GREEN AND SUSTAINABLE CHEMISTRY: FRAMEWORK MANUAL

Revised draft (10 November 2020)

This is a draft for review purposes, please do not cite or distribute. End notes used to reference content sources will be put into the standard UNEP referencing system in the final document.

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 is taking place during the fourth quarter of 2020. During this final phase, reviewers are requested to validate, if all important points raised at the June expert meeting and in written comments have been addressed and share any other strategic comment relevant for finalizing the manual.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

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 UNEP report ‘Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution 2/7”, which was discussed at the fourth session of the United Nations Environment Assembly (UNEA-4) in 2019.

The above cited UNEP 2019 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 l. 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, 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 the United Nations Environment Assembly at its fourth session (UNEA4) 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 introduces, in a structured way, various facets of green and sustainable chemistry, with the intention to foster learning, reflection and scale up action based on a common global understanding of the concept. It features an organizing framework that unpacks various topics relevant for green and sustainable chemistry literature. The Manual is setting objectives and guiding considerations from green and sustainable chemistry, as well as an innovation and research framework are offered to stimulate stakeholder action at various levels and in different settings. Ultimately, the Manual seeks to promote innovation that unveils the full power of chemistry, and is compatible with, and supports implementation of global sustainable development goals and targets.

The range of topics covered in the Manual 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.

Overview of the framework manual

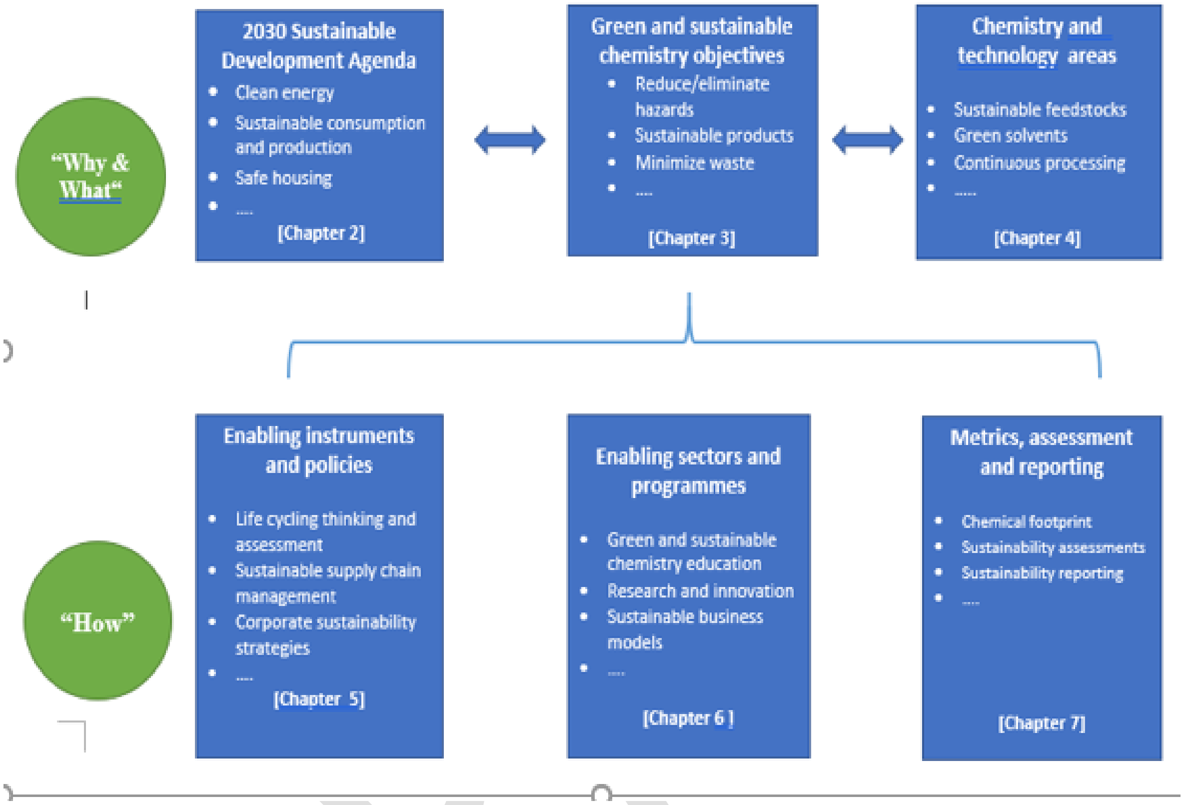
The Framework Manual is structured into eight chapters. Following this introduction, Chapter 2 discusses challenges and opportunities of chemistry in achieving the UN General Assembly endorsed 2030 Sustainable Development Agenda which seeks to advance meeting human needs within planetary boundaries. 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 introduces 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 areas and topics of chemistry and technology research and innovation which are relevant to green and sustainable chemistry.

Chapter 5 introduces management tools and instruments that can help advance green and sustainable chemistry action. Closely related, Chapter 6 discusses enabling sector policies and programmes that advance green and sustainable chemistry innovation, for example through networks and communities of interest. Chapter 7 takes a look at metrics, assessment tools, 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 below. 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 tools and measures to advance green and sustainable chemistry (the “How”). These action-enabling elements range from promoting life cycle approaches, to strengthening research and innovation policies and programmes. An important cross-cutting topic is the need to scale up awareness raising and education initiatives at all levels that bring the green and sustainable chemistry agenda to potential actors, through formal and informal education.

Figure 1.1: Advancing sustainability through green and sustainable chemistry



Who are the stakeholders encouraged to use this Manual?

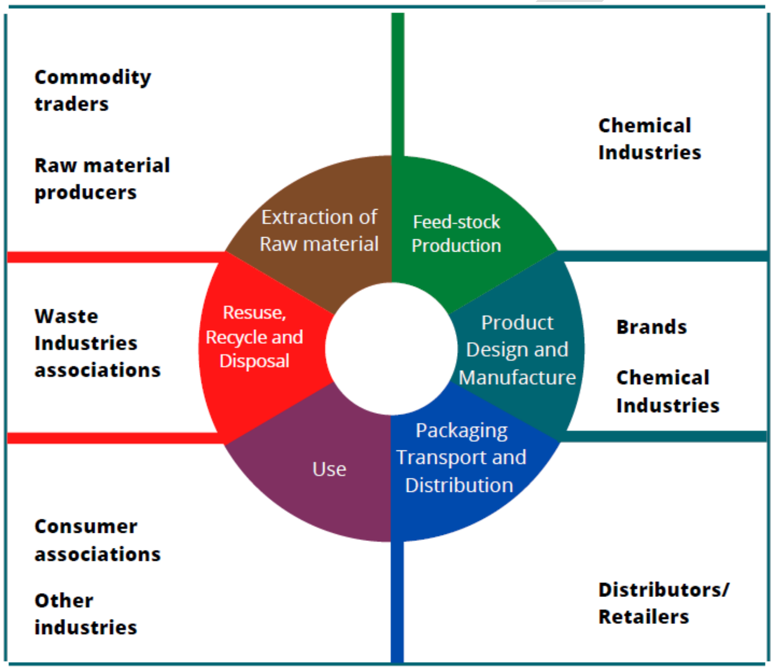
This Framework Manual targets a range of audiences and stakeholders concerned with the sound *management of chemicals and waste. They include decision-makers and managers in:*

- **Public authorities** responsible for regulating chemicals of concern and promoting innovation for safer chemistry
- **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 in chemistry, process engineering and product design
- **Private sector entities** engaged in all stages of the value chain, from sourcing raw materials and feedstocks, to production, to recycling and disposal.
- **Consumers** who can shape the market demand towards safer and more sustainable products, with the choice 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 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 **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. A practical measure which private sector actors are encouraged to undertake is to use the 10 objectives and guiding considerations presented in Chapter 3 to assess and guide innovation programs and assess current management practices.

Figure 1.2: Private sector actors in the value chain



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 this revised draft. A final consultative process to provide input on the draft Framework Manual will take place during the third quarter of 2020.

2 Chemistry and sustainable development: challenges and opportunities

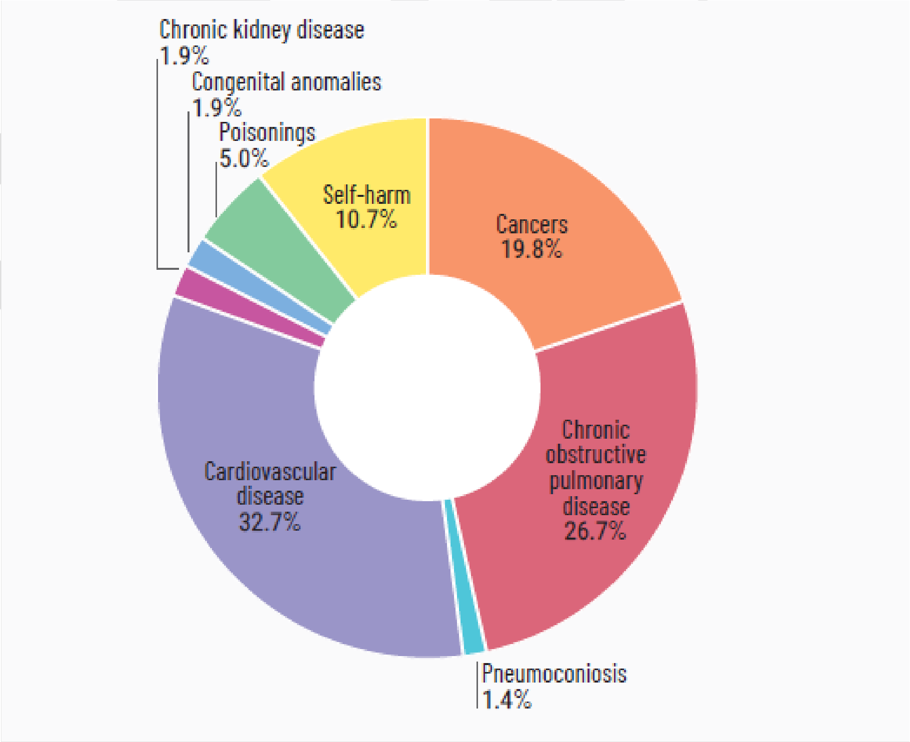
2.1 Why is systemic action to advance green and sustainable chemistry needed?

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

Global trends cause significant concerns

The recently published Global Chemicals Outlook-II, while recognizing that many chemicals are important for sustainable development, 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 and disposed of in large quantities, affecting individuals and communities worldwide. Synthetic chemicals are now ubiquitous in humans and the environment and chemical pollution has become a major cause of human disease and premature deaths. The World Health Organization (WHO) estimated the burden of disease from selected chemicals at 1.6 million lives and 44.8 million disability-adjusted life years (DALYs) in 2016 (WHO 2018) which is likely to be an underestimate. Workers, women, and children are particularly at risk (UNEP 2019). 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)

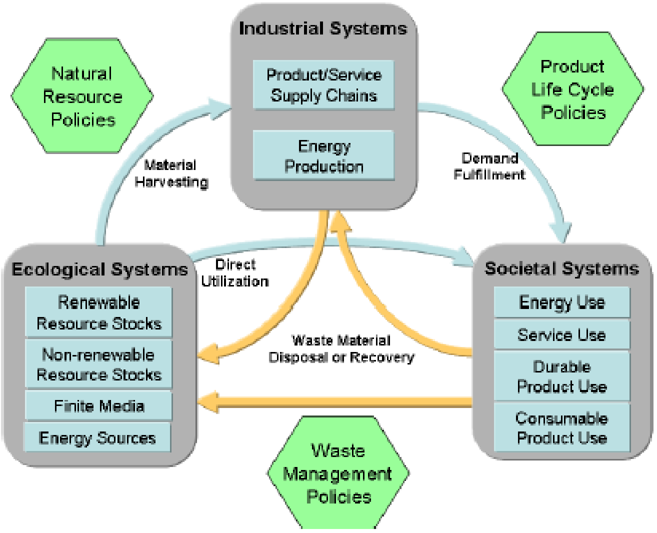


The GCO-II concludes that the global goal to minimize adverse impacts of chemicals and waste will not be achieved by 2020, calls for more ambitious and urgent worldwide action by all stakeholders, and concludes that "Business as usual is not an option". Enhanced action needs to include immediate measures 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 supporting greener and more sustainable chemistry innovations. This can be achieved by scaling up of innovation programmes and by developing and commercializing more sustainable supply and value chains for chemicals and products.

Global material and product flows and their chemistry dimension

Since the year 2000, the global production capacity of the chemical industry almost doubled from about 1.2 to 2.3 billion tonnes. Global sales of chemicals totalled United States 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. 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. The GCO-II states 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 that respects a more balanced relationship with the earth.

Figure 2.2: Systems View of Material Flow Cycles (OECD 2010)

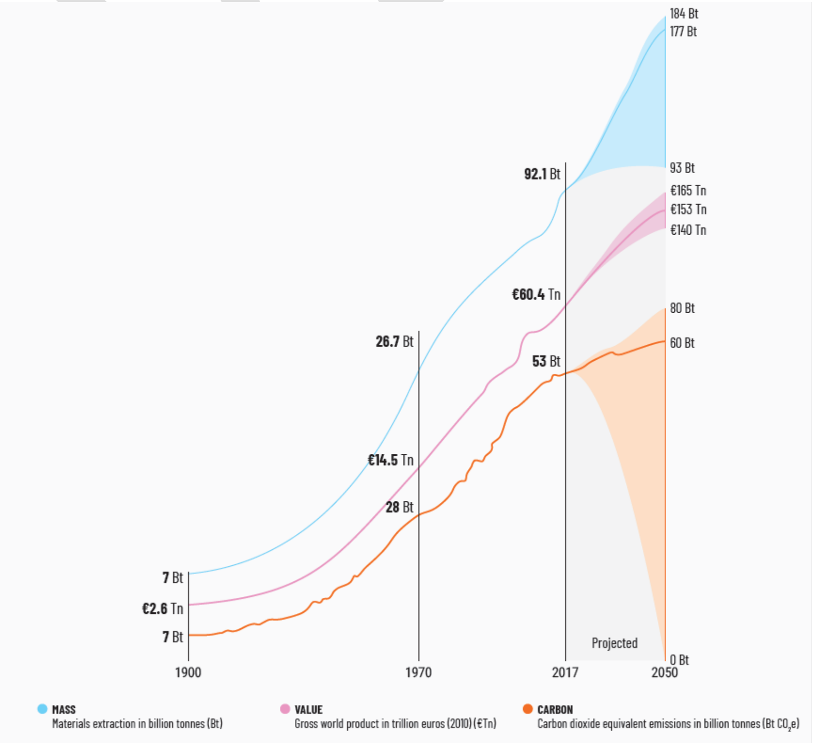


The chemical industry plays a key role in turning raw materials and feedstocks into products, with materials flowing through ecological, industrial and societal systems. According to the OECD (2010) Ecological Systems provide the natural capital from which materials are derived. They include renewable resource stocks, such as forests, non-renewable resource stocks (e.g. 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).

Sustainability challenges associated with materials and products flow

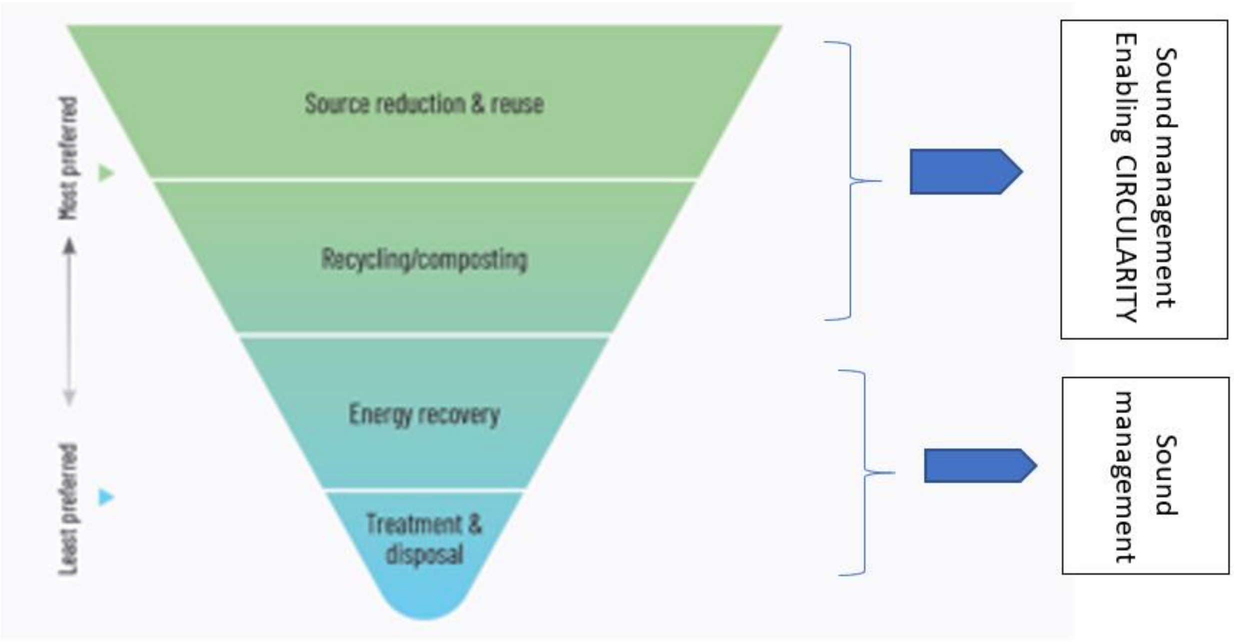
The International Resources Panel's Global Resources Outlook 2019 (Oberle *et al.* 2019) presents data that approximately 92 billion tonnes of materials were extracted globally in 2017. It also projects that extraction will reach 190 billion tonnes by 2060 and highlight that less than 10% of resources extracted is 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).

Figure 2.3: 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 the 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.

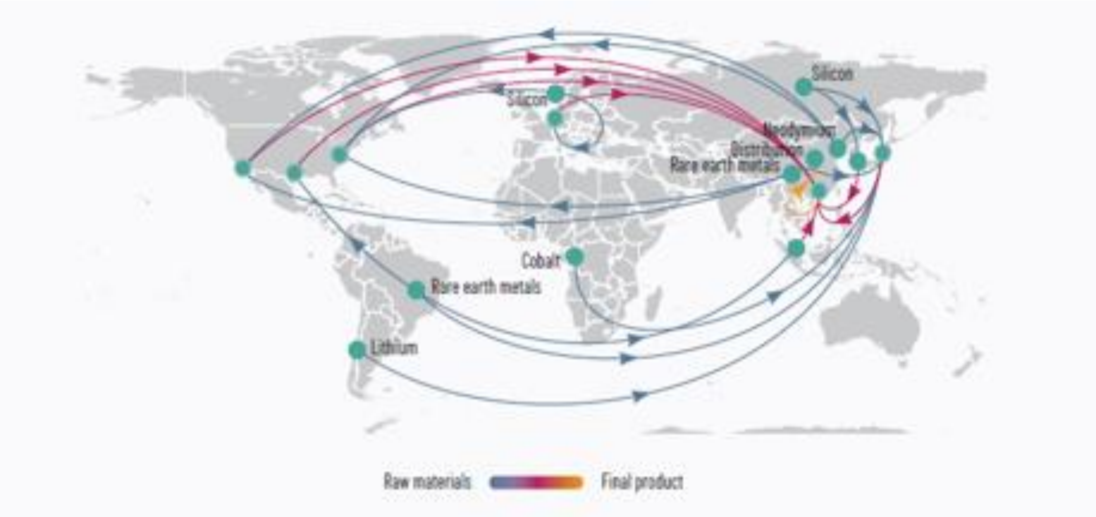
Figure 2.4: The waste hierarchy: Potential driver for sustainable materials management and a circular economy (adapted from United States Environmental Protection Agency [US EPA] 2017)



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 the chemicals potentially released throughout the product life cycle. These limitations create challenges for taking action across the product life cycle, such as minimizing chemical releases in 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.

Figure 2.5: The complexity of global supply chains: the case of an electronic product (adapted from Sourcemap 2012)



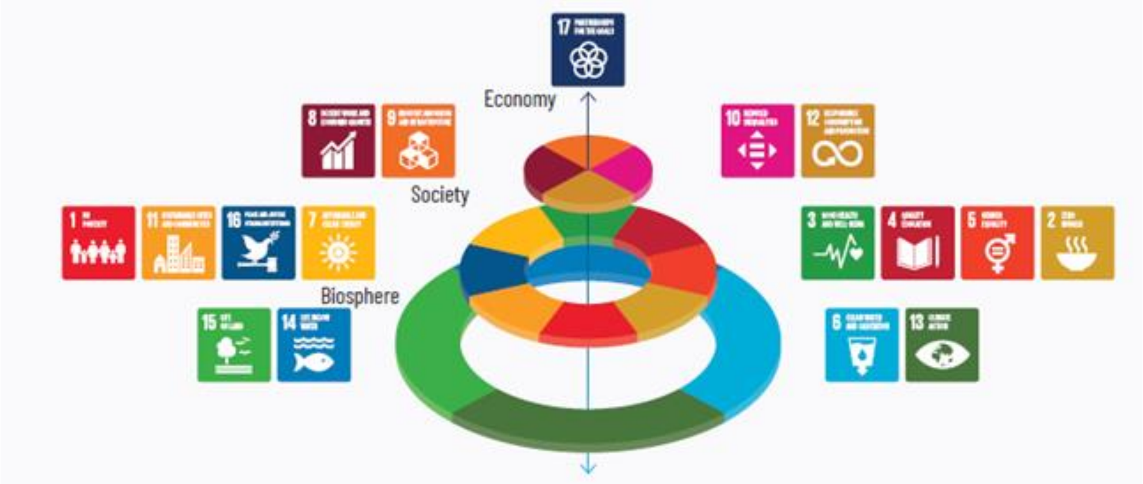
Meeting fundamental human needs, while protecting environment and human health

The increasing burden from chemical pollution, increasing growth of the chemical industry and the failure to fully manage product life cycles in a way that preserves material values are interconnected issues related to the consumption patterns of a growing 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 in a sustainable manner. Recognizing this can be an important step for promoting more sustainable consumption and production patterns and lifestyle choices. The challenge is to explore and advance a system in which knowledge about and use of sustainable and green 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 at 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 question how to extend sustainability with resiliency considerations. Figure 2.6 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.

Figure 2.6: The three dimensions of sustainability (adapted from Stockholm Resilience Centre 2016)



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

Potential of green and sustainable chemistry innovations

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 (UNEP 2019). Greener and more sustainable innovation at the interface of chemistry, biology and computer science is particularly promising (UNEP 2019).

Legacies associated with past chemistry innovation point to the importance of putting in place robust criteria to help ensure that future chemistry innovations are fully compatible with the 2030 Sustainable Development Agenda. Consistently applying such criteria would help reap the full potential of chemistry to advance sustainability and make a contribution to implement SDG 12 on sustainable consumption and production. Specifically, green and sustainable chemistry innovation could help to advance sustainable product design, foster sustainable and resilient supply chains, reduce pollution, enhance resource efficiency, improve environmental health and safety, and increase reuse and recyclability of products to foster a circular economy.

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

Sectors		**SDG targets**	**Examples of opportunities for management and innovation**
Agriculture and food	2 NO 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 good agricultural practices
Health	3 GOOD HEALTH	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

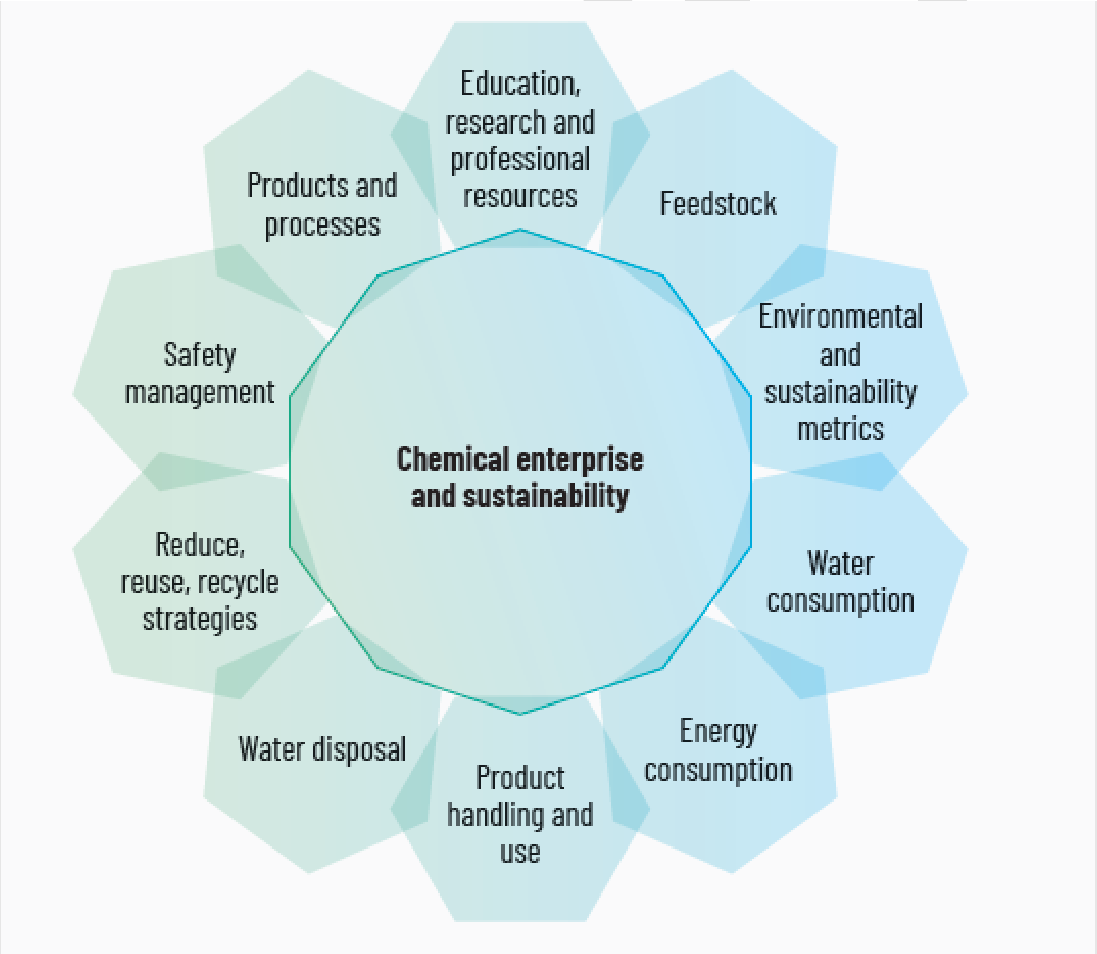
Tourism	8 DECENT WORK AND ECONOMIC GROWTH	Target 8.9: sustainable tourism	Adopt practices to reduce the chemical footprint of tourism services
Mining	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Target 12.2: Sustainable use of natural resources	Ensure environmentally sound management of tailings
Labour	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

Multiple dimensions of the chemical enterprise affecting sustainably

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 2.8 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 CO_2-emissions through composite materials that may not be recyclable. 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. For these types of questions, using tools such as a life cycle or social assessment tools may provide valuable insights.

Figure 2.8: Dimensions of a chemical enterprise: towards sustainability (adapted from Hill, Kumar and Verma 2013, p. 27)



2.2 The evolving understanding of green and sustainable chemistry concepts

Green chemistry as a foundation for sustainable chemistry

The term “green chemistry” was first used in the early 1990s. It gained momentum after it received support by the United States Environmental Protection Agency (US EPA) (Linthorst 2010) by 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 processes, safer products, and the use of renewable feedstocks (Clark 2006; Mubofu 2016).

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.*

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” (Anastas and Warner 1998). They proposed 12 Principles of Green Chemistry (**Error! Reference source not found.**). The American Chemical Society provides a short explanation of each of the 12 Green Chemistry principles as well as guidance for making a greener chemical or reaction.[i] Meanwhile, many countries around the world have engaged the creation of green chemistry networks and green chemistry policy statements.

The green chemistry and engineering concept fundamentally challenge and motivate chemists to explore the design of more benign chemicals and production processes under conditions that do not require heat and high pressure to catalyze chemicals reactions, essentially mimicking conditions in nature. Table 2.2 provides some illustrations how green chemistry approaches help move from traditional to green and biomimetic chemistry technologies.

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 and sodium make up 96 per cent of atoms in living systems; other elements are used in trace amounts • Controlling risk by adopting the inherent properties of the materials

Research on green chemistry 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 have documented the contribution of how green chemistry enhances environmental health and safety (EHS) and provides economic and competitive advantages. These accounts include, for example, the special ACS journal issue on "Building on 25 Years of Green Chemistry and Engineering for a Sustainable Future (American Chemical Society [ACS] (Anastas and Allen 2016), or the ACS publication "How Industrial Applications in Green Chemistry Are Changing Our World" (ACS 2015).

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 fulfillment. Greener is the intention, and the principles are to be used a means toward the ends. 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).

Essentially, the green chemistry narrative is about, and 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 on these commitments. Using and complying with the 12 principles is a motivating and potent factor for chemistry researchers and chemical enterprises, and their users alike and has created opportunities for reward. It is this approach of encouragement and flexibility which can be considered one of the 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 Organisation for Economic Co-operation and Development (OECD) in the late 1990s and early 2000s (OECD 2012) (UBA 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 "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), inclusion of downstream users such as consumers" (Friege and Zeschmar-Lahl 2017).

While green chemistry is characterized and guided by scientific principles related to chemistry itself, recent discussions on sustainable chemistry referred a broader concept and more holistic interpretation, that takes into account economic, environmental and social dimensions. They recognize that these dimensions are nested systems (economy within society within the biosphere). This mean that the sustainable chemistry includes, a broader set of topics, such as advanced manufacturing, safe working conditions, local communities and human rights, consumption and disposal patterns, citizens and ethics, new business and service models, and other related topics (Kümmerer 2017; Blum *et al.* 2017). Ensuring that chemicals can be managed in a sound manner is a fundamental condition for sustainable chemistry.

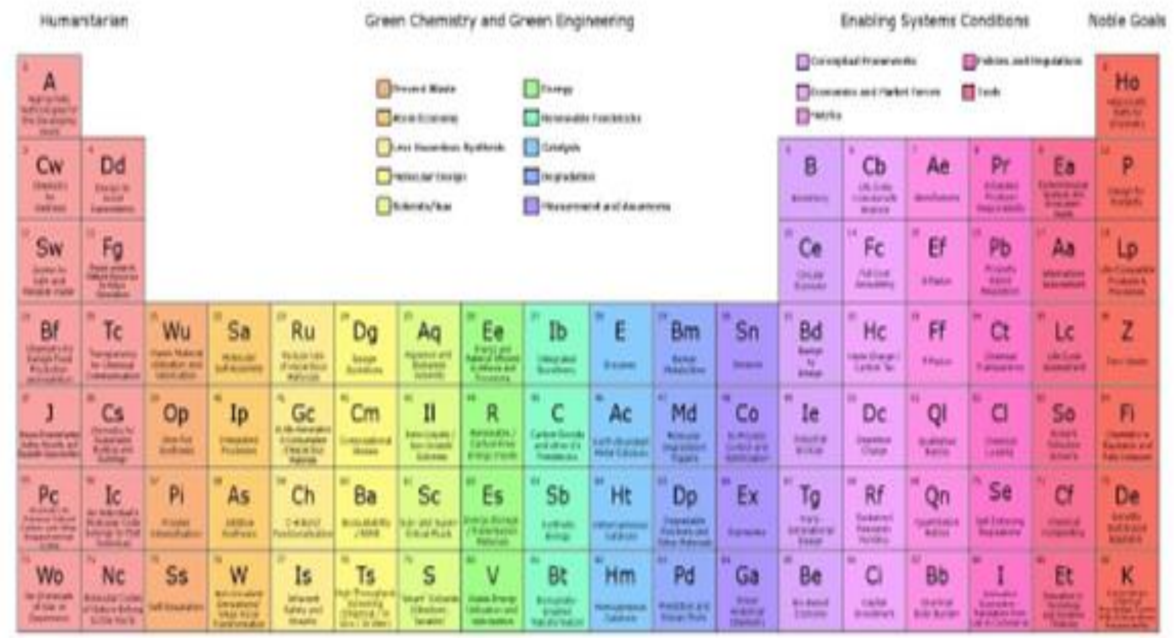
As highlighted in the GCO-II, a recent study by the United States Government Accountability Office (US GAO) on chemistry innovation identified several common themes on “what sustainable chemistry strives to achieve,” including:

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

An initiative which seeks to facilitate a common understanding of sustainable chemistry is the ISC3 stakeholder dialogue process, which brings together different perspectives, expectations and criteria discussed in the context of sustainable chemistry.[ii]

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 green chemistry 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).

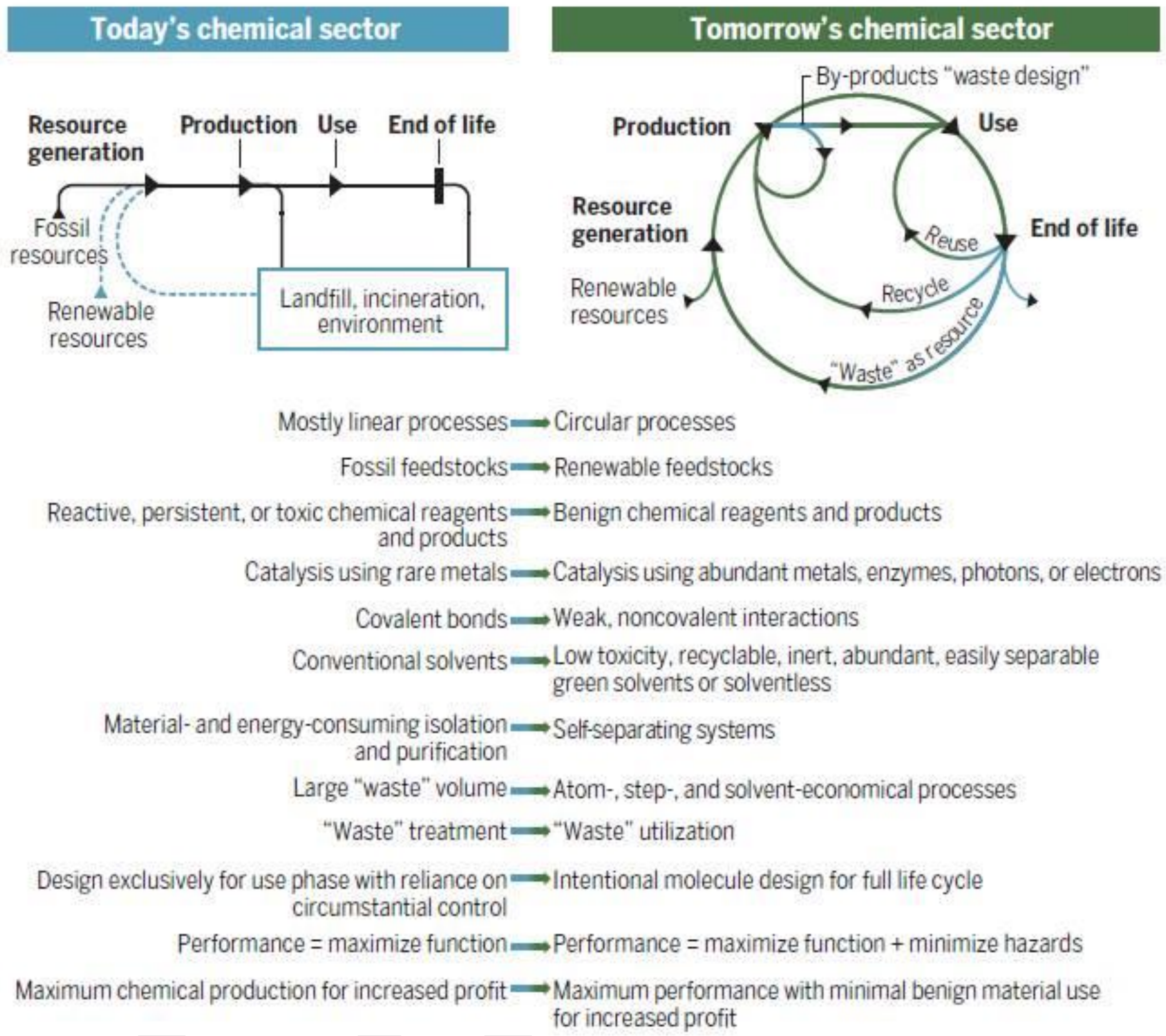
Figure 2.9: The Periodic Table of the Elements of Green and Sustainable Chemistry (Anastas and Zimmermann 2019, p. 6546)



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". 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).

Figure 2.10: Characteristics of today's and tomorrow's chemical sector (Zimmerman *et al.* 2020).

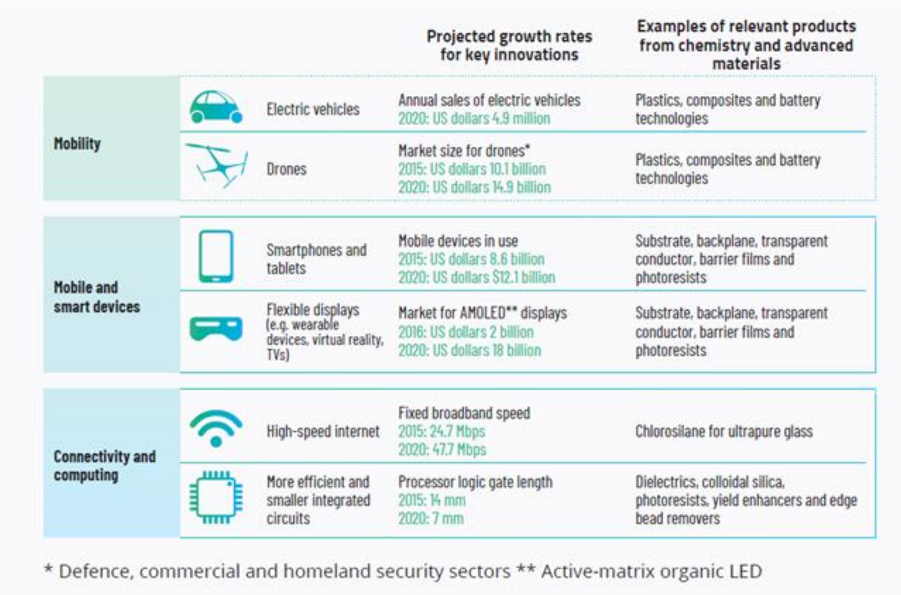


Today's chemical sector	Tomorrow's chemical sector
Mostly linear processes	Circular processes
Fossil feedstocks	Renewable feedstocks
Reactive, persistent, or toxic chemical reagents and products	Benign chemical reagents and products
Catalysis using rare metals	Catalysis using abundant metals, enzymes, 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 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 2.11 provides selected examples on how chemistry contributes to industries that play a role in sustainable development in the future.

Figure 2.11: Examples of how chemistry contributes to industries expected to play important roles in the future (adapted from World Economic Forum [WEF] 2017, p. 7)



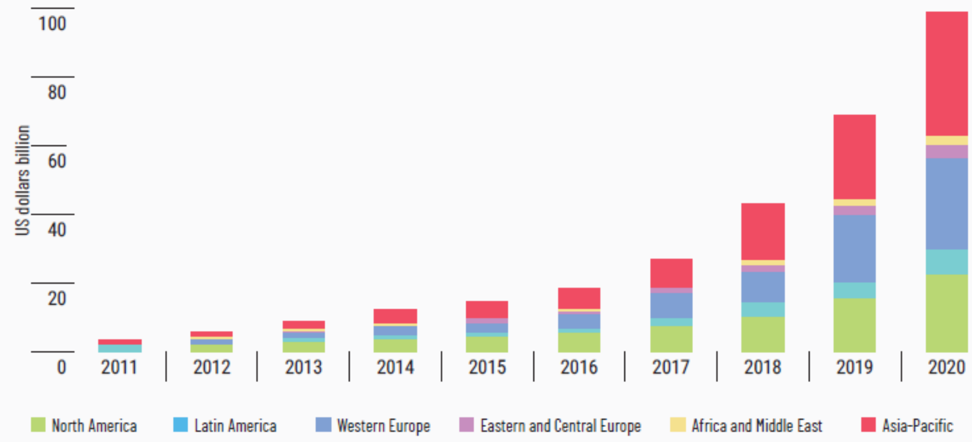
		Projected growth rates for key innovations	Examples of relevant products from chemistry and advanced materials
Mobility	Electric vehicles	Annual sales of electric vehicles 2020: US dollars 4.9 million	Plastics, composites and battery technologies
	Drones	Market size for drones* 2015: US dollars 10.1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

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

The market potential for green and sustainable chemistry

While differences exist in the characterization of green and sustainable chemistry, available data suggests that supply and demand for greener and more sustainable chemistry product has significantly grown over the past years. 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 is projected to grow to US dollars 100 billion by 2020 (Bernick 2016). Asia and the Pacific, Western Europe and North America are the key market growth regions (Pike Research 2011) (Figure 2.12).

Figure 2.12: 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? Guiding considerations

A vision for green and sustainable chemistry

A vision of green and sustainable chemistry 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 should become fully sustainable. The vision covers both greener and more sustainable innovations, as well as the need to address toxic and persistent legacies associated with past chemistries though a life cycle approach.

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 (SGD 3), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), sustainable consumption and production (SDG 12), and climate action (SGD 13). By reducing and/or eliminating chemical hazards, associated health and environmental impacts and pollution, green and sustainable chemistry will also contribute to other SDGs, such as decent working conditions, and economic growth (SDG 8), and innovation and infrastructure (SDG 9) life below water (SGD 14) or life on land (SGD 15).

Green and Sustainable Chemistry Objectives and Guiding Considerations

This Framework Manual offers 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.

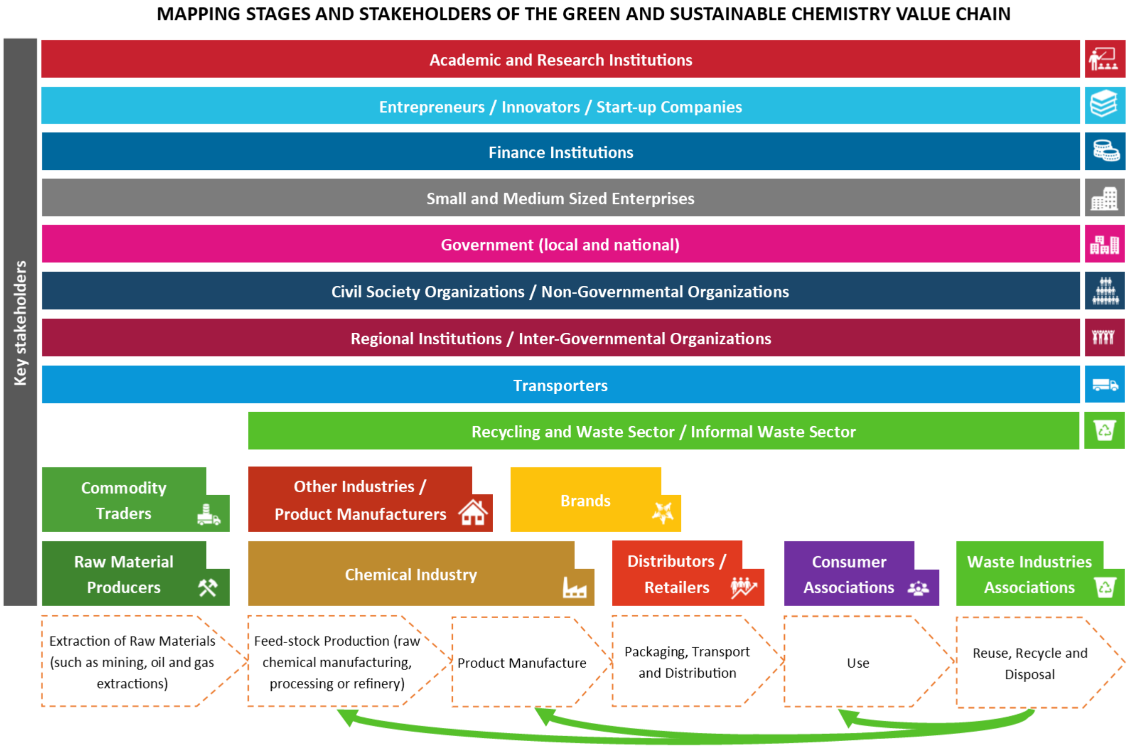
1. Minimizing chemical hazards
2. Avoiding regrettable substitutions and alternatives
3. Sustainable sourcing of resources and feedstocks
4. Advancing sustainability of production processes
5. Advancing sustainability of products
6. Minimizing chemical releases and pollution
7. Enabling non-toxic circularity
8. Maximizing social benefits
9. Protecting workers, consumers and vulnerable populations
10. Developing solutions for sustainability challenges

Objectives and guiding considerations

The vision of green and sustainable chemistry can be achieved through new designs and innovations in chemistry that provide the 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 both innovation in chemistry (i.e. new molecules/chemical compounds) as well as the innovations in chemical engineering sciences (i.e. chemical processes and sustainable production).

Apart from the 12 Principles of Green Chemistry and the 12 Principles of Green Engineering, a thorough reference framework that helps to understand a broader “green and sustainable chemistry” framework does not exist. Similarly, an agreed set of criteria to determine how “green” or “sustainable” a chemical or industrial process is does not exist (UNEP 2019). This Framework Manual aims to contribute to this discussion, by presenting 10 objectives and guiding considerations what green and sustainable chemistry seeks to achieve. They are offered to actors engaged in chemistry innovation, management and policy development. Those include, but are not limited to chemists, chemical engineers, users and consumers, as well as decision makers managers in the private sector, Government and other stakeholder groups. The intention of presenting the objectives and guiding considerations is to encourage and inspire actors to shift chemistry innovations towards green and sustainable chemistry innovation.

Figure 3.1: Stakeholder and targets audiences of green and sustainable chemistry in the value chain



A deeper look at the 10 green and sustainable chemistry objectives

The following sections introduce each of the 10 objectives and guiding considerations in more detail. For each objective, an explanatory line is offered, followed by the targets groups for which the objective is relevant and a longer description what is seeks to achieve. 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 potential 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) hazard potential, in order to advance safer and sustainable materials, and to develop sustainable products and production processes in which chemicals are used. Indirectly, such designs respond to consumers’ demand, strengthen competitiveness, and are likely to move across borders more freely, in compliance with most regulatory frameworks worldwide, 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 alternatives for chemicals of concern through material and product innovations without creating negative trade-offs

The second objective addresses more directly 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) that create concern for human health and the environment. Alternatives should be designed and used to avoid negative impacts, nor compromise other development objectives (e.g. mitigating climate change). Otherwise, they might become regrettable substitutions. Alternatives may also provide desired functions through non-chemical approaches.

Objective 3: Sustainable sources of resources and feedstocks

Use of sustainably sourced resources 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 renewable resources as feedstocks in the business of chemistry, while ensuring that the production and use of bio-based feedstocks meets broader sustainability criteria. Relevant considerations include, but are not limited to, the vital need to care for arable and agricultural land or limiting destructive impacts on forests and ecosystems.

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 reuse and recycling. It encourages chemistry innovation to enhance resource efficiency, minimize industrial waste, and foster reuse and recycling of chemicals and materials during production processes.

Objective 5: Advancing sustainability of products

Use green and sustainable chemistry innovation to create sustainable products 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, have longevity (i.e. duration of shelf and service-life, repairability), are safe, and can be reused or recycled within a circular economy.

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. It encourages chemistry innovations to minimize intended and un-intended releases of chemicals to indoor and outdoor environments during manufacturing production processes, during use phase, and during disposal of the products. That can be achieved by creating new designs and minimizing or eliminating hazardous chemicals in products, maximizing the use of closed systems, and ensuring reuse and recycle of materials, through life cycle assessments and information transparency.

Objective 7: Enabling non-toxic circularity

Use of chemistry innovations to enable non-toxic circular material flows and sustainable supply 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 product development and industrial processes. It encourages green and sustainable chemistry innovation to foster sustainable material management, including maintaining the highest possible value of materials during the life cycle of a product. It encourages elimination of toxic compounds in products to allow sustainable re-use and recycling.

Objective 8: Maximizing social benefits

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

The eighth objective is relevant for all stakeholders, including citizen, 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 far from being distributed equally. It encourages that chemistry innovation is fully compatible with broader social sustainability considerations, including, but not limited to ethics, education, socio-economic-justice aspects and justice considerations.

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. It encourages 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 discussion 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 for sustainability challenges, including, but not limited to food security, human wellbeing, climate change, biodiversity, pollution, and supply chain resiliency, locally and globally.

4 Chemistry and technology innovation areas 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 providing an overview of chemistry topics which are considered relevant for advancing the green and sustainable chemistry agenda. It therefore seeks to inform the development of an international research framework and agenda for green and sustainable chemistry.

The topics featured in this chapter have been identified following a review of green and sustainable chemistry publications[iii] 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[iv], or the annual Elsevier Green & Sustainable Chemistry Conference.[v] The topics featured in relevant publications and conferences 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. The chapter also features the energy sector as an example for how green and sustainable chemistry innovation may contribute to sustainable development at the sectoral level.

The topics and examples featured in this chapter have not been assessed from a sustainability perspective. In order to assess 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 using a life cycle approach. Various dimension may also need to be considered from a qualitative sustainability perspective 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 the GCO-II.

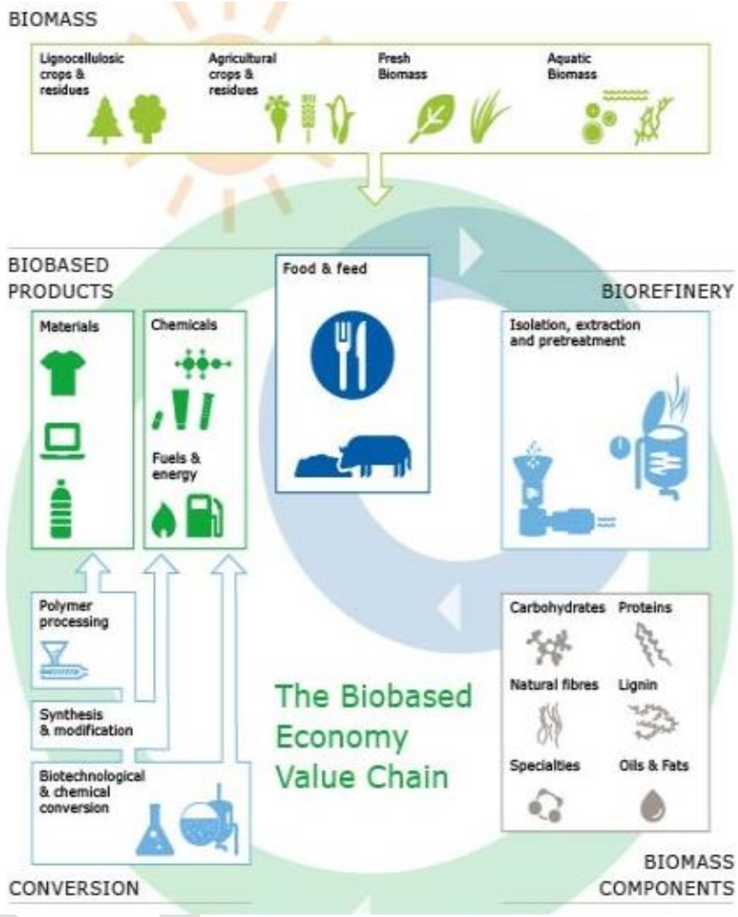
4.2 Chemical feedstock and product innovation opportunities

Bio-based and renewable 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. Using biorefinery technologies has the potential to yield a range of basic chemicals traditionally produced energy intensive and polluting petrochemical refinery technology (Kohli *et al.* 2019).[vi] 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 provide the foundation for a range of products and applications, including food, energy, materials, and pharmaceuticals to name a few.

Figure 4.1: Biobased Value Chain (Wageningen University n.d) [vii]



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

Using biomass and renewable feedstocks in the chemical industry is raising important sustainability questions and concerns.

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. A case in point is the development of PCV 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 make a product safer, if the respective chemicals are equally hazardous to health or the environment.

Carbon dioxide as resource and feedstock

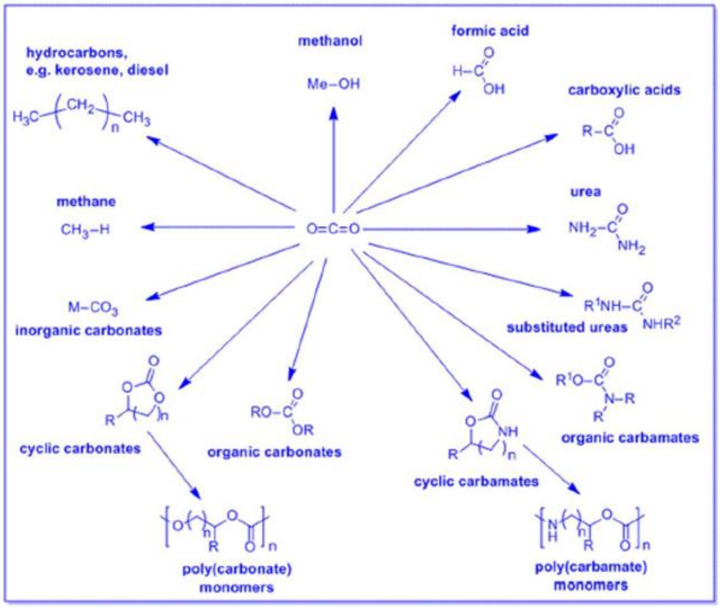
Several pathways exist to utilize CO_2, a potent greenhouse gas, as a resource. These include the conversion of CO_2 into fuels, the use of CO_2 as a feedstock for the chemical industry, and non-conversion uses of CO_2 (IEA 2019).[ix] These technologies have the potential to absorb significant amounts of CO_2 from the atmosphere, and thus may contribute to global efforts to mitigate climate change. Relevant innovations are at different stages of the technology innovation process. While in some cases they are still at the stage of basic research, other technologies are already matured, but have not yet achieved commercial breakthroughs, due to challenges to enter the market. Opportunities to use carbon dioxide as a resource and feedstock in the chemical industry are manifold. Figure 4.2 provides an overview of such opportunities.

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). Significant amounts of energy are needed for this type of conversion. The use of renewable energy in these processes is therefore essential to meet sustainability criteria.

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.

Figure 4.2: Overview of chemicals derived from Carbon Dioxide (Coninck *et al.* 2012)[x]



Plastics

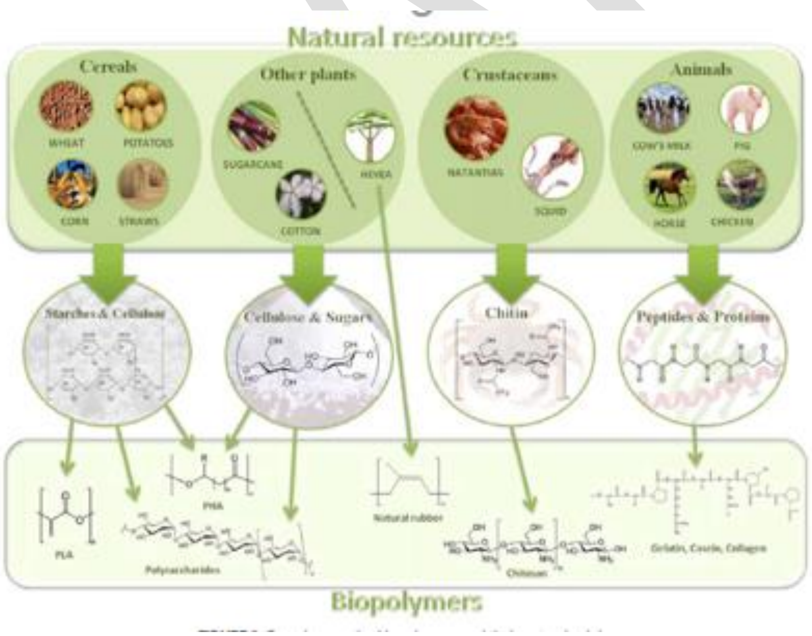
Plastics are organic polymers, which include a wide range of synthetic or semi-synthetic materials used in applications such as clothes, cars, toys, televisions, computers, etc. They are commonly derived from crude oil, coal, or natural gas. However, significant amounts of plastics are disposed into 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 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).[xi] Polylactic Acid (PLA), for example, is a biodegradable, thermoplastic, aliphatic polyester derived from sugar through fermentation which can replace polyethylene in several application, 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 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 material reach end of life, sound recycling takes places (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 (UNEP 2015).[xii]

Figure 4.3: Overview of biopolymers and their natural original (Bocque *et al.* 2015) [xiii]



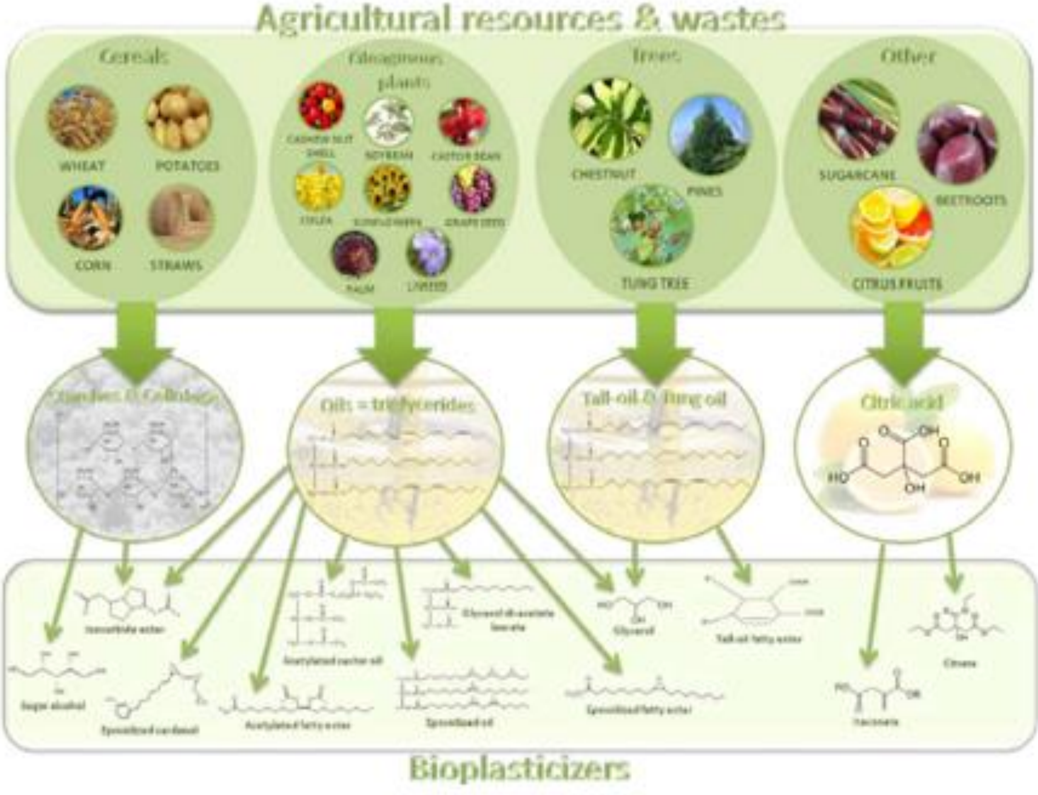
Plasticizers

Plasticizers are chemicals added to plastics to enhance flexibility of polymer blends and improve their processability. Many plasticizers typically do not have covalent bounds with the polymers and therefore may leach, resulting in potential human exposure and environmental contamination (Jamarani *et al.* 2018).[xiv] Several phthalates used as plasticizers are causing concern due to their leaching from products, potential health effects (e.g. endocrine disruption), and ubiquity in the environment (Benjamin *et al.* 2017).[xv]

Innovation to advance sustainability of plasticizers include the design of plasticizers with low migration level, low volatility, no adverse health effects, and good biodegradability. Alky diol dibenzoate compounds, for example, provide many of the functions of DEHP, a current plasticizer of concern. According to Erythropel (2018), they degrade rapidly in soil and have, a low toxicity profile.[xvi]

Like other functional molecules, plasticizers can also 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).[xvii] However, despite the potential of bio-based plasticizers to advance green and sustainable chemistry objectives, their toxicity and impact need to be further researched (Harmon and Otter 2017).[xviii] Since bio-based does not necessarily mean non-toxic, generating more complete knowledge about the potential hazards of bio-based plasticizers would provide a better understanding about potential sustainability opportunities and trade-offs.

Figure 4.4: Overview on the biopolymers and their natural origin (Bocque *et al.* 2015) [xix]



Solvents

Solvents have the function to dissolve a solid, liquid, or gaseous solute. While water is the most well-known solvent, many solvents are organic chemicals, including alcohols, ethyl ether, hexane, tetrachloroethane, toluene, or xylene. They are used, for example, as stripping agents, in extraction processes, as degreasing agents, or additives and diluting compounds. Many organic solvents have hazardous properties and are released to the environment in significant quantities. In particular, the manufacturing of pharmaceutical drugs, as well as crop protection formulations are known to produce large amount of solvents, in comparison to the active ingredients of main interests. Possible health effects of solvents include irritation of the skin, eyes and lungs, headache, nausea, dizziness and light-headedness, while high exposure can cause unconsciousness and even death (HSE n.d).[xx]

To address the adverse effects and impact of solvents, the development of green and more substantiable solvents, including through renewable feedstocks, has received significant attention (Freire and Countinho 2019;[xxi] Sheldon 2019).[xxii] Examples of relevant innovation areas include: development of non-toxic solvents; use of water as a solvent in the production of pharmaceuticals and other chemicals (to replace organic solvents); or designing materials so that they do not require solvents at all (e.g. a new building materials not requiring paints and coatings (van der Waals *et al.* 2018)).[xxiii]

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 bio-accumulate in living organisms, creating opportunities for green and sustainable chemistry (UNEP 2019).

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 brings 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).[xxiv]

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 bio sources have a significant potential. Advantages cited include they tend to be low cost, are generally non-toxic, 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 *et al.* 2018a).[xxv] 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 epoxy resin, a polymer used in electronics, automobiles and aircraft (Howell *et al.* 2018 b).[xxvi] Another promising area of innovation is the development of novel bio-based flame-retardant systems from tannic acid (Laoutid *et al.* 2018). [xxvii]

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 2018).[xxviii]

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 (Cosmetics Special 2015).[xxix] Often, more ecofriendly surfactant molecules are derived from renewable biomass building blocks (Bhandani *et al.* 2020). The surfactant algal betaine, for example, is made through controlled fermentation from renewable microalgae (Business Wire 2015).[xxx] It is used in products that need foams, such as shampoos, liquid soaps, or hand dishwashing liquids.

Further innovation opportunities exist through modifying technologies and microbial strain improvement methods (Kandasami 2019).[xxxi] A new surfactant recently developed through biotech methods consists of well-known sophorolipids. It shows good cleaning properties, is gentle on the skin, and rapidly biodegrade after use (Bhadani *et al.* 2020).[xxxii]

Chemical preservatives

Chemicals preservatives are chemicals added to products to prevent decay of the product by microbial growth or unwanted chemical changes. They are widely used in food products, beverages, pharmaceutical drugs, paints, cosmetics, wood, etc. They are also part of a range of cleaning products and detergents used directly by consumers in a closed/indoor environment. Preservatives may have potential adverse on human health and the environment. For example, some parabens, i.e. butylparaben and propyl paraben, were characterized to have potential endocrine effects and oestrogenic properties (EU 2011).[xxxiii] Formaldehyde and formaldehyde-releasing preservatives used in shampoos and liquid baby soaps are of concern because of their carcinogenic and allergic properties (van der Waals 2018).

Given direct contact of many chemical preservatives with the human body, chemistry innovation to develop safer chemical preservatives is important. However, since chemical preservatives are inherently antimicrobial, finding completely non-toxic chemical preservatives is unlikely. Efforts therefore 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 2017).[xxxiv] 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).

Box 4.2: Green and sustainable chemistry in agriculture[xxxv]

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 2019). Green and sustainable chemistry therefore has an important role to place in advancing the sustainability of agriculture.

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.

4.3 Process innovation opportunities

4.3.1 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 help ensure that a specific chemical reaction requires less energy (e.g. heat) and that the raw material is used more effectively. In most cases, only small amounts of catalyst are required to alter the reaction rate.

Traditionally, chemists have used rare transition-metal catalysts based on palladium, rhodium, ruthenium, and iridium for organic transformations. 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

Abundant earth metals, such as manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), vanadium, or chrome have a potential to enhance sustainable use of catalysts in chemicals reaction. This has led to research efforts towards the development of homogeneous catalysts based on earth-abundant, low-toxicity metal complexes. Complexes based on the first-row metals Fe, Co, Ni and Mn are particularly appealing (Chakraborty *et al.* 2016). [xxxvi]

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 2020).[xxxvii] 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).[xxxviii] 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. [xxxix]

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.[xl] Organocatalysts may be produced from waste, thereby satisfying the principles of a green and more sustainable chemistry (Meninno. 2020).[xli] Advantages are their ready 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 (Liuab Chen 2014).[xlii]

Bio-catalysis

Bio-catalysis uses enzymes for reactions under mild conditions, e.g. ambient temperature, which requires little energy. Other advantages include that enzymes are non-hazardous, non-toxic and biodegradable. The catalytic properties of enzymes allow developing new technologies, such as the production of chiral molecules, speciality chemicals, and commodity chemicals. Enzymes are produced from inexpensive renewable resources and the 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 to access a broad range of wild-type enzymes (Sheldon 2018).[xliii] 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 *et al.* 2019) [xliv]

Figure 4.5: Scope of Biocatalysis in Sustainable Organic Synthesis (Sheldon and Brady 2019) [xlv]

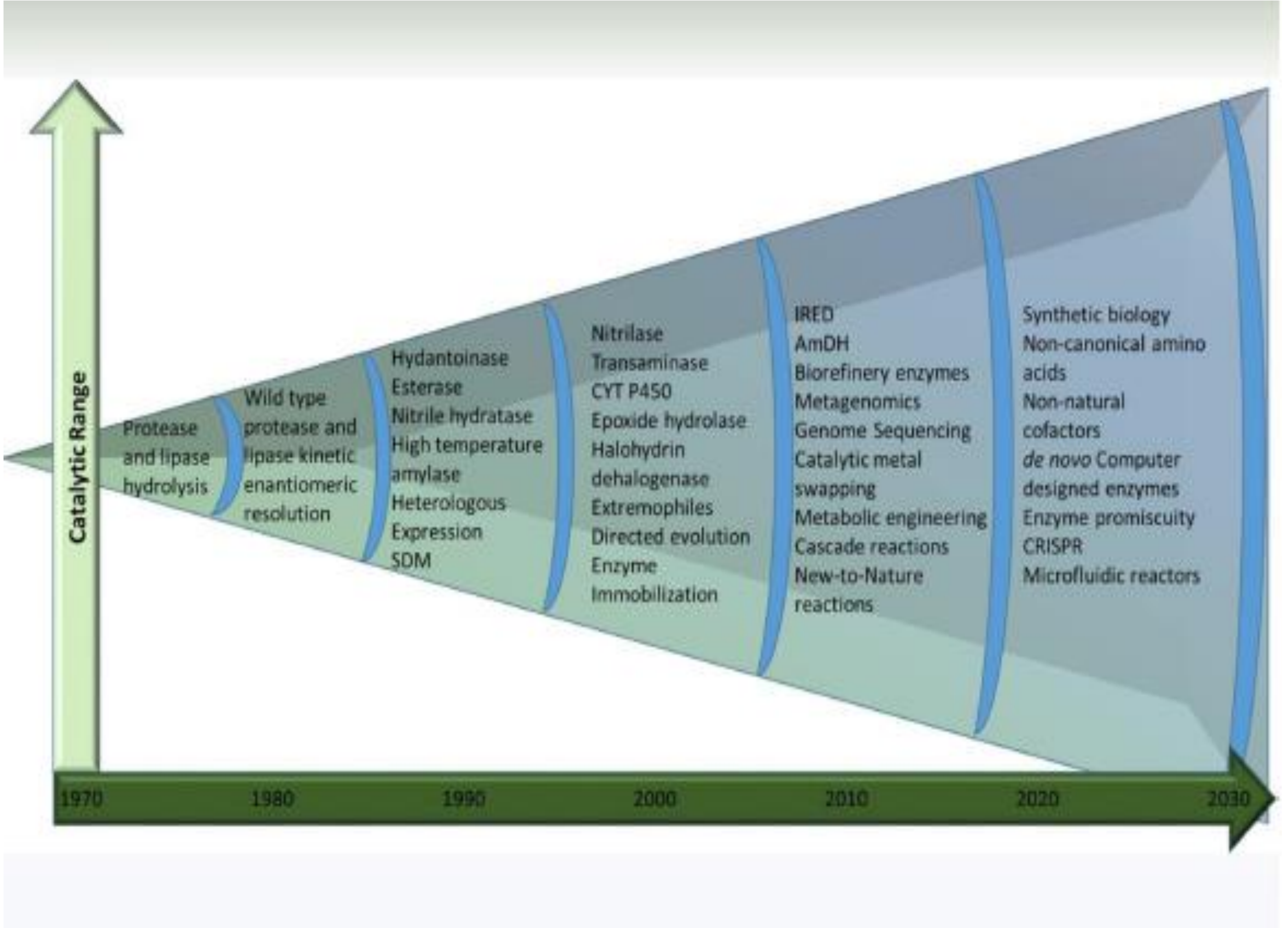


Photo-catalysis

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 catalysis, such as TiO2, as the 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.2009).[xlvi] 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.

4.3.2 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 GAO (2018) continuous processing uses materials more efficiently than batch processing, has lower energy consumption, less waste production, less consumption of solvents, safer processes, and less exposure to chemicals. The technology can therefore meet many of the 12 Principles of Green Chemistry (GAO 2018).[xlvii]

4.3.3 Biorefineries (ACS)

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, and value-added chemicals from biomass. The 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) (IEA 2014). [xlviii]. Biorefineries can develop multiple chemicals by fractioning biomass into intermediates (carbohydrates, proteins, triglycerides) that can be further converted into value-added products.

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

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

Innovation areas and examples to use biorefineries to advance green and sustainable chemistry include (Wageningen University n.d.):[l]

- Fermentation of glucose to succinic acid replacing petroleum feedstock and using 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 CO2 as energy and carbon sources to produce high-quality oils and biodiesel, among other products

4.4 Green and sustainable chemical innovation: The case of the energy sector

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 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. At the same time, chemistry innovation has a significant potential to increase energy efficiency and reduce greenhouse gas emissions through the development of novel products and materials.

Enhancing energy efficiency through chemistry innovation

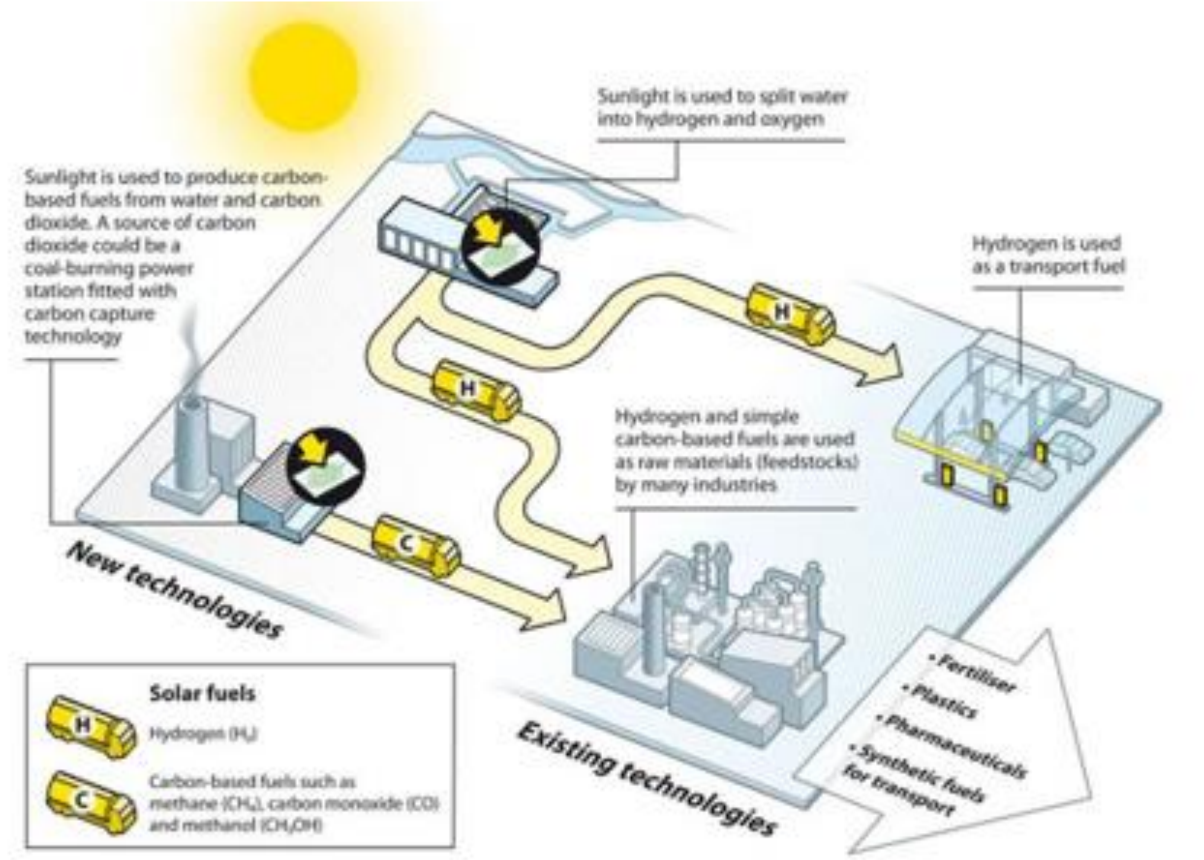
Chemistry innovation plays a key role in developing advanced materials that can advance energy efficiency. Examples are lightweight and recyclable composite materials contribute to reduced energy consumption because of their reduced weight. Their applications are manifold and include mobility (airplanes, cars), energy generation through windmills, etc. Another area of application is 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. 2019).[li] The green and sustainable chemistry challenge is not only to develop high-performing materials but also ensuring they are non-toxic and recyclable. Therefore, “green materials” promoted for their energy saving potential need to be screened for broader green and sustainability chemistry criteria, before considered to be 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 consists in 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 n.d.).[lii]

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).[liii]

Figure 4.6: What could the production of solar fuels look like (Royal Society of Chemistry n.d) [liv]



Innovation areas to convert sun radiation and CO_2 into valuable organic molecules include: photocatalytic water splitting converting water into hydrogen and oxygen, a major research topic in artificial photosynthesis; light-driven carbon dioxide absorption hat 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 microbial biofuel and biohydrogen production from sunlight.

Improving photo-voltaic energy generation through chemistry innovation

Chemistry innovation also plays a role in advancing solar photovoltaics. Organic and dye-sensitised solar photovoltaic technologies offer the possibility of lightweight, flexible, coloured and inexpensive solar panels. New materials for solar shingles 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 (SusChem 2019).[lv]

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. 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 (PF^{6-}, TFSI$^-$, FSI$^-$) which are less toxic than their lithium counterparts (Larcher and Tarascon 2015).[lvi]

5 Enabling instruments and policies to advance green and sustainable chemistry

5.1 Policies, regulatory action and standard setting

Government policies to stimulate substitution and green and sustainable chemistry innovation

Identifying chemicals of concern and setting explicit limits on selected uses and substitution goals by public authorities can be a strong driver for voluntary frontrunner innovation action. 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 convey the intention of the regulator to take risk management action (ECHA 2011). Hoffman- La Roche, for example, implemented a substitution action programme to comply with REACH in advance of regulatory timelines by evaluating and testing alternatives (Buxton 2016).

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.[lvii]lviii

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.[lix] 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.

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 the display of ingredients, for example, 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.

New information tools, such as smartphone apps that link to regulatory initiatives and consumer report publications are valuable tools to bring information to consumers., The apps ToxFox and AskReach, for example, draws attention to chemicals on the REACH candidate list, helping users to make informed decisions and creating demand for sustainable products. Enabling policies, such as right-to-know for workers, consumers and communities, public participation, and access to justice, coupled with innovative technologies, can therefore be driving forces to advance green and sustainable chemistry.

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

5.2 Life cycle assessment and sustainable design approaches

Life cycle assessment

Life cycle assessment (LCA) is defined by 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). The closely related method of social life cycle assessment (SLCA) is relevant for assessing human health impacts (Arvidsson *et al.* 2018)[lx]. With this, life cycle assessment methods can be a valuable tool to evaluate solutions and alternatives that can drive green and sustainable chemistry.

Assessing and managing chemicals along entire chemical and product life cycles also allows to benchmark environmental performance of products against pollution and exposure reduction targets (Fantke and Illner 2019). LCA 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). At the same time, life cycle assessment also has its limitations, e.g. an LCA does not necessary reveal the extent a product is designed for recyclability. Sometimes, a lack of alignment between the methodologies of different LCA studies make a comparison of results challenging. Aa more holistic approach that also includes qualitative analysis may help to spot potential trade-offs across 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 n.d).[lxi] 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 knowledge is relevant for sustainable product design informed by green and sustainable chemistry considerations. It is also important for minimizing potential future chemical releases from material stocks and products, and for generating safe and sustainable secondary raw materials in a circular economy. Sustainable packing is an example of an important area where sustainable material management is relevant that embraces the use of non-toxic materials developed through green and sustainable chemistry innovation. [lxii]

Design Thinking and sustainable product design

Design Thinking is an approach to solve complex problems, including sustainability challenges (Buhl *et al.* 2019)[lxiii] 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 consideration 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 address, amongst others, harmful chemicals in sectors including electronics, and IT, textiles, furniture, steel, and cement.lxiv

Sustainable supply chain management and procurement

Sustainable supply chain management plays a key role in ensuring that purchasing and procurement decisions comply with sustainability criteria. 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.[lxv] Sustainable supply chain management thus creates a force for upstream suppliers to participate in growing markets for sustainable products.

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, creating cost savings, profitability, and advancing 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.[lxvi]

5.3 Knowledge-sharing and award programs

Public and private knowledge sharing is an essential instrument to ensure that knowledge in the public domain is shared widely and in an organized way. Scaling-up knowledge management platforms, at different levels, has the potential to support public and private sectors stakeholders in the advancement of green and sustainable chemistry. Government to government information exchanges on green and sustainable chemistry could help create cooperation, resolve issues, and may lead toward harmonized approaches and practices. Knowledge on chemicals, sustainable innovative solutions, products and alternatives could be shared, as well as knowledge on best practices, policies and enabling conditions and their impact. From an international perspective, developing countries could benefit from a more fluid and organized flow of information that is adapted toward their green and sustainable chemistry needs.

Award programs provide important and credible recognition to green and sustainable chemistry innovations, when expert judgement is used during the selection process. 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.[lxvii] 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.[lxviii] The ISC3 Innovation Challenge, launched in 2018, calls for applications by start-ups pioneering in thematic sustainable chemistry topics that change annually.[lxix] Finally, featuring promising research initiatives in scientific journals that have open access can foster their recognition.

5.4 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).[lxx] 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 and 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 have a responsibility to act.[lxxi] 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, including through green and sustainable chemistry innovation.

Extended producer responsibility

Extended producer responsibility (EPR) is a voluntary policy approach which requires producers to take responsibility for a product during sub-sequent stages of the value chain, including disposal. Responsibilities may be financial and/or physical. They create incentives for innovative business models that prevent wastes at the source and promote sustainable and non-toxic product design needed for a circular economy. EPR is particularly relevant to new product development as well as for product groups and waste streams, such as electrical appliances and electronics.[lxxii] For example, consumer safety concerns triggered proactive action by Coop Denmark to commission innovation research by a supplier to replace certain fluorinated chemicals in food packaging products with a (non-chemical) sustainable alternative (Green Science Policy Institute 2013).

Extended consumer responsibility

The related concept of “Extended consumer responsibility” seeks to emphasize the importance of consumer behavior, which can shape the market through their choice, for instance by embracing trade-in-for upgrade (TIFU) programs in the consumer electronics markets (Sheu and Choi 2019). [lxxiii] Such TIFU type of business model targets consumers to upgrade their old devices and contributes to shaping more sustainable consumption patterns and decreasing waste generation. As consumers are offered and take up these opportunities, it may influence and further motivate private sector actors to design more sustainable and circular business models.

Corporate and social responsibility

Corporate Social Responsibility (CSR) is a concept used by companies to integrate social and environmental consideration into business operations and interactions with their stakeholders. It aims at helping companies to achieve a balance of economic, environmental and social imperatives ("Triple-Bottom-Line-Approach") which have become of interest for shareholders and stakeholders.[lxxiv] Corporate Social Responsibility policies at the company may include 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 (UNEP 2019) (Temper *et al.* 2018; Woo *et al.* 2018) (Johnston and Cushing 2020).[lxxv] 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 [ILO] 2000). [lxxvi]

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.

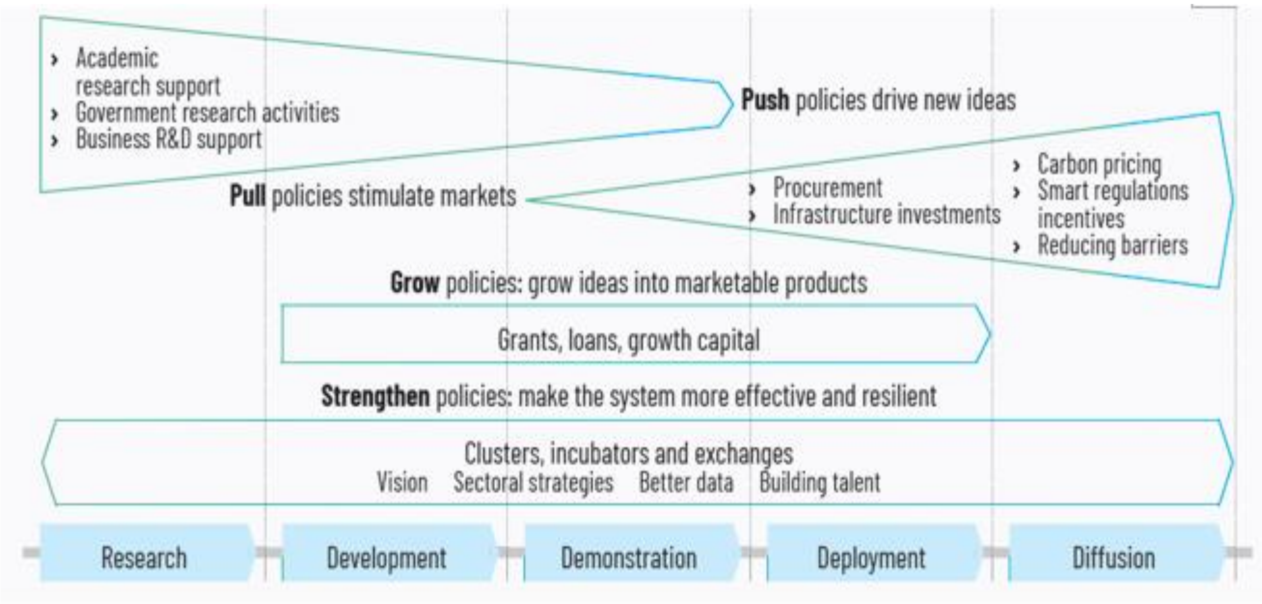
For a detailed discussion of this topic, pleases refer to GCO-II, Part IV, Chapter 8.

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.[lxxvii]

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



5.5 Corporate sustainability governance

A growing number of retailers, product manufacturers and chemical companies include sustainability objectives, sustainable supply chain management, and extended producer responsibility in their corporate governance frameworks. Corporate sustainability measures of particular relevance for advancing green and sustainable chemistry innovation include: scaling up voluntary standard-setting 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 sustainability of products throughout their life cycle; and scaling up 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.

6 Enabling sectors and programmes to advance green and sustainable chemistry

6.1 Green and sustainable chemistry education

Scaling-up chemistry research, innovation and product development that integrates social, economic and environmental considerations requires a new generation of chemists capacitated to do so. Furthermore, a range of stakeholders need to be educated on green and sustainable chemistry through formal, informal and non-formal education, creating an opportunity to prepare specialized guidance on how this could be achieved.

Measures to educate a future chemist through formal education includes integrating toxicology, green chemistry, sustainable chemistry and relevant topics of the 2030 Agenda for Sustainable Development in curricula at all levels, i.e. primary, secondary and tertiary education and professional education. The Indian Ministry of Education, for example, is piloting a programme in which all chemists take a one-year course in green chemistry (UNEP 2019). Such efforts may serve as an inspiration to scale up efforts in other countries. 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 a global awareness and capacities on green chemistry worldwide which makes available materials for free. Pilot activities have been conducted in Brazil, Colombia, Egypt Serbia, South Africa, and Sri Lanka.[lxxviii]

An increasing number of relevant educational tools and materials on green and sustainable chemistry are available for use at primary, secondary, tertiary and professional levels. Further action is needed 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.

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

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

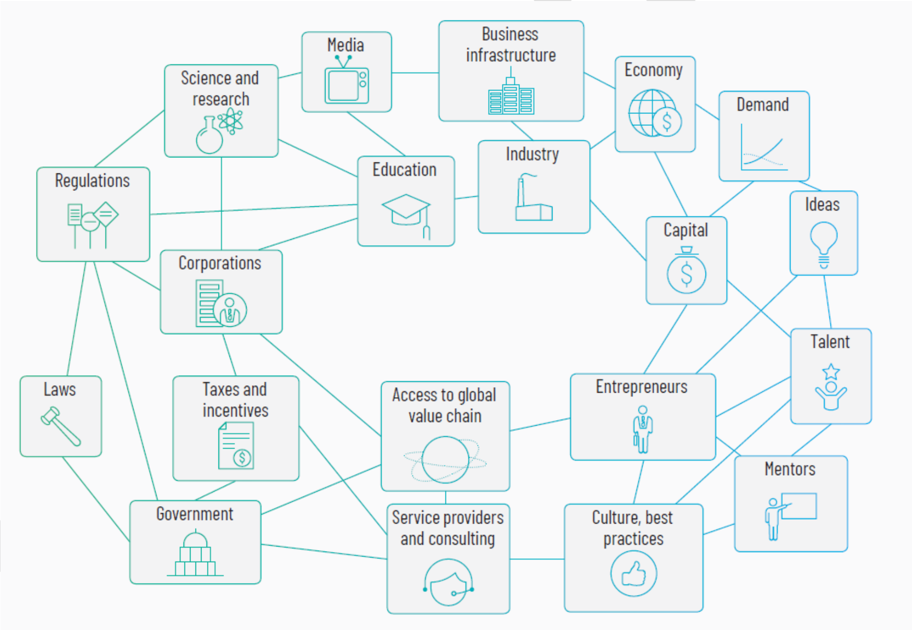
For a detailed discussion on this topic, pleases refer to GCO-II, Part IV, Chapter 2.

6.2 Green and sustainable chemistry research and innovation

6.2.1 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.

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



Universities

Universities traditionally have focused on teaching and research but are increasingly engaging in entrepreneurial and business activities (Etzkowitz *et al.* 2008). This mean that they become problem-solvers, inventors and entrepreneurs (EC and OECD 2012). With this, they become important stakeholders in the innovation landscape of green and sustainable chemistry. Examples of relevant university activities include patenting or licensing of innovations as well as the establishing start-up support systems, including spin-off venture formation (Klofsten and Jones-Evans 2000). Training young researchers is key to ensure the feasibility of these start-ups in the long term. To overcome current constraints in curricula to generate conditions that favor the development of new businesses, creating linkages between research groups, curricula, and the industry are key elements to nurture the development of green chemistry-oriented ventures (Ocampo-López *et al.* 2019). [lxxix]

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 2017).

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 consideration and using these 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.[lxxx] SMEs are particularly responsive to eco-innovation due to their adaptability and flexibility and are potentially a key driver of a resource efficient economy (UNEP 2014). Since many SMEs face resource constraints, in particular for research and innovation, supporting measures as those suggested for start-ups are important to advance their engagement 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, 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 high costs of research and innovation, collaboration between industry and academia is growing. Over the past years, important chemistry innovations have been co-invented or developed, such as heterogeneous catalysis, the synthesis of monomers 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 2019).

Government

Governments play an important enabling role in fostering chemistry innovation, helping to correct market failures to produce innovation (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). Broader enabling strategies include development of national industrial policies or programmes that foster green and sustainable chemistry innovation. These functions 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, for example, has invested more than $16 million to help establish GreenCentre, which support innovations in green chemistry to support sustainable, prosperous, and healthy communities, high-quality jobs, and better lives for all Ontarians.[lxxxi]

Other important actors

NGOs and the general public usually do not conduct chemistry research, yet the 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 also play a key role in helping to hold companies accountable for their actions and are increasingly utilizing market-based campaigns in conjunction with regulatory action to drive green and sustainable chemistry innovation.

6.2.2 Conducive measures and considerations

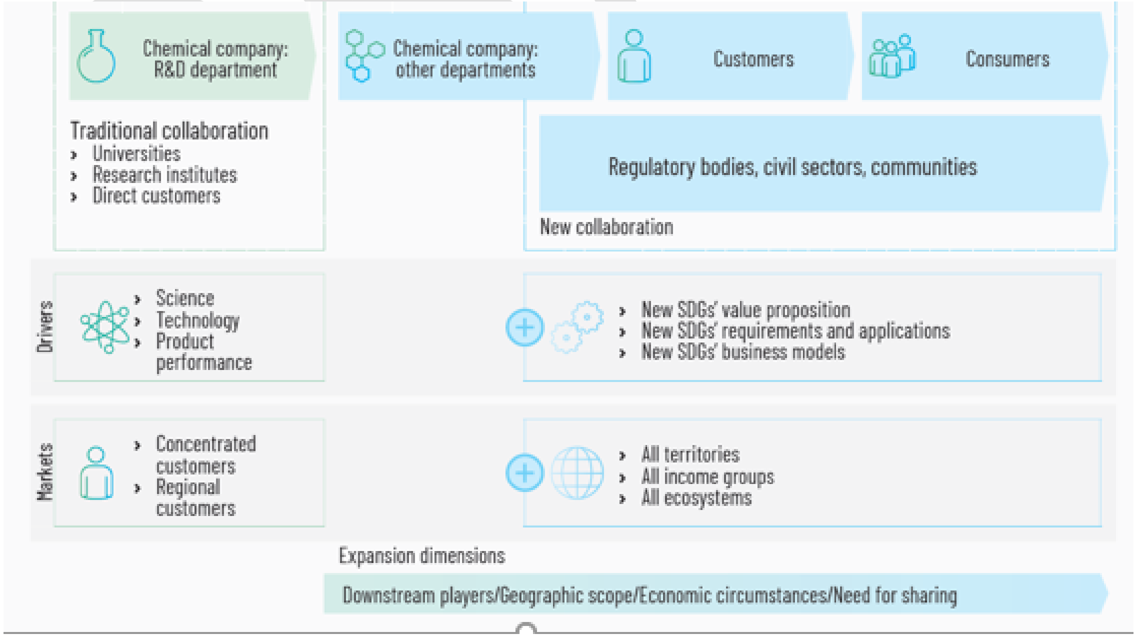
Linking research to development needs

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. The European Technology Platform for Sustainable Chemistry (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 2020). 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 in 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 between chemical companies and external entities, such as customers and consumers, regulators and civil society organizations. 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.

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



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

6.3 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 use charges to speed up the phasing out of substances of very high concern.

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)

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 [EY] 2016), their potential to advance sustainable chemistry investment and innovation could also be explored.

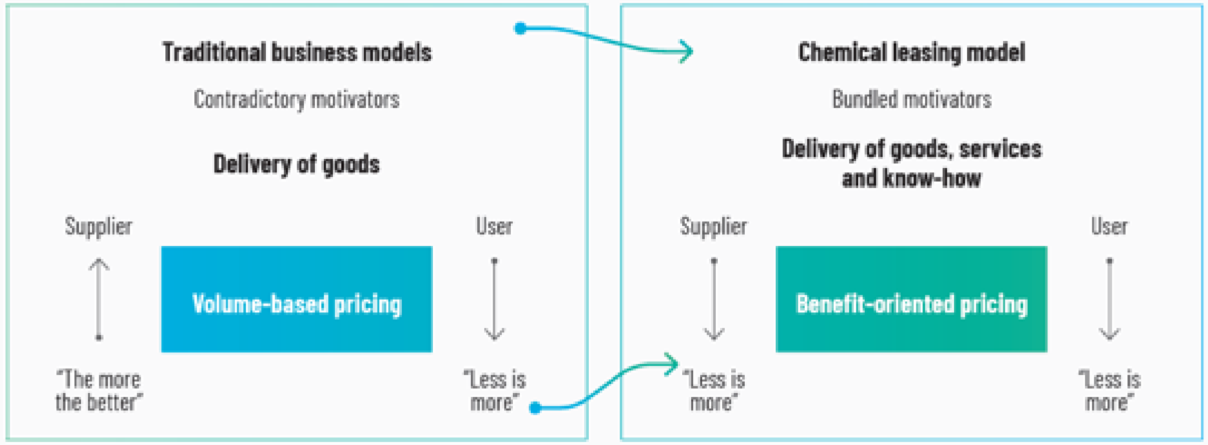
Sustainable business models

Business models with a strong focus on sustainability and circularity require a company to re-think its products and processes in order 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, and as a result, 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. 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.

Figure 6.3: Traditional business models vs. Chemical Leasing (adapted from Joas, Abraham and Joas 2018, p. 398)



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

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 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; and persistence in environmental media (UNEP 2019). 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. The much-used GreenScreen®, for example, is a recognized tool that identifies hazardous chemicals and safer alternatives (GreenScreen 2020). An overview and review of relevant tools is provide in Gauthier *et al.* (2014) and Panko *et al.* (2017).

E-factor

The "E-factor" is a metrics which allows to calculate the ratio of waste generated per weight unit of product (Sheldon 2017).[lxxxii] 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 environmentally benign is a process is. 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.

Table 7.1: Resource efficiency in the chemical industry: ratio of products and waste generated (Sheldon 2017, p. 19)

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

Process Mass Intensity (PMI)

The process mass intensity (PMI) 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)[lxxxiii].

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. The metrics has been developed and is used in the Chemical Foot Print 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).

7.2 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. They usually contain a range of criteria and indictors but have to date not yet systematically integrated chemical specific issues (UNEP 2019).

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 and grow the contribution of the chemical industry into a sustainable development. At the center of these measures is a variety of information and support services designed to put in practice 12 Sustainability Guidelines for the Chemical Industry in Germany into business practice and measure its implementation.[lxxxiv]

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.

A further area of exploration is how overarching sustainability frameworks, such as the Framework for Strategic Sustainable Development (Broman and Robèrt 2015), could be applied to the domain of chemicals, materials and product life cycles.[lxxxv] 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 (Natural Step, n.d).[lxxxvi]

Box 7.1: NSI/ACS Greener Chemical Products & Processes Standards

The Greener Chemical Products and Processes Greener Chemical Products and Processes 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.

Self-assessment and reporting are also advancing in downstream sectors, such as under the ZDHC initiative, where compliance rates are being made publicly available. 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.

8 Developing green and sustainable chemistry stakeholder road maps

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 *et al.* 2004).[lxxxvii] 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. They have, for example, been a powerful instrument to drive innovation in the semiconductor industry (Voorhees and Hutchison 2015).[lxxxviii]

Road maps in the chemical sector

The road map approach has been used by several actors in the chemical sector to advance action to achieve the sound management of chemicals and waste. Under the auspices of the World Business Council for Sustainable Development, for example, chemical companies and industry associations have developed a roadmap exploring how the chemical sector can contribute to achieving various SDGs and targets (WBCSD 2017).[lxxxix] The WHO Chemical Road Map, adopted in May 2017 by the World Health Assembly, identifies 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.[xc] 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 2019).

Figure 8.1: Chemical Sector Road Map (WBCSD 2017)

Opportunities to develop Green and Sustainable Chemistry Road Maps

Consistent with the suggestion made by GCO-II, 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. 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.

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

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;
- 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 approaches throughout the value chain and set innovations targets for replacing chemicals of concerns; or
- civil society organizations could assist in bringing knowledge to consumer to help create demand for green and sustainable chemicals and products.

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)[xci]. 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):[xcii]

- 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?

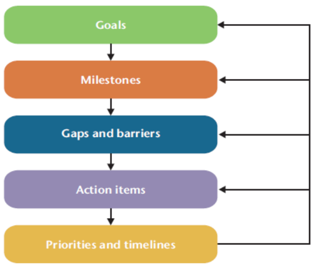
Box 8.1: Developing a roadmap across a value chain: The example of VinylPlus[xciii]

One approach of developing a road map is to take a value chain approach that builds around a specific material and its diverse applications. An example of this is the European PVC industry and its voluntary sustainability commitment VinylPlus. Faced with serious stakeholder pressures in the late 1990’s, the European PVC industry launched a first voluntary commitment (2001-2010). While this was largely seen as a defensive strategy, an achievement at the time was to bring key actors across the value chain together. These actors ranged from converters who make and sell PVC products in many different sectors, all the way up the chain to additive manufacturers and resin producers.

When a second voluntary commitment was proposed for the period 2010-2020, through consultation, capacity building and systems analysis of PVC sustainability issues, a new, more holistic set of challenges, commitments and targets were set. The basis for this was a gap analysis defining what problems need to be solved for the industry to move toward alignment with principles of sustainability (system conditions). This has allowed the PVC industry to address issues such as closing the loop with a dedicated recycling network; optimizing additive formulations with circularity in mind; addressing emissions; evaluating options for more sustainable energy and feedstock alternatives, and building sustainability awareness across the industry. A third voluntary commitment is now under development with a focus on leveraging achievements, setting more ambitious targets including global application.

Developing a technology road map: Methodological considerations

Figure 8.3: Logic of a road map process (IEA 2014)



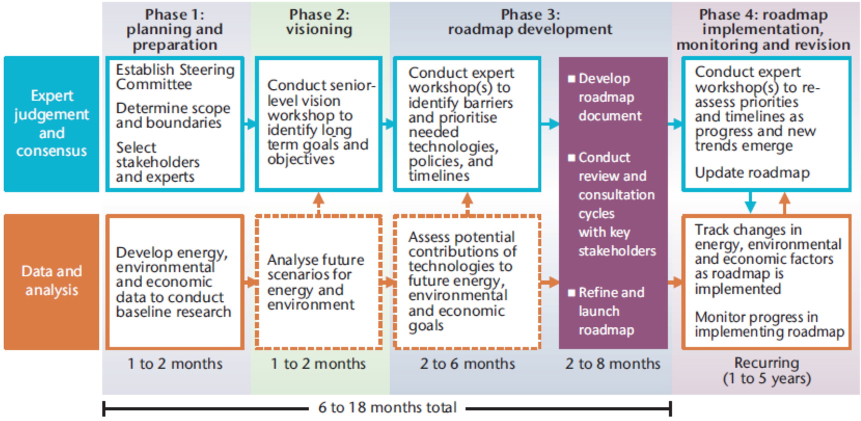
A range of methodological approaches exist to support the development of technology innovation road maps. Following a review of various road map approaches and considering that the energy and chemical sector both face strategic sustainability and technology challenges, guidance developed by International 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).[xciv] 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.

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?
- What is the time frame for developing the road map?
- What technology opportunities are under consideration?
- How will the leading organization use and implement and use 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 may want to consider and adapt this guidance, as appropriate.

Figure 8.4: Process for developing an energy technology road map (IEA 2014)

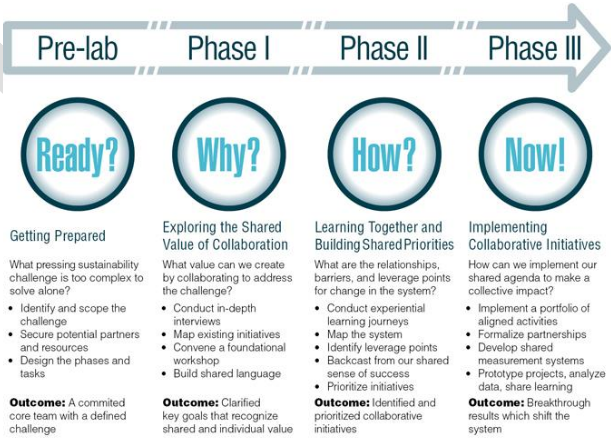


Note: dotted lines indicate optional steps, based on analysis capabilities and resources.

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 and stakeholders in addressing a complex issue (McCrory *et al.* 2020). [xcv] 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. [xcvi]

Figure 8.5: Natural Step "Sustainability Transition Lab"s[xcvii]



Getting Prepared

What pressing sustainability challenge is too complex to solve alone?

- Identify and scope the challenge
- Secure potential partners and resources
- Design the phases and tasks

Outcome: A commited core team with a defined challenge

Exploring the Shared Value of Collaboration

What value can we create by collaborating to address the challenge?

- Conduct in-depth interviews
- Map existing initiatives
- Convene a foundational workshop
- Build shared language

Outcome: Clarified key goals that recognize shared and individual value

Learning Together and Building Shared Priorities

What are the relationships, barriers, and leverage points for change in the system?

- Conduct experiential learning journeys
- Map the system
- Identify leverage points
- Backcast from our shared sense of success
- Prioritize initiatives

Outcome: Identified and prioritized collaborative initiatives

Implementing Collaborative Initiatives

How can we implement our shared agenda to make a collective impact?

- Implement a portfolio of aligned activities
- Formalize partnerships
- Develop shared measurement systems
- Prototype projects, analyze data, share learning

Outcome: Breakthrough results which shift the system

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. What is lacking and needed is leadership at all levels to reap the full potential of green and sustainable chemistry. All actors and decision-makers, from public officials, to company CEOs, to 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 will be pleased to learn about relevant initiatives, facilitate knowledge sharing across countries and stakeholders, and explore opportunities for capacity development. Beyond, at international and at national/regional levels, leading stakeholders such as governments, 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 transition countries.

Together, we make green and sustainable chemistry a reality!

References

American Chemical Society (2015). *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.

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

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

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

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

Bernick, L. (2016). The $100 billion business case for safer chemistry, 6 May. *Greenbiz*. https://www.greenbiz.com/article/100-billion-business-case-safer-chemistry. Accessed 24 June 2020.

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.

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.

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

de Wit, M., Verstraeten-Jochemsen, J., Hoogzaad, J. and Kubbinga, B. (2019). *The Circularity Gap Report 2019*. Amsterdam: Circle Economy. https://www.circularnorway.no/wp-content/uploads/2019/01/ad6e59_ce56b655bcdc4f67ad7b5ceb5d59f45c.pdf.

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

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

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 Comminities* L(257), 26-40. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.1996.257.01.0026.01.ENG&toc=OJ:L:1996:257:TOC.

European Commission 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.

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.

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.

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.

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

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.

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.

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.

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.

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.

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

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

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.

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.

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.

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

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

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

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.

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.

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.

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

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.

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

SusChem (2020). *Strategic Innovation and Research Agenda*. http://www.suschem.org/publications.

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 (2019). *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 Industrial Development Organization (2017). *Industrial Development Report 2018. Demand for Manufacturing: Driving Inclusive and Sustainable Industrial Development*. https://www.unido.org/news/industrial-development-report-2018-launched.

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

Van Hamelen, E. (2018). *Without Chemistry There Can Be No Circular Economy: The Imperative of a New Perspective on Chemicals and Materials Management.* Planegg: The Natural Step. https://thenaturalstep.org/wp-content/uploads/2018/05/20180508- Circular-chemistry-EN-BioEDIT-TNSinternational.pdf.

Waerder, B., Stinnes, S. and Erdenberger, O. (2017). Design thinking as driver for innovation in the chemical industry. *Journal of Business Chemistry* 14(2), 41-50. http://www.businesschemistry.org/article/?article=247.

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

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/.

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.

---

[i] https://www.acs.org/content/acs/en/greenchemistry/principles/12-principles-of-green-chemistry.html

[ii] https://www.isc3.org/en/activities/collaboration.html

[iii] https://science.sciencemag.org/content/367/6476/397.abstract

[iii] https://www.umweltbundesamt.de/en/publikationen/identification-of-priority-topics-in-the-field-of

[iv] https://www.gcande.org/

[v] https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference

[vi] Kohli *et al.* 2019. Based Chemicals from Renewable Biomass for Integrated Biorefineries https://www.mdpi.com/1996-1073/12/2/233

[vii] https://www.wur.nl/en/Research-Results/Research-Institutes/food-biobased-research/Research-themes/Biorefinery.htm

[viii] Zimmerman *et al.* 2020. Are bioplastics and plant-based materials safer than conventional plastics? In vitro toxicity and chemical composition

https://www.sciencedirect.com/science/article/pii/S0160412020320213?via%3Dihub

[ix] https://www.iea.org/reports/putting-co2-to-use

[x] https://www.semanticscholar.org/paper/Carbon-Capture-and-Utilisation-in-the-green-economy-Coninck-ECN/5d2c7d791478526465b2d5dd68d7962414b34526

[xi] Karan *et al.* 2019. Green Bioplastics as Part of a Circular Bioeconomy https://www.sciencedirect.com/science/article/abs/pii/S1360138518302723

[xii] http://wedocs.unep.org/handle/20.500.11822/7468

[xiii] Bocque *et al.*2015. Petro-Based and Bio-Based Plasticizers: Chemical Structures to Plasticizing Properties https://onlinelibrary.wiley.com/doi/full/10.1002/pola.27917

[xiv] Jamarani *et al.* 2018. https://www.mdpi.com/2073-4360/10/8/834

[xv] Benjamin *et al.* 2017. Phthalates impact human health: Epidemiological evidences and plausible mechanism of action https://www.sciencedirect.com/science/article/abs/pii/S0304389417304570

[xvi] Erythropel. 2018. Designing Green Plasticizers: Linear Alkyl Diol Dibenzoate Plasticizers and a Thermally Reversible Plasticizer https://www.mdpi.com/2073-4360/10/6/646

[xvii] Bocque *et al.*2015. Petro-Based and Bio-Based Plasticizers: Chemical Structures to Plasticizing Properties https://onlinelibrary.wiley.com/doi/full/10.1002/pola.27917

[xviii] Harmon and Otter. 2017. Green chemistry and the search for new plasticizers https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.7b03508

[xix] Bocque *et al.*2015. Petro-Based and Bio-Based Plasticizers: Chemical Structures to Plasticizing Properties https://onlinelibrary.wiley.com/doi/full/10.1002/pola.27917

[xx] HSE Solvent Construction Information Sheet No 27 (revision 2) https://www.hse.gov.uk/pUbns/cis27.pdf

[xxi] Freire and Coutinho. 2019. A closer look on sustainable solvents and processes https://www.sciencedirect.com/science/article/abs/pii/S2452223619300355?via%3Dihub

[xxii] Sheldon. 2019. The greening of solvents: Towards sustainable organic synthesis https://www.sciencedirect.com/science/article/abs/pii/S2452223618301172

[xxiii] Van der Vaals *et al.* 2018. Safe Chemicals Innovation Agenda. The Netherlands Ministry of Infrastructure an Development and Wood Environment and Infrastructure Solution

https://www.chemischestoffengoedgeregeld.nl/sites/default/files/39982%20-%20Safe%20Chemicals%20Innovation%20Agenda%20-%2020180613i6%20final%20copy.pdf

[xxiv] https://www.inno4sd.net/chromatogeny-green-chemistry-to-make-paper-water-repellent-246

[xxv] Howell et al 2018a. Flame Retardants from Renewable Sources: Food Waste, Plant Oils, and Starch

https://pubs.acs.org/doi/pdf/10.1021/bk-2018-1310.ch025

[xxvi] Howell et al 2018b. Phosphorus Flame Retardants for Polymeric Materials from Gallic Acid and Other Naturally Occurring Multihydroxybenzoic Acids https://www.hindawi.com/journals/ijps/2018/7237236/

[xxvii] Laoutid et al (2018) Novel Bio-based Flame Retardant Systems Derived fromTannic Acid

https://www.ingentaconnect.com/content/tsp/jrm/2018/00000006/00000006/art00001?crawler=true&mimetype=application/pdf

[xxviii] Van der Vaals *et al.* 2018. Safe Chemicals Innovation Agenda. The Netherlands Ministry of Infrastructure an Development and Wood Environment and Infrastructure Solution

https://www.chemischestoffengoedgeregeld.nl/sites/default/files/39982%20-%20Safe%20Chemicals%20Innovation%20Agenda%20-%2020180613i6%20final%20copy.pdf

[xxix] https://cosmetics.specialchem.com/news/industry-news/organic-monitor-discusses-future-of-green-surfactants-emulsifiers-000177331

[xxx] https://www.businesswire.com/news/home/20150728005434/en/BASF-Solazyme-Launch-Commercial-Microalgae-Derived-Betaine-Surfactant

[xxxi] Kandasamy *et al.* 2019. Biobased Surfactants and Biosurfactants

https://pubs.acs.org/doi/abs/10.1021/bk-2019-1329.ch011

[xxxii] Bhadani *et al.* 2020.Current Perspective of Sustainable Surfactants Based on Renewable Building Blocks https://www.sciencedirect.com/science/article/pii/S1359029420300042

[xxxiii] EU.2011 Scientific Committee on Consumer Safety. Opinion on Parabens.

https://ec.europa.eu/health/scientific_committees/consumer_safety/docs/sccs_o_041.pdf

[xxxiv] Buckeley *et al.* 2017. Design and Testing of Safer, More Effective Preservatives for Consumer Products https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.7b00374

[xxxv] O'Brien et al (2009). Green Chemistry and Sustainable Agriculture: The Role of Biopesticideshttp://advancinggreenchemistry.org/wp-content/uploads/Green-Chem-and-Sus.-Ag.-the-Role-of-Biopesticides.pdf

[xxxvi] Chakraborty *et al.* 2015. Selective hydrogenation of nitriles to primary amines catalyzed by a novel iron complex https://pubs.rsc.org/en/content/articlelanding/2016/cc/c5cc08204h#!divAbstract

[xxxvii] https://www.gcande.org/

[xxxviii] Kaushik and Moores. 2017. New trends in sustainable nanocatalysis: Emerging use of earth abundant metals https://www.sciencedirect.com/science/article/abs/pii/S2452223617300469

[xxxix] https://www.cmu.edu/cmnews/extra/030911_saferliving.html

---

[xl] Maxime R Vitale, Sylvain Oudeyer, Vincent Levacher, Jean-Francois Briere.2017. Radical and Ion-pairing Strategies in Asymmetric Organocatalysis

[xli] Meninno. 2020. Valorization of Waste: Sustainable Organocatalysts from Renewable Resources https://chemistry-europe.onlinelibrary.wiley.com/doi/full/10.1002/cssc.202000007

[xlii] Liuab and Eugene. 2014. Organocatalysis in biorefining for biomass conversion and upgrading https://pubs.rsc.org/en/content/articlelanding/2014/gc/c3gc41934g#!divAbstract

[xliii]Sheldon.2018. Role of Biocatalysis in Sustainable Chemistry https://pubs.acs.org/doi/abs/10.1021/acs.chemrev.7b00203

[xliv] Kobayashi et al (2019) Enzymatic Polymerization towards Green Polymer Chemistry

https://www.springer.com/gp/book/9789811338120

Editors: Kobayashi, Shiro, Uyama, Hiroshi, Kadokawa, Jun-ichi (Eds.)

[xlv] Sheldon Brady. 2019. Broadening the Scope of Biocatalysis in Sustainable Organic Synthesis https://chemistry-europe.onlinelibrary.wiley.com/doi/abs/10.1002/cssc.201900351

[xlvi] Ravelli.2009. Photocatalysis. A multi-faceted concept for green chemistry

https://pubs.rsc.org/en/content/articlelanding/2009/cs/b714786b/unauth#!divAbstract

[xlvii]GAO.2018. Technologies to Make Processes and Products More Sustainable https://www.gao.gov/products/GAO-18-307

[xlviii] IEA.2014. IEA Bioenergy Task Force 42: Biorefining .https://www.ieabioenergy.com/wp-content/uploads/2014/09/IEA-Bioenergy-Task42-Biorefining-Brochure-SEP2014_LR.pdf

[xlix] Verster *et al.* 2014. Introducing the wastewater biorefinery concept

[l] https://www.wur.nl/en/Research-Re Introducing the wastewater biorefinery concept

sults/Themes/theme-biobased-economy.htm

[li] Kaya and Tabak. 2019. Recycling of an Agricultural Bio-waste as a Novel Cellulose Aerogel: A Green Chemistry Study

https://link.springer.com/article/10.1007/s10924-019-01609-6g

[lii] https://www.rsc.org/campaigning-outreach/global-challenges/energy/#solarfuels

[liii] https://www.sciencedaily.com/releases/2019/05/190522153121.htm

[liv] https://www.rsc.org/campaigning-outreach/global-challenges/energy/#solarfuels

[lv] SusChem. 2019. Strategic Innovation and Research Agenda Innovation Priorities for EU and Global Challenges

http://www.suschem.org/newsroom/suschem-identifies-key-technology-priorities-to-address-eu-and-global-challenges-in-its-new-strategic-research-and-innovation-agenda

[lvi] Larcher and Tarascon. 2015. Towards greener and more sustainable batteries for electrical energy storage https://www.nature.com/articles/nchem.2085

[lvii] EU.2019. European Green Deal. COM(2019) 640 final

[lviii] https://ec.europa.eu/environment/strategy/chemicals-strategy_en

[lix] https://www.congress.gov/bill/116th-congress/house-bill/2051

[lx] https://link.springer.com/article/10.1007/s11367-016-1116-7

[lxi] https://www.epa.gov/smm

[lxii] https://sustainablepackaging.org/

[lxiii] Buhl *et al.* 2019. Design thinking for sustainability: Why and how design thinking can foster sustainability-oriented innovation development

https://www.sciencedirect.com/science/article/pii/S0959652619317950

[lxiv] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative

[lxv] Handbook on the Sustainable Supply Chain edited by Joseph Sarkis

http://www.sustainable-scf.org/

[lxvi] https://tfs-initiative.com/

[lxvii] https://www.epa.gov/greenchemistry/information-about-green-chemistry-challenge

[lxviii]https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference/about/green-and-sustainable-chemistry-challenge

[lxix] https://www.isc3.org/en/activities/innovation/innovation-challenge.html

[lxx]Gee *et al.* 2013. Late lessons from early warnings: science, precaution, innovation" https://www.eea.europa.eu/publications/late-lessons-2

[lxxi] http://productstewardship.net/about/what-product-stewardship

[lxxii] https://www.oecd.org/env/tools-evaluation/extendedproducerresponsibility.htm

[lxxiii] https://www.sciencedirect.com/science/article/pii/S1366554518309918

[lxxiv]https://www.unido.org/our-focus/advancing-economic-competitiveness/competitive-trade-capacities-and-corporate-responsibility/corporate-social-responsibility-market-integration/what-csr

[lxxv] Temper *et al.* 2018. The Global Environmental Justice Atlas (EJAtlas): ecological distribution conflicts as forces for sustainability

https://link.springer.com/article/10.1007/s11625-018-0563-4

Woo et al 2018. Residential Segregation and Racial/Ethnic Disparities in Ambient Air Pollutionhttps://link.springer.com/article/10.1007/s12552-018-9254-0

Johnston and Cushing. 2020. Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry

[lxxvi]

https://books.google.ch/books?hl=en&lr=&id=sHy17sbX__oC&oi=fnd&pg=PR9&ots=J9KQRe9Hsw&sig=cxF1nRSk1m201jifvdYMTskClfY&redir_esc=y#v=onepage&q&f=false

[lxxvii] https://www.bmbf.de/files/2020_1501_National-Bioeconomy-Strategy_Summary_accessible.pdf

[lxxviii] https://www.global-green-chemistry-initiative.com/

[lxxix] Ocampo-López *et al.* (2019). Applied research in biotechnology as a source of opportunities for green chemistry start-ups

---

https://doi.org/10.1016/j.scp.2018.12.005

[lxxx] https://www.worldbank.org/en/topic/smefinance

[lxxxi] https://www.greencentrecanada.com/about-us/

[lxxxii] Sheldon. 2017. The E factor 25 years on: the rise of green chemistry and sustainability.

https://pubs.rsc.org/en/content/articlelanding/2017/gc/c6gc02157c#!divAbstract

[lxxxiii] https://pubs.acs.org/doi/10.1021/op200097d

[lxxxiv] https://www.chemiehoch3.de/nachhaltigkeitscheck/

[lxxxv] Broman and Robèrt.2015. A framework for strategic sustainable development

https://www.sciencedirect.com/science/article/abs/pii/S0959652615015930

[lxxxvi] https://thenaturalstep.org/approach/

[lxxxvii] https://www.sciencedirect.com/science/article/pii/S0040162503000726

[lxxxviii] https://cen.acs.org/articles/93/i38/Green-Chemistry-Education-Roadmap-Charts.html

[lxxxix]https://www.wbcsd.org/Programs/People/Sustainable-Development-Goals/Resources/Chemical-Sector-SDG-Roadmap

[xc] https://www.who.int/ipcs/saicm/roadmap-links/en/

[xci] https://cen.acs.org/acs-news/comment/Mapping-future-green-chemistry-education/97/i31

[xcii] https://cen.acs.org/articles/93/i38/Green-Chemistry-Education-Roadmap-Charts.html

[xciii] Case study: Smith, C. & Jarisch D., 2016. INEOS ChlorVinyls: A Positive Vision for PVC. INSEAD Business School

[xciv] https://www.iea.org/reports/technology-roadmap-a-guide-to-development-and-implementation

[xcv] McCrory et al 2020. Sustainability-oriented labs in real-world contexts: An exploratory review

https://www.sciencedirect.com/science/article/pii/S0959652620332479

[xcvi] https://thenaturalstep.org/services/transition-labs/

[xcvii] https://thenaturalstep.org/services/transition-labs/