNEP encourages and welcomes sharing of relevant initiatives to facilitate knowledge sharing across countries and stakeholders and to explore opportunities for capacity development. Beyond, at international and at national/regional levels, leading stakeholders such as government and regional/local authorities are encouraged to coordinate action, and build with relevant stakeholders, a coherent plan for action (or roadmap). Altogether, these efforts could enhance and scale-up concerted global action to advance green and sustainable chemistry, including in developing and transitioning countries.

Together we can make green and sustainable chemistry a reality

REFERENCES

Alcántar, K., Blake, A., Edwards, S. and Singla, V. (2017). *Selecting Safer Alternatives to Toxic Chemicals and Ensuring the Protection of the Most Vulnerable.* New York, NY: Selecting Safer Alternatives to Toxic Chemicals and Ensuring the Protection of the Most Vulnerable. https://www.nrdc.org/sites/default/files/toxic-chemicals-vulnerable-populations-report.pdf.

American Chemical Society (2015a). *How Industrial Applications in Green Chemistry are Changing our World.* https://www.acs.org/content/dam/acsorg/membership/acs/benefits/extra-insights/green-chemistry-applications.pdf.

American Chemical Society (2015b). Special issue, earth abundant metals in homogeneous catalysis. *Accounts of Chemical Research.* Chirik, P. and Morris, R. (eds.). https://pubs.acs.org/page/achre4/earth_abundant_metals.html. Accessed 12 December 2020.

American Chemical Society (2020a). 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 7 December 2020.

American Chemical Society (2020b). The 25th annual green chemistry & engineering conference. ACS Green Chemistry Institute. https://www.gcande.org/. Accessed 7 December 2020.

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. (2019). The periodic table of the elements of green and sustainable chemistry. *Green Chemistry.* https://doi.org/10.1039/c9gc01293a.

Andrews, E.S., Barthel, L.-P., Tabea, B., Benoît, C., Ciroth, A., Cucuzzella, C., Gensch, C.-O., Hébert, J., Lesage, P., Manhart, A., Mazeau, P., Mazijn, B., Methot, A.-L., Moberg, A., Norris, G., Parent, J., Prakash, S., Reveret, J.-P., Spillemaeckers, S., Ugaya, C.M.L., Valdivia, S. and Weidema, B. (2009). *Guidelines for Social Life Cycle Assessment of Products: Social and Socio-Economic LCA Guidelines Complementing Environmental LCA and Life Cycle Costing, Contributing to the Full Assessment of Goods and Services within the Context of Sustainable Development.* Benoît, C. and Mazijn, B. (eds.). Nairobi: United Nations Environment Programme. http://www.unep.fr/shared/publications/pdf/dtix1164xpa-guidelines_slca.pdf.

Arvidsson, R., Hildenbrand, J., Baumann, H., Islam, K.M.N. and Parsmo, R. (2018). A method for human health impact assessment in social LCA: lessons from three case studies. *International Journal of Life Cycle* Assessment 23(3), 690-699. https://doi.org/10.1007/s11367-016-1116-7.

Bazzanella, A., Friege, H. and Zeschmar-Lahl, B. (2017). *Identification of Priority Topics in the Field of Sustainable Chemistry.* Dessau-Roßlau: Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. https://www.umweltbundesamt.de/en/publikationen/identification-of-priority-topics-in-the-field-of.

BCC Research (2016). Global concerns promoting growth of ‘green’ chemistry markets, reports BCC Research, 4 April. *Marketwired.* https://www.bccresearch.com/pressroom/env/global-concerns-promoting-growth-of-green-chemistry-markets. Accessed 24 June 2020.

Becker, M. and Tickner, J.A. (2020). Driving safer products through collaborative innovation: lessons learned from the Green Chemistry & Commerce Council’s collaborative innovation challenge for safe and effective preservatives for consumer products. *Sustainable Chemistry and Pharmacy* 18(100330), 1-6. https://doi.org/10.1016/j.scp.2020.100330.

Bell, G., Schuck, S., Jungmeier, G., Wellisch, M., Felby, C., Jørgensen, H., Stichnothe, H., Clancy, M., De Bari, I., Kimura, S., van Ree, R., de Jong, E., Annevelink, B., Kwant, K., Torr, K. and Spaeth, J. (2014). *Task Force 42 Biorefining: Sustainable and Synergetic Processing of Biomass into Marketable Food & Feed Ingredients, Products (Chemicals, Materials) and Energy (Fuels, Power, Heat) The Netherlands (Coordinator) Electronic Copies.* van Ree, R. and van Zeeland, A. (eds.). Wageningen: IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2014/09/IEA-Bioenergy-Task42-Biorefining-Brochure-SEP2014_LR.pdf.

Benjamin, S., Masai, E., Kamimura, N., Takahashi, K., Anderson, R.C. and Faisal, P.A. (2017). Phthalates impact human health: epidemiological evidences and plausible mechanism of action. *Journal of Hazardous Materials* 340, 360–383. https://doi.org/10.1016/j.jhazmat.2017.06.036.

Bhadani, A., Kafle, A., Ogura, T., Akamatsu, M., Sakai, K., Sakai, H. and Abe, M. (2020). Current perspective of sustainable surfactants based on renewable building blocks. *Current Opinion in Colloid and Interface Science 45, 124-135.* https://doi.org/10.1016/j.cocis.2020.01.002.

Bisgaard, T. and Tuck, K. (2014). *The Business Case for Eco-Innovation.* Pegram, J., Madhuvantthe and Panild, U.N. (eds.). Nairobi: United Nations Environment Programme. http://unep.ecoinnovation.org/wp-content/uploads/2017/07/UN_Environment_Eco—i_Business-case.pdf.

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.

Bocqué, M., Voirin, C., Lapinte, V., Caillol, S. and Robin, J.J. (2015). Petro-based and bio-based plasticizers: chemical structures to plasticizing properties. *Journal of Polymer Science, Part A: Polymer Chemistry* 54(1), 11-33. https://onlinelibrary.wiley.com/doi/full/10.1002/pola.27917.

Broman, G.I. and Robèrt, K.H. (2017). A framework for strategic sustainable development. *Journal of Cleaner Production* 140, 17-31. https://doi.org/10.1016/j.jclepro.2015.10.121.

Buckley, H.L., Hart-Cooper, W.M., Kim, J.H., Faulkner, D.M., Cheng, L.W., Chan, K.L., Vulpe, C.D., Orts, W.J., Amrose, S.E. and Mulvihill, M.J. (2017). Design and testing of safer, more effective preservatives for consumer products. *ACS Sustainable Chemistry and Engineering* 5(5), 4320-4331. https://doi.org/10.1021/acssuschemeng.7b00374.

Buhl, A., Schmidt-Keilich, M., Muster, V., Blazejewski, S., Schrader, U., Harrach, C., Schäfer, M. and Süßbauer, E. (2019). Design thinking for sustainability: why and how design thinking can foster sustainability-oriented innovation development. *Journal of Cleaner Production 231, 1248-1257.* https://doi.org/10.1016/j.jclepro.2019.05.259.

Business Wire (2015). BASF and solazyme launch the first commercial microalgae-derived betaine surfactant, 28 July. https://www.businesswire.com/news/home/20150728005434/en/BASF-Solazyme-Launch-Commercial-Microalgae-Derived-Betaine-Surfactant. Accessed 7 December 2020.

Business Wire (2019). Global green chemicals market will grow at a CAGR of 10% during 2019-2023, 29 May. *Technavio Research.* https://www.businesswire.com/news/home/20190529005081/en/Global-Green-Chemicals-Market-Will-Grow-at-a-CAGR-of-10-During-2019-2023-Technavio. Accessed 11 December 2020.

Buxton, L. (2016). Hoffmann-La Roche´s goal to phase out SVHCs, December. *Chemical Watch.* https://chemicalwatch.com/51621/hoffmann-la-roches-goal-to-phase-out-svhcs. Accessed 26 June 2020.

Carroll, W.F. (2019). Mapping out the future of green chemistry education. *Chemical & Engineering News* 97(31). https://cen.acs.org/acs-news/comment/Mapping-future-green-chemistry-education/97/i31.

Chakraborty, S., Leitus, G. and Milstein, D. (2016). Selective hydrogenation of nitriles to primary amines catalyzed by a novel iron complex. *Chemical Communications* 52(9), 1812-1815. https://doi.org/10.1039/c5cc08204h.

Chemie³ (n.d.). Wesentlichkeitsanalyse: der chemie3-nachhaltigkeits-check. https://www.chemiehoch3.de/nachhaltigkeitscheck/. Accessed 15 December 2020.

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

Davies, D.W., Butler, K.T., Jackson, A.J., Morris, A., Frost, J.M., Skelton, J.M. and Walsh, A. (2016). Computational screening of all stoichiometric inorganic materials. *Chem 1(4),* 617-627. https://doi.org/10.1016/j.chempr.2016.09.010.

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

Elhacham, E., Ben-Uri, L., Grozovski, J., Bar-On, Y.M. and Milo, R. (2020). Global human-made mass exceeds all living biomass. *Nature 588(7838), 442-444.* https://doi.org/10.1038/s41586-020-3010-5.

Elsevier (2020). 5th green & sustainable chemistry conference: online – live and on-demand | 10-11 November 2020. https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference. Accessed 7 December 2020.

Elsevier (2020b). 2020 Elsevier green and sustainable chemistry challenge. https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference/about/green-and-sustainable-chemistry-challenge. Accessed 14 December 2020.

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.

Erythropel, H., Börmann, A., Nicell, J., Leask, R. and Maric, M. (2018). Designing green plasticizers: linear alkyl diol dibenzoate plasticizers and a thermally reversible plasticizer. *Polymers* 10(6), 646. https://doi.org/10.3390/polym10060646.

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 Chemicals Agency (2011). *Guidance on the Preparation of an Application for Authorisation.* Version 1. https://echa.europa.eu/documents/10162/13643/authorisation_application_en.pdf.

European Commission (1996). Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control. *Official Journal of the European Communities* 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 (2011). *Opinion on Parabens: COLIPA N° P82.* SCCS/1348/10. Brussels: Scientific Committee on Consumer Safety. https://doi.org/10.2772/30176.

European Commission (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal.* COM(2019) 640 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2.

European Commission (2020). Chemicals strategy: the EU's chemicals strategy for sustainability towards a toxic-free environment. https://ec.europa.eu/environment/strategy/chemicals-strategy_en. Accessed 14 December 2020.

European Commission (n.d.). Sustainable products initiative. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative. Accessed 14 December 2020.

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.

European Technology Platform for Sustainable Chemistry (2019). *Strategic Innovation and Research Agenda: Innovation Priorities for EU and Global Challenges.* Brussels. http://www.suschem.org/highlights/suschem-identifies-key-technology-priorities-to-address-eu-and-global-challenges-in-its-new-strategic-research-and-innovation-agenda.

Fanelli, F., Parisi, G., Degennaro, L. and Luisi, R. (2017). Contribution of microreactor technology and flow chemistry to the development of green and sustainable synthesis. *Beilstein Journal of Organic Chemistry* 13, 520-542. https://doi.org/10.3762/bjoc.13.51.

Fantke, P. and Illner, N. (2019). Goods that are good enough: introducing an absolute sustainability perspective for managing chemicals in consumer products. *Current Opinion in Green and Sustainable Chemistry* 15, 91-97. https://doi.org/10.1016/j.cogsc.2018.12.001.

Fermeglia, M., Longo, G. and Toma, L. (2009). Computer aided design for sustainable industrial processes: specific tools and applications. *AIChE Journal* 55(4), 1065-1078. https://doi.org/10.1002/aic.11730.

Freire, M.G. and Coutinho, J.A.P. (2019). Editorial overview: a closer look on sustainable solvents and processes. *Current Opinion in Green and Sustainable Chemistry* 18, A4-A6. https://doi.org/10.1016/j.cogsc.2019.07.003.

Gauthier, A.M., Fung, M., Panko, J., Kingsbury, T., Perez, A.L., Hitchcock, K., Ferracini, T., Sahmel, J., Banducci, A., Jacobsen, M., Abelmann, A. and Shay, E. (2014). Chemical assessment state of the science: evaluation of 32 decision-support tools used to screen and prioritize chemicals. *Integrated Environmental Assessment and Management* 11(2), 242-255. https://doi.org/10.1002/ieam.1605.

Gaona, S. (2017). The Utility of the Toxic Release Inventory (TRI) in Tracking Implementation and Environmental Impact of Industrial Green Chemistry Practices in the United States. *Green Chemistry,* 147. https://doi.org/10.5772/intechopen.70716

Gee, D., Grandjean, P., Hansen, S.F., van den Hove, S., MacGarvin, M., Martin, J., Nielsen, G., Quist, D. and Stanners, D. (2013). Late Lessons from Early Warnings: Science, Precaution, Innovation: Summary. No 1/2013. Copenhagen: European Environment Agency. https://www.eea.europa.eu/publications/late-lessons-2.

German Environment Agency (2009). *Sustainable Chemistry: Positions and Criteria of the Federal Environment Agency.* https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/3798.pdf.

German Ministry of Education and Research and German Ministry of Food and Agriculture (2020). *National Bioeconomy Strategy: Summary.* https://www.bmbf.de/files/2020_1501_National-Bioeconomy-Strategy_Summary_accessible.pdf.

Government of the United States (n.d.). Indicator 12.6.1: number of companies publishing sustainability reports. *U.S. National Statistics for the U.N. Sustainable Development Goals.* https://sdg.data.gov/12-6-1/. Accessed 14 December 2020.

Green Chemistry & Commerce Council (n.d.). GC3 publications. *Lowell Center for Sustainable Production.* https://greenchemistryandcommerce.org/resources/gc3-publications. Accessed 11 December 2020.

Green Science Policy Institute (2013). Pop Stop: Denmark retailer stops sale of microwave popcorn amid health fears, 3 June. http://greensciencepolicy.org/pop-stop/. Accessed 24 June 2020.

GreenCentre Canada (2020). About us. https://greencentrecanada.com/about-us/. Accessed 14 December 2020.

GreenScreen (2020) GreenScreen for safer chemicals. https://www.greenscreenchemicals.org/. Accessed 24 June 2020.

Harmon, J.P. and Otter, R. (2017). Green chemistry and the search for new plasticizers. *ACS Sustainable Chemistry and Engineering* 6(2), 2078-2085. https://doi.org/10.1021/acssuschemeng.7b03508.

Health and Safety Executive (2003). *HSE Information Sheet - Solvents: Construction Information Sheet No 27 (Revision 2).* https://www.hse.gov.uk/pUbns/cis27.pdf.

Hellweg, S. and Milà i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science.* 344(6188), 1109-1113. https://doi.org/10.1126/science.1248361.

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.

Howell, B.A., Daniel, Y.G. and Ostrander, E.A. (2018). Flame retardants from renewable sources: food waste, plant oils, and starch. In *Green Polymer Chemistry: New Products, Processes, and Applications.* Cheng, H.N., Gross, R.A. and Smith, P.B. (eds.). Washington, DC: American Chemical Society. Chapter 25. 405-421. https://doi.org/10.1021/bk-2018-1310.ch025.

Howell, B.A., Oberdorfer, K.L. and Ostrander, E.A. (2018). Phosphorus flame retardants for polymeric materials from gallic acid and other naturally occurring multihydroxybenzoic acids. *International Journal of Polymer Science* 2018, 1-12. https://doi.org/10.1155/2018/7237236.

Innovation for Sustainable Development Network (2019). Chromatogeny: green chemistry to make paper water-repellent, 18 April. https://www.inno4sd.net/chromatogeny-green-chemistry-to-make-paper-water-repellent-246. Accessed 7 December 2020.

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 Energy Agency (2014). *Energy Technology Roadmap: A Guide to Development and Implementation.* https://webstore.iea.org/download/direct/443.

International Energy Agency (2019). *Putting CO2 to Use: Creating Value from Emissions. https://www.iea.org/reports/putting-co2-to-use.*

International Labour Organization (2000). *ABC of Women Workers' Rights and Gender Equality.* 1st edn. http://www.ilo.org/global/publications/books/WCMS_080613/lang--en/index.htm.

International Organization for Standardization (2016). *ISO 14040:2006(En) Environmental Management — Life Cycle Assessment — Principles and Framework.* ISO/TC 207/SC 5 Life cycle assessment. 2nd edn. https://www.iso.org/standard/37456.html.

International Sustainable Chemistry Collaborative Centre (2020a). ISC3 - International Sustainable Chemistry Collaborative Centre: activities. https://www.isc3.org/en/activities/collaboration.html. Accessed 7 December 2020.

International Sustainable Chemistry Collaborative Centre (2020b). Finalists of the ISC3 innovation challenge in sustainable building and living 2019/20 selected! https://www.isc3.org/en/activities/innovation/innovation-challenge.html. Accessed 14 December 2020.

Inter-Organization Programme for the Sound Management of Chemicals (2018). *Chemicals and Waste Management: Essential to Achieving the Sustainable Development Goals (SDGs).* http://www.who.int/iomc/Chemicals_SDGs_interactive_Feb2018.pdf.

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

Jamarani, R., Erythropel, H., Nicell, J., Leask, R. and Marić, M. (2018). How green is your plasticizer? *Polymers* 10(8), 834-851. https://doi.org/10.3390/polym10080834.

Jimenez-Gonzalez, C., Ponder, C.S., Broxterman, Q.B. and Manley, J.B. (2011). Using the right green yardstick: why process mass intensity is used in the pharmaceutical industry to drive more sustainable processes. *Organic Process Research and Development* 15(4), 912-917. https://doi.org/10.1021/op200097d.

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.

Johnston, J. and Cushing, L. (2020). Chemical exposures, health, and environmental justice in communities living on the fenceline of industry. *Current Environmental Health Reports* 7(1), 48-57. https://doi.org/10.1007/s40572-020-00263-8.

Kalantari, F., Tahir, O.M., Joni, R.A. and Fatemi, E. (2018). Opportunities and challenges in sustainability of vertical farming: a review. *Journal of Landscape Ecology* 11(1), 35-60. https://doi.org/10.1515/jlecol-2017-0016.

Kandasamy, R., Rajasekaran, M., Venkatesan, S.K. and Uddin, M. (2019). New trends in the biomanufacturing of green surfactants: biobased surfactants and biosurfactants. In *Next Generation Biomanufacturing Technologies.* Rathinam, N.K. and Sani, R.K. (eds.). Washington, DC: American Chemical Society. Chapter 11. 243-260. https://doi.org/10.1021/bk-2019-1329.ch011.

Karan, H., Funk, C., Grabert, M., Oey, M. and Hankamer, B. (2019). Green bioplastics as part of a circular bioeconomy. *Trends in Plant Science* 24(3), 237-249. https://doi.org/10.1016/j.tplants.2018.11.010.

Kaushik, M. and Moores, A. (2017). New trends in sustainable nanocatalysis: emerging use of earth abundant metals. *Current Opinion in Green and Sustainable Chemistry* 7, 39-45. https://doi.org/10.1016/j.cogsc.2017.07.002.

Kaya, M. and Tabak, A. (2020). Recycling of an agricultural bio-waste as a novel cellulose aerogel: a green chemistry study. *Journal of Polymers and the Environment* 28(1), 323-330. https://doi.org/10.1007/s10924-019-01609-6.

Kershaw, P.J. (2015). *Biodegradable Plastics and Marine Litter: Misconceptions, Concerns and Impacts on Marine Environments.* Nairobi: United Nations Environment Programme. http://wedocs.unep.org/handle/20.500.11822/7468.

King, A. (2017). Technology: the future of agriculture. *Nature 544(7651), S21-S23.* https://doi.org/10.1038/544s21a.

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

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.

Kobayashi, S., Uyama, H. and Kadokawa, J. (eds.) (2019). *Enzymatic Polymerization towards Green Polymer Chemistry. Green Chemistry and Sustainable Technology. Gateway East: Springer Singapore.* https://doi.org/10.1007/978-981-13-3813-7.

Kohli, K., Prajapati, R. and Sharma, B. (2019). Bio-based chemicals from renewable biomass for integrated biorefineries. *Energies* 12(2), 1-40. https://doi.org/10.3390/en12020233.

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

Kümmerer, K., Clark, J.H. and Zuin, V.G. (2020). Rethinking chemistry for a circular economy. *Science* 367(6476), 369-370. https://doi.org/10.1126/science.aba4979.

Laoutid, F., Karaseva, V., Costes, L., Brohez, S., Mincheva, R. and Dubois, P. (2018). Novel bio-based flame retardant systems derived from tannic acid. *Journal of Renewable Materials* 6(6), 559-572. https://doi.org/10.32604/jrm.2018.00004.

Larcher, D. and Tarascon, J.-M. (2015). Towards greener and more sustainable batteries for electrical energy storage. *Nature Chemistry* 7(1), 19-29. https://doi.org/10.1038/nchem.2085.

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.

Lipinski, D. (2019). *H.R.2051: Sustainable Chemistry Research and Development Act of 2019.* 116th Congress (2019-2020). Washington, DC: United States Congress. https://www.congress.gov/bill/116th-congress/house-bill/2051.

Liu, D. and Chen, E.Y.X. (2014). Organocatalysis in biorefining for biomass conversion and upgrading. *Green Chemistry* 16(3), 964-981. https://doi.org/10.1039/c3gc41934g.

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.

McCrory, G., Schäpke, N., Holmén, J. and Holmberg, J. (2020). Sustainability-oriented labs in real-world contexts: an exploratory review. *Journal of Cleaner Production* 277(123202), 1-18. https://doi.org/10.1016/j.jclepro.2020.123202.

Meninno, S. (2020). Valorization of waste: sustainable organocatalysts from renewable resources. *ChemSusChem* 13(3), 437-437. https://doi.org/10.1002/cssc.202000007.

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.

Northwest Product Stewardship Council (n.d.). What is product stewardship? http://productstewardship.net/about/what-product-stewardship. Accessed 14 December 2020.

NSF International (n.d.). *Questions and Answers on NSF/GCI 355: Greener Chemicals and Processes Information Standard.* https://d2evkimvhatqav.cloudfront.net/documents/GC_355_Insert_LT_EN_LGC26050812.pdf.

Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., Cabernard, L., Che, N., Chen, D., Droz-Georget, H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt, A., Geschke, A., Haupt, M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr, J., Miatto, A., Newth, D., Oberschelp , C., Obersteiner, M., Pfister, S., Piccoli, E., Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z. and Zhu, B. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want*. A report of the International Resource Panel. Nairobi: United Nations Environment Programme. http://www.resourcepanel.org/file/1172/download?token=muaePxOQ.

Ocampo-López, C., Ramírez-Carmona, M., Rendón-Castrillón, L. and Vélez-Salazar, Y. (2019). Applied research in biotechnology as a source of opportunities for green chemistry start-ups. *Sustainable Chemistry and Pharmacy* 11, 41-45. https://doi.org/10.1016/j.scp.2018.12.005.

Organisation for Economic Co-operation and Development (2010). *OECD Global Forum on Environment Focusing on Sustainable Materials Management: Policy Report 1 - Policy Principles for Sustainable Materials Management Working Document*. http://www.oecd.org/env/waste/46111789.pdf.

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 June 2020.

Organisation for Economic Co-operation and Development (n.d.). Extended producer responsibility. https://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm. Accessed 14 December 2020.

Organisation for Economic Co-operation and Development. (n.d.). Database on policy instruments for the environment. https://pinedatabase.oecd.org/. Accessed 24 June 2020.

Oviatt, B.M. and McDougall, 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.

Panko, J., Hitchcock, K., Fung, M., Spencer, P., Kingsbury, T. and Mason, A. (2017). A comparative evaluation of five hazard screening tools. *Integrated Environmental Assessment and Management*. 13(1), 139-154. https://doi.org/10.1002/ieam.1757.

Peabody O'brien, K., Franjevic, S. and Jones, J. (2009). *Green Chemistry and Sustainable Agriculture: The Role of Biopesticides*. Charlottesville, VA: Advancing Green Chemistry. http://advancinggreenchemistry.org/wp-content/uploads/Green-Chem-and-Sus.-Ag.-the-Role-of-Biopesticides.pdf.

Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2004). Technology roadmapping - a planning framework for evolution and revolution. *Technological Forecasting and Social Change 71(1-2), 5-26*. https://doi.org/10.1016/s0040-1625(03)00072-6.

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.

Platt, D. (2004). Terry Collins develops 'green' catalysts for potential use in industry and biological warfare, 8 April. *Carnegie Mellon Today*. https://www.cmu.edu/cmnews/extra/030911_saferliving.html. Accessed 10 December 2020.

Pradeep, P., Friedman, K.P. and Judson, R. (2020). Structure-based QSAR models to predict repeat dose toxicity points of departure. *Computational Toxicology* 16, 100139. https://doi.org/10.1016/j.comtox.2020.100139.

Ravelli, D., Dondi, D., Fagnoni, M. and Albini, A. (2009). Photocatalysis. a multi-faceted concept for green chemistry. *Chemical Society Reviews* 38(7), 1999-2011. https://doi.org/10.1039/b714786b.

ReportLinker (2020). Global green chemicals industry, 7 July. *GlobeNewswire*. https://www.globenewswire.com/news-release/2020/07/07/2058992/0/en/Global-Green-Chemicals-Industry.html. Accessed 25 January 2021.

RoadToBio (2020). Welcome to RoadToBio: roadmap for the chemical industry in Europe towards a bioeconomy. https://www.roadtobio.eu/. Accessed 15 December 2020.

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.

Royal Society of Chemistry (2020). Energy: supporting the chemical science community to help create a sustainable energy future. https://www.rsc.org/campaigning-outreach/global-challenges/energy/#solarfuels. Accessed 14 December 2020.

Ryberg, M.W.R., Laurent, A. and Hauschild, M. (2018). *Mapping of Global Plastics Value Chain and Plastics Losses to the Environment: With a Particular Focus on Marine Environment.* Nairobi: United Nations Environment Programme. https://wedocs.unep.org/handle/20.500.11822/26745.

Ryzhonkov, V. (2013). Innovation ecosystem model, 3 August. *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 25 June 2020.

Sarkis, J. (ed.) (2019). *Handbook on the Sustainable Supply Chain.* Cheltenham: Edward Elgar Publishing. https://doi.org/10.4337/9781786434272.

ScienceDaily (2019). Artificial photosynthesis transforms carbon dioxide into liquefiable fuels, 22 May. *University of Illinois at Urbana-Champaign, News Bureau.* https://www.sciencedaily.com/releases/2019/05/190522153121.htm. Accessed 14 December 2020.

Sheldon, R.A. (2017). The E factor 25 years on: the rise of green chemistry and sustainability. *Green Chemistry* 19(1), 18-43. https://doi.org/10.1039/c6gc02157c.

Sheldon, R.A. (2019). The greening of solvents: towards sustainable organic synthesis. *Current Opinion in Green and Sustainable Chemistry 18, 13-19.* https://doi.org/10.1016/j.cogsc.2018.11.006.

Sheldon, R.A. and Brady, D. (2019). Broadening the scope of biocatalysis in sustainable organic synthesis. *ChemSusChem* 12(13), 2859-2881. https://doi.org/10.1002/cssc.201900351.

Sheldon, R.A. and Woodley, J.M. (2018). Role of biocatalysis in sustainable chemistry. *Chemical Reviews* 118(2), 801-838. https://doi.org/10.1021/acs.chemrev.7b00203.

Sheu, J.B. and Choi, T.M. (2019). Extended consumer responsibility: syncretic value-oriented pricing strategies for trade-in-for-upgrade programs. *Transportation Research Part E: Logistics and Transportation Review* 122, 350-367. https://doi.org/10.1016/j.tre.2018.12.016.

Smith, N.C. and Jarisch, D. (2019). INEOS chlorvinyls: a positive vision for PVC (a). In *Managing Sustainable Business. Lenssen,* G.G. and Smith, N.C. (eds.). Dordrecht: Springer Netherlands. Chapter 5. 83-102. https://doi.org/10.1007/978-94-024-1144-7_5.

Sourcemap (2012). *IPhone 5.* [Map]. https://open.sourcemap.com/maps/57d28966df2ac24b524c8ffb. Accessed 24 June 2020.

SpecialChem (2015). Organic monitor discusses future of green surfactants & emulsifiers in its latest study, 4 September. *Industry News.* https://cosmetics.specialchem.com/news/industry-news/organic-monitor-discusses-future-of-green-surfactants-emulsifiers-000177331. Accessed 7 December 2020.

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.

Stockholm Resilience Centre (2016). How food connects all the SDGs. http://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html. Accessed 26 June 2020.

Styring, P., Jansen, D., de Coninck, H., Reith, H. and Armstrong, K. (2012). *Carbon Capture and Utilisation in the Green Economy: Using CO_2 to Manufacture Fuel, Chemicals and Materials.* York: The Centre for Low Carbon Futures and CO2Chem Publishing. https://www.semanticscholar.org/paper/Carbon-Capture-and-Utilisation-in-the-green-economy-Coninck-ECN/5d2c7d791478526465b2d5dd68d7962414b34526.

Sustainable Packaging Coalition (2020). For people + the planet. https://sustainablepackaging.org/. Accessed 14 December 2020.

Temper, L., Demaria, F., Scheidel, A., Del Bene, D. and Martinez-Alier, J. (2018). The Global Environmental Justice Atlas (EJAtlas): ecological distribution conflicts as forces for sustainability. *Sustainability Science* 13(3), 573-584. https://doi.org/10.1007/s11625-018-0563-4.

The Natural Step (2020a). Our approach: the natural step framework. https://thenaturalstep.org/approach/. Accessed 15 December 2020.

The Natural Step (2020b). Transition labs. https://thenaturalstep.org/services/transition-labs/. Accessed 15 December 2020.

The Natural Step Canada (n.d.). Sustainability transition lab process. http://www.naturalstep.ca/sustainability-transition-lab-process. Accessed 15 December 2020.

Together for Sustainability (2020). What is TFS? https://tfs-initiative.com/. Accessed 14 December 2020.

United Nations Conference on Trade and Development (2019). *Methodology for SDG Indicator 12.6.1: Proposal from the Custodian Agencies.* https://environmentlive.unep.org/media/docs/projects/draft_proposal_methodology_12_6_1_may_2019.pdf.

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 (2017a). *Guidelines for Providing Product Sustainability Information: Global Guidance on Making Effective Environmental, Social and Economic Claims, to Empower and Enable Consumer Choice.* https://www.oneplanetnetwork.org/sites/default/files/guidelines_for_providing_product_sustainability_information_ci-scp_2017_revised.pdf.

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

United Nations Environment Programme (2019a). *Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution 2/7.* SAICM/OEWG.3/INF/22. http://www.saicm.org/Portals/12/Documents/meetings/OEWG3/inf/OEWG3-INF-22-Analysis.pdf.

United Nations Environment Programme (2019b). *Global Chemicals Outlook II: From Legacies to Innovative Solutions - Implementing the 2030 Agenda for Sustainable Development.* https://wedocs.unep.org/bitstream/handle/20.500.11822/28113/GCOII.pdf?sequence=1&isAllowed=y.

United Nations Environment Programme (2019c). *UNEP circularity platform.* https://buildingcircularity.org/wp-content/uploads/2019/11/Circularity_Diagram_UNEP.pdf.

United Nations Environment Programme (2020). Life cycle initiative. https://www.lifecycleinitiative.org/. Accessed 14 December 2020.

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 Industrial Development Organization (2020). What is CSR? https://www.unido.org/our-focus/advancing-economic-competitiveness/competitive-trade-capacities-and-corporate-responsibility/corporate-social-responsibility-market-integration/what-csr. Accessed 14 December 2020.

United States Environmental Protection Agency (2017). Sustainable materials management: non-hazardous materials and waste management hierarchy, 10 August. https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy. Accessed 26 June 2020.

United States Environmental Protection Agency (2020a). Sustainable materials management, 30 October. https://www.epa.gov/smm. Accessed 14 December 2020.

United States Environmental Protection Agency (2020b). Information about the green chemistry challenge, 12 September. https://www.epa.gov/greenchemistry/information-about-green-chemistry-challenge. Accessed 14 December 2020.

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 National Research Council (2014). *A Framework to Guide Selection of Chemical Alternatives.* Washington, D.C.: National Academies Press. http://www.nap.edu/catalog/18872.

United States Occupational Safety and Health Administration (n.d.). Transitioning to safer chemicals: a toolkit for employers and workers. https://www.osha.gov/dsg/safer_chemicals/index.html. Accessed 15 December 2020.

van der Waals, J., Bougas, K., Keyte, I., Kreissig, J. and Smit, J. (2018). *Safe Chemicals Innovation Agenda: Towards a Research Agenda for Safe Chemicals, Materials and Products.* The Hague: The Netherlands, Ministry of Infrastructure and Water Management. https://www.chemischestoffengoedgeregeld.nl/sites/default/files/39982%20-%20Safe%20Chemicals%20Innovation%20Agenda%20-%2020180613i6%20final%20copy.pdf.

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.

Verster, B., Madonsela, Z., Minnaar, S., Cohen, B. and Harrison, S.T.L. (2014). *Introducing the Wastewater Biorefinery Concept: A Scoping Study of Poly-Glutamic Acid Production from a Bacillus-Rich Mixed Culture Using Municipal Wastewater.* WRC Report No. TT 587/13. Cape Town: Water Research Commission. https://www.researchgate.net/publication/283048384_Introducing_the_wastewater_biorefinery_concept.

Vitale, M.R., Oudeyer, S., Levacher, V. and Brière, J.-F. (2016). *Radical and Ion-Pairing Strategies in Asymmetric Organocatalysis.* London: ISTE Press Ltd and Elsevier Ltd. https://www.sciencedirect.com/book/9781785481277/radical-and-ion-pairing-strategies-in-asymmetric-organocatalysis.

Voorhees, K. and Hutchison, J.E. (2015). Green chemistry education roadmap charts the path ahead. *Chemical & Engineering News Archive* 93(38), 46. https://doi.org/10.1021/cen-09338-comment.

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.

Wageningen University & Research (n.d. a). Creating value from biomass. https://www.wur.nl/Landingspagina-redacteuren-29/en/Research-Results/Research-Institutes/food-biobased-research/Research-themes/Creating-value-from-biomass.htm. Accessed 7 July 2020.

Wageningen University & Research (n.d. b). Circular & biobased economy. https://www.wur.nl/en/Research-Results/Themes/theme-biobased-economy.htm. Accessed 13 December 2020.

Wang, F., Talaue McManus, L. and Xie, R. (eds.) (2019). *Addressing Marine Plastics: A Roadmap to a Circular Economy*. Arendal: United Nations Environment Programme. https://gefmarineplastics.org/publications/addressing-marine-plastics-a-roadmap-to-a-circular-economy.

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

Woo, B., Kravitz-Wirtz, N., Sass, V., Crowder, K., Teixeira, S. and Takeuchi, D.T. (2019). Residential segregation and racial/ethnic disparities in ambient air pollution. *Race and Social Problems* 11(1), 60-67. https://doi.org/10.1007/s12552-018-9254-0.

World Bank Group (2020). Small and medium enterprises (SMEs) finances: improving SMEs' access to finance and finding innovative solutions to unlock sources of capital. https://www.worldbank.org/en/topic/smefinance. Accessed 14 December 2020.

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.

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.

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

World Health Organization (2018a). *The Public Health Impact of Chemicals: Knowns and Unknowns - Data Addendum for 2016*. http://www.who.int/ipcs/publications/chemicals-public-health-impact/en/.

World Health Organization (2018b). *Chemicals Road Map: Workbook - Road Map to Enhance Health Sector Engagement in the Strategic Approach to International Chemicals Management towards the 2020 Goal and Beyond*. https://apps.who.int/iris/bitstream/handle/10665/273136/9789241513630-eng.pdf?ua=1.

World Health Organization (2020). International Programme on Chemical Safety: WHO chemicals road map and workbook - document links. https://www.who.int/ipcs/saicm/roadmap-links/en/. Accessed 15 December 2020.

Yale University (n.d.). The global green chemistry initiative. *Yale Center for Green Chemistry and Green Engineering*. https://www.global-green-chemistry-initiative.com/. Accessed 14 December 2020.

Zimmerman, J.B., Anastas, P.T., Erythropel, H.C. and Leitner, W. (2020). Designing for a green chemistry future. *Science* 367(6476), 397-400. https://doi.org/10.1126/science.aay3060.

Zimmermann, L., Dombrowski, A., Völker, C. and Wagner, M. (2020). Are bioplastics and plant-based materials safer than conventional plastics? in vitro toxicity and chemical composition. *Environmental International* 145, 1-11. https://doi.org/10.1016/j.envint.2020.106066.

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.

Żukiewicz-Sobczak, W.A. (2013). The role of fungi in allergic diseases. *Postepy Dermatologii i Alergologii* 30(1), 42-45. https://doi.org/10.5114/pdia.2013.33377.

UN environment programme

science.chemicals@un.org
www.unep.org

International Environment House I
Chemin des Anémones 15
1219 Châtelaine-Geneva

ISBN 9789280738391
90000 >
9 789280 738391