RSC Sustainability

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2023, **1**, 2092

An actionable definition and criteria for "sustainable chemistry" based on literature review and a global multisectoral stakeholder working group†

Amy Cannon,[a] Sally Edwards,[b] Molly Jacobs,[c] Jonathon W. Moir,[a] Monika A. Roy[c] and Joel A. Tickner*[c]

Received 1st July 2023
Accepted 10th October 2023

DOI: 10.1039/d3su00217a

rsc.li/rscsus

The chemistries and chemical processes used today and practiced over the last 100 years have resulted in innovative materials and products that have significantly contributed to economic development, public health, and improved quality of life. However, many of these chemical innovations have detrimentally impacted (and continue to impact) workers, communities, ecosystems, and the climate throughout their lifecycles. Many efforts to improve safety and sustainability have occurred in recent decades; however, there is not yet a global consensus on the meaning and understanding of "sustainable chemistry", which is needed to guide industries, governments, academia, and others in innovation, investments, and policy while avoiding regrettable substitutions and discouraging greenwashing. A landscape review of forty-five literature sources was undertaken to support a global, multisectoral twenty-member Expert Committee on Sustainable Chemistry (ECOSChem) in the development of a robust and actionable definition and criteria for "sustainable chemistry", which was refined through external feedback. The landscape review, ECOSChem process, and final outputs are summarized herein, and the future applications and outlook for this work are discussed.

Sustainability spotlight

Chemistry has contributed significantly to economic development and quality of life but it has also resulted in harm to humans and ecosystems. There is a need for chemicals and chemistries to better align with the SDGs but a clear definition and criteria are lacking that account for a broad range of sustainability attributes, including social impacts. This article describes efforts to develop an actionable definition and set of criteria for "Sustainable Chemistry" and outlines a consensus-based collaborative, cross-sectoral process. The definition and criteria can be used to guide the development and application of chemicals, materials, products, processes, and chemical services that are safer and more sustainable, addressing SDG 9 "Industries, innovation, and infrastructure" and SDG 12 "Responsible consumption and production".

Introduction

The chemistries and chemical processes of today significantly improve global economies, public health, and the quality of human life through innovative materials and products. They also contribute to global toxic chemical pollution, climate change, plastics crises, and the overstepping of planetary boundaries.[1,2]

There is a growing opportunity to address the negative impacts of the chemical enterprise while continuing to positively improve public health and the global economy. There are actions underway globally to make chemical products and processes safer and more sustainable for research and development, industrial manufacturing, consumer use, and at end-of-life. Some of these actions include industrial innovations, educational reform, grassroots community organizing, and governmental policies restricting chemicals of concern. However, the challenge remains staggering. The global chemical market doubled from 2000 to 2017 and is set to double again by 2030.[3] There is an urgent need to transition the chemical industry and its full value chain towards safer and more sustainable chemistry and manufacturing practices.[2] Several groups have laid out roadmaps to do so for various chemical sectors[3–6] as well as for educational systems,[7] though further work is needed to accelerate this transition.

[a]Beyond Benign, 18 Church Street, P.O. Box 1016, Wilmington, MA, USA 01887
[b]Lowell Center for Sustainable Production, University of Massachusetts Lowell, Lowell, MA, 01854, USA
[c]Sustainable Chemistry Catalyst, University of Massachusetts Lowell, Lowell, MA, 01854, USA. E-mail: joel_tickner@uml.edu

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d3su00217a

One key barrier to the growth of solutions is the lack of consensus on what *sustainable chemistry* means, as well as how to measure it. This barrier was recently expanded upon in a report on accelerating the adoption of "green chemistry", which noted that having a common definition is critical for advancing discussions, collaborations, investment, and action – otherwise, a "tug-of-war" may occur between those who want change and those who prefer the status quo.[8] As discussed by Horváth, aspects of green chemistry may not be sustainable in practice so it is important to establish a definition of sustainable chemistry that can be applied as new chemicals and chemical processes are developed.[9]

Additionally, absent a consensus between different stakeholders, different ideas of what sustainable chemistry means can result in confusion and potential "greenwashing". For example, a manufacturer may claim their chemical product or process is "sustainable" under a certain set of definitions or criteria that are not considered sustainable by other groups (or worse, have no scientific basis). This may also result in regrettable substitution, where a known toxic chemical is replaced with another that proves to be just as concerning or even more harmful to human health or the environment. In contrast, a consensus definition and criteria can support the informed development and selection of chemicals, materials, and products through well-developed and thoughtful criteria that consider health and environmental impacts, social equity implications, and trade-offs between different factors.

In 1987, Gro Harlem Brundtland chaired the World Commission on Environment and Development, which was tasked by the General Assembly of the United Nations (UN) with proposing long-term strategies for achieving sustainable development by the year 2000 and beyond.[10] The following quote from the Commission's report has become known as the Brundtland definition of "sustainable development", the most widely used definition globally: "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."

A parallel definition for "sustainable chemistry" has been much less well defined, as evidenced by numerous variations seen in the academic literature,[11–14] in government and intergovernmental agency documents,[15–23] and in industry and industry association documents.[24,25] In contrast, "green chemistry", which was coined in the 1990s following the push for pollution prevention in the United States (U.S.), has a well-established definition that provides chemists with a framework and set of principles to "design chemical products or processes that reduce or eliminate the generation of hazardous substances".[26] Green chemistry forms an important foundation for sustainable chemistry, which must encompass a broader set of stakeholders and context, and set of criteria to align with sustainable development.

Recently, the UN Sustainable Development Goals (SDGs)[27] have served to shape global sustainability frameworks and chemicals management strategies. These were put forward in September 2015 as the necessary collective actions to address the needs of all the world's inhabitants and to "protect the planet and ensure that all people enjoy peace and prosperity by 2030". While these goals do not address chemical impacts directly, chemistry and the chemical enterprise play pivotal roles in supporting global sustainable development for five of the seventeen SDGs, as outlined by the American Chemical Society. For instance, SDG 12 is "responsible consumption and production", where chemical industries are responsible for the efficiency of industrial production processes, which is related to water stewardship, energy efficiency, recycling efforts, and the transition to a circular economy.[28]

More recently, the European Commission initiated work on a framework for advancing the concept of Safe and Sustainable by Design[15] to support the implementation of its Chemicals Strategy for Sustainability (CSS)[29] zero-pollution goal, a component of the European Green Deal launched in 2019. The framework is specifically designed to help guide an industrial transition towards safer and more sustainable chemicals and materials, including driving "innovation towards the substitution or minimisation of the production and use of substances of concern". The framework takes a "safety first" approach, arguing that to be sustainable, a chemical product or material must first be safe for both humans and the environment. However, while the framework can be applied more broadly than in the context of the CSS, there are missing elements that would be critical to include in a definition of "sustainable chemistry".

In parallel to work in Europe, the U.S. Sustainable Chemistry Research and Development Act (passed with the 2021 National Defense Authorization Act)[30] mandates the U.S. Office of Science and Technology Policy to develop a definition of sustainable chemistry "to identify research questions and priorities to promote transformational progress in improving the sustainability of the chemical sciences".[31] To support this effort and to address the lack of a clear and actionable definition and criteria for sustainable chemistry in the literature, the Sustainable Chemistry Catalyst at the University of Massachusetts Lowell and Beyond Benign – organizations that foster and support broad, trusted networks in government, industry, academia, and the non-profit sector – initiated an effort to establish an actionable definition and criteria for "sustainable chemistry".

Methodology

Literature review and analysis

To support the development of a robust and actionable definition and criteria for "sustainable chemistry", the project team undertook a landscape literature review of peer-reviewed and grey literature to understand current and prior efforts in this area and to support discussions of a global, multisectoral twenty-member Expert Committee on Sustainable Chemistry (ECOSChem). The concepts "sustainable chemistry", "green and sustainable chemistry", "safe and sustainable by design (SSbD)", and "safe by design (SbD)" were included in the search. Broader concepts such as "sustainability" and "climate change", were deemed to be too broad or independent of safer/sustainable chemistry and were not included. Searches focused on work by key governmental organizations (*e.g.*, European

Commission, the German Environment Agency (UBA), the U.S. Government Accountability Office (GAO)), intergovernmental organizations (*e.g.*, UN Environment Programme (UNEP), Organization for Economic Cooperation and Development (OECD)), academic institutions, professional societies (*e.g.*, Royal Society of Chemistry (RSC), American Chemical Society (ACS)), non-governmental organizations (*e.g.*, International Sustainable Chemistry Collaborative Centre (ISC_3), Green Chemistry & Commerce Council (GC3)), and trade organizations (*e.g.*, European Chemical Industry Council (CEFIC), American Chemistry Council (ACC)). The project team also leveraged input from the ECOSChem group to identify additional references not included in the literature search.

In all, forty-five journal articles, reports, and website documents were identified as being relevant (ESI Table S1†). The initial set of documents was narrowed down to eleven "key documents" based on whether they included clear and explicit definitions, principles, and/or criteria for "sustainable chemistry." A thematic review was then conducted to identify key terms, concepts, and recurrent themes across the documents. The results were compiled in a matrix (ESI Table S2†) to allow for simplified analysis across sector types and to assess definitional elements, including terms of focus, principles, definitions or definitional elements, implementing criteria, and other useful information. While the definitions and criteria reviewed should not be considered exhaustive, based on discussions with ECOSChem, they are representative of a broad cross-section of those in the literature.

Establishing and engaging an Expert Committee on Sustainable Chemistry (ECOSChem)

To guide the development of a definition and set of criteria, a twenty-member expert committee was created, envisioned to consist of leaders from networks in the U.S. and Europe that have contributed to and currently work in fields related to green and sustainable chemistry. To form the committee, an interest survey was created and sent out *via* email to these networks to identify potential candidates. Information was collected on the individual's sector of work, organization, experience in the field, and their interest in the project. Responses to the survey were reviewed internally by the project team, with a goal of balancing representation across sectors, geographies, and lived experiences.

The project team finalized ECOSChem with four members representing academia, four representing government, four representing industry, one representing the investment community, and seven representing the non-profit sector. Ten ECOSChem members were from the U.S. and ten from countries outside of the U.S., including Canada, Denmark, France, Germany, Kenya, Sweden, and the United Kingdom. Thirteen ECOSChem members identified as women and seven as men. Members of ECOSChem were chosen to represent multiple perspectives and for their ability to work collaboratively in a facilitated process.

At the time that ECOSChem was formed, the project team acknowledged that the majority of committee members represented North America and Europe, with the recognition that while chemicals are manufactured, used, and disposed of in other regions, that there is great economic power and governance over chemical manufacturing within North America and Europe that can influence chemistry practices throughout the world. However, it was also acknowledged that this ECOSChem composition would result in outputs that would be developed in English and mainly from North American and European cultural viewpoints, potentially limiting the acceptance and use of the definition and criteria by those from outside of these areas. To address this shortcoming proactively, ECOSChem formed a subcommittee to discuss in depth how to incorporate perspectives into the project work during the drafting and development of the definition and criteria that might not be represented in the group, particularly as related to environmental justice.

How the committee worked together: timeline

Throughout 2022, five ECOSChem meetings were held, each focusing on a main topic and one or more subtopics (ESI Table S3†). In between the full committee meetings, sixteen subcommittee meetings were held with subsets of ECOSChem members who volunteered to advance discussion on points not resolved in the full committee meetings. Each full or subcommittee meeting was held virtually *via* Zoom and was guided by the project team to allow for productive discussion and consensus where possible. The first meetings focused on creating a vision and principles, which were internal to ECOSChem to guide the project. The development of the definition and criteria was iterative and non-linear. For example, the definition was not finalized until after the criteria were developed, as committee members felt that detailed language left out of the definition to keep it succinct would need to be addressed in the criteria. Likewise, meetings towards the end of 2022 revisited the vision and principles that were developed early in the project to ensure that the definition and criteria were in alignment.

Environmental justice[32] was a central element discussed throughout this project and is a unique aspect in this work compared to other definitions to date.[11,13,14,21] It was important for ECOSChem to acknowledge in the project's outputs that chemistry as it has been traditionally – and is still currently – conducted, disproportionately harms specific communities based on race and socioeconomic status, and that these concerns must be addressed in the definition and criteria.

To obtain external feedback on the draft definition and criteria, two virtual meetings were held *via* Zoom in November 2022. Approximately 60 people representing a range of stakeholder groups and business sectors attended the external engagement sessions and provided feedback on the outputs of the committee. For those not able to attend, feedback was accepted *via* email, virtual and in-person conversations with different organizations, as well as through a survey form that was created online. Sixteen feedback responses were collected representing both individuals and organizations. ECOSChem members also engaged their own networks to obtain additional feedback, which was relayed during one of the full-committee ECOSChem meetings. All feedback was reviewed and considered in subsequent drafts of the definition and criteria.

Results

Analysis of the literature

History of Sustainable Chemistry. The landscape analysis of the forty-five reference documents allowed for an examination into the history and timeline of the growth and development of the concept of "sustainable chemistry" over the last several decades. The earliest documents reviewed date back to the 1990s, when the European Council issued a directive on pollution prevention, encouraging industrial activities – including chemicals and chemical processes – to adopt more sustainability practices.[33] A series of workshops on sustainable chemistry organized by the OECD also took place in the late 1990s "to encourage fundamental breakthroughs in chemistry that would prevent pollution and, in most cases, improve performance and reduce costs".[20] In 2001, van Roon *et al.* discussed sustainable chemistry as integrating sustainable development, in particular addressing equity between nations and generations, shifting towards renewable resources, and re-evaluating societal needs.[34] In 2004, the OECD created a widely used definition of sustainable chemistry as "the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. Within the broad framework of sustainable development, government, academia and industry should strive to maximise resource efficiency through activities such as energy and non-renewable resource conservation, risk minimisation, pollution prevention, minimisation of waste at all stages of a product life-cycle, and the development of products that are durable and can be reused and recycled." That definition was more recently updated on the OECD website.[21]

Efforts by UBA in 2009 established a definition and criteria for "sustainable chemistry" that highlighted two key fields of activity: sustainable processing and production, and chemicals and products, along with five principles, one being to conduct a comprehensive lifecycle assessment.[22] In 2016, the UBA released a "Guide on Sustainable Chemicals: a decision tool for substance manufacturers, formulators and end users of chemicals" which included a set of nine "golden rules" for sustainable chemicals.[22] In 2017, UBA released further supporting documentation, including a series of studies identifying "priority topics" in sustainable chemistry (*i.e.*, technical solutions, concepts, business models, *etc.*).[23] In this work, innovative solutions from ten industries were assessed using quantifiable indicators, including indicators related to the UN SDGs.

In 2015, Dow Chemical released a public statement and document on sustainable chemistry with its Sustainable Chemistry Index in which it described a system that rates the company's product portfolio among eight criteria categories such as renewable or recycled content, social need benefit, and public policy and end of life risk.[35] Soon after, the Green Chemistry & Commerce Council (GC3, now known as Change Chemistry), a network of over 100 companies along the chemicals value chain, released a joint statement on using green chemistry and safer alternatives to advance sustainable products and also referenced the OECD's 2004 definition of sustainable chemistry.[36]

During the same period, two separate but related academic documents were published. Kümmerer and Clark published a book chapter in 2016 that outlined a definition for "sustainable chemistry", explaining the key differences between "green chemistry" and "sustainable chemistry" and emphasizing the importance of Life Cycle Analysis (LCA) as a critical measure of sustainability of chemical products and processes.[11] The second document was published in 2017 by Blum *et al.* and proposed a definition in one hundred words, which reads in part: "Sustainable chemistry uses approaches, substances, materials and processes with the least adverse effects. Therefore, sustainable chemistry applies substitutes, alternative processes and recycling concept, supporting resource recovery and efficiency. Thus, sustainable chemistry avoids rebound effects, damage and impairments to human beings, ecosystems and natural resources". The article outlines seven objectives and guiding principles for "sustainable chemistry".[14]

More recent key documents from 2017 onward have been published by the European Commission, the U.S. GAO, UNEP, UNEA, and CEFIC. The European Commission's work has focused on SSbD, which is defined as "an approach to the design, development and use of substances, materials and/or products that focuses on providing a function (or service), while reducing harmful impacts to human health and the environment along life cycle stages",[15] as it forms part of the EU's Chemical Strategy for Sustainability (CSS).[29] Both the GAO and UNEP in 2018 and 2019, respectively, compiled and analyzed feedback on the different perspectives stakeholders have of "sustainable chemistry".[37,38] Similarly, Halpaap and Dittkrist summarized feedback on the UNEA-2 Resolution 2/7 on the sound management of chemicals and waste around best practices towards "sustainable chemistry".[18] Furthermore, documents published by CEFIC in 2020 and 2021 were primarily responses and position papers related to the CSS as well as the concept of SSbD, although neither document provides an explicit definition for "sustainable chemistry."[24,25]

In 2017, a workshop in Berlin co-hosted by UNEP and ISC_3, in partnership with the UN International Development Organization (UNIDO), the Free University, and the United Nations Institute for Training and Research (UNITAR), identified important policy-relevant knowledge and lessons learned that would eventually feed into the writing and publication of UNEP's Global Chemicals Outlook II in 2019.[3,39] Later, in 2021, UNEP would publish the "Green and Sustainable Chemistry: Framework Manual", which provides nuance on green *vs.* sustainable chemistry and notes that "while green chemistry is characterized and guided by scientific principles that focus on chemistry innovation, recent discussions on sustainable chemistry suggest a broader concept and more holistic interpretation that takes into account economic, environmental and social dimensions".[19] While the above summary of prior work is only a sampling, the complete list of definitions, principles,

Table 1 Eleven key documents identified during the literature analysis as key to the scope of the ECOSChem committee

Year	Authors (or authoring organization, if applicable)	Title	Overarching concept	Definition
2004	OECD	Sustainable chemistry	Sustainable chemistry	"Sustainable chemistry is the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. Within the broad framework of sustainable development, government, academia and industry should strive to maximise resource efficiency through activities such as energy and non-renewable resource conservation, risk minimisation, pollution prevention, minimisation of waste at all stages of a product life-cycle, and the development of products that are durable and can be reused and recycled"
2015	Dow chemical	Sustainable chemistry: the sustainable chemistry index	Sustainable chemistry	"Sustainable chemistry involves the application of lifecycle thinking to the products and solutions Dow brings to society, in order to understand how to use resources more efficiently, minimize its footprint, provide value to its shareholders and stakeholders, deliver solutions to its customers, and enhance the quality of life of current and future generations. Sustainable chemistry is a lens through which Dow examines its products, to better understand the role of those products in addressing sustainability challenges. It is a concept that identifies the existence of global sustainability challenges, applies Dow's technology and innovation capabilities to develop products and solutions that address these challenges, and recognizes that chemistry has an essential role to play in advancing sustainability for society. The successful application of sustainable chemistry results in commercially viable products that help society to address sustainability challenges related to areas such as climate change, water scarcity, food provision and safety, and healthy societies. Sustainable chemistry differs from green chemistry in that sustainable chemistry is a general concept that seeks to understand and optimize the role of a chemical product in addressing sustainability challenges. Green chemistry, on the other hand, seeks to apply a set of well-defined principles to the design and development of chemical products and processes. In this sense, sustainable chemistry can be advanced by applying the tools of green chemistry to develop new products and processes that help to solve sustainability challenges"
2016	Kümmerer and Clark	Green and sustainable chemistry	Green and sustainable chemistry	"Sustainable chemistry includes economical, social and other aspects related to manufacturing and application of chemicals and products. It aims not only at green synthesis or manufacturing of chemical products but also includes the contribution of such products to sustainability itself" "In general, only rarely are aspects that go beyond the chemicals themselves and their technical issues addressed by green chemistry, whereas sustainable chemistry generally includes all aspects of a product related to sustainability, *e.g.* social and economic aspects related to the use of resources, the shareholders, the stakeholders and the consumers"
2017	Blum *et al.*	The concept of sustainable chemistry: Key drivers for the transition towards sustainable development	Sustainable chemistry	"Sustainable chemistry in 100 words: Sustainable chemistry contributes to positive, long-term sustainable development. With new approaches, technologies and structures, sustainable chemistry stimulates social innovations and develops value-creating products and services. Sustainable chemistry uses approaches, substances, materials and processes with the least adverse effects. Therefore, sustainable chemistry applies substitutes, alternative processes and recycling concept, supporting resource recovery and efficiency. Thus sustainable chemistry avoids rebound effects, damage and impairments to human beings, ecosystems and natural resources.

Table 1 (*Contd.*)

Year	Authors (or authoring organization, if applicable)	Title	Overarching concept	Definition
				Sustainable chemistry is based on a holistic approach, setting policies and measurable objectives for a continuous process of improvement. Networking sustainable chemistry with interdisciplinary scientific research, education, consumer awareness, corporate social responsibility and sustainable entrepreneurship serves as important basis for sustainable development"
2017	Marion *et al.*	Sustainable chemistry: how to produce better and more from less?	Sustainable chemistry	"Sustainable chemistry can be defined as the development of an even safer and more environmentally-friendly chemistry but one which also equally integrates the priorities of economic competitiveness and societal concerns. Sustainable chemistry is a complex equation which must ensure the longevity of the human, animal, and vegetable species whilst taking into consideration issues related to accessing different resources (carbon, water, metals), problems of access to energy, global warming, the exponential increase in the human population, for which chemistry must allow a serene development, the social and environmental impact of the value chain, and the erosion of biodiversity, while of course maintaining economic competitiveness to create profit and business"
2019	GC3 sustainable chemistry alliance	Working definition of sustainable chemistry	Sustainable chemistry	"The term "sustainable chemistry" includes the design, development, demonstration, commercialization and/or use of chemicals and materials that: are less toxic to human health and the environment; have lower energy consumption and related emissions; have reduced natural resource impacts; include optimized product design that results in the reduction of waste and the reuse or recycling of chemicals and materials across the product lifecycle. Products of sustainable chemistry demonstrate improvements in at least one of these properties, without significant degradation in another property, in their production, use, and/or end of life as compared to chemicals and materials in similar use"
2020	OECD	Moving towards a Safe(r) Innovation Approach (SIA) for more sustainable nanomaterials and nano-enabled products	Safe by design	"The SbD (safe-by-design, safer-by-design, or safety-by-design) concept refers to identifying the risks and uncertainties concerning humans and the environment at an early phase of the innovation process so as to minimize uncertainties, potential hazard(s) and/or exposure. The SbD approach addresses the safety of the material/product and associated processes through the whole life cycle: from the research and development (R&D) phase to production, use, recycling and disposal"
2021	CEFIC	Safe and sustainable by design: Boosting innovation and growth within the European chemical industry	Safe and sustainable by design	"The chemical industry defines safe and sustainable-by-design as a process to innovate and put on the market chemicals, materials, products and technologies that are safe and deliver environmental, societal, and/or economical value through their applications. Those chemicals, materials, products and technologies enable accelerating the transition towards a circular economy and climate-neutral society and preventing harm to human health and the environment throughout the life cycle"
2021	EU commission	Life cycle assessment approach being taken to ensure that chemicals are designed for sustainability	Safe and sustainable by design	"At this stage, SSbD can be defined as a pre-market approach to chemicals that focuses on providing a function (or service), while avoiding volumes and chemical properties that may be harmful to human health or the environment, in particular groups of chemicals likely to be (eco) toxic, persistent, bio-accumulative or mobile. Overall sustainability should be ensured by minimising the environmental footprint of chemicals in particular on climate change, resource use, ecosystems and biodiversity from a lifecycle perspective"

Table 1 (*Contd.*)

Year	Authors (or authoring organization, if applicable)	Title	Overarching concept	Definition
2021	ISC3	Key characteristics of sustainable chemistry	Sustainable chemistry	"Sustainable chemistry is a framework giving guidance on how chemistry as a scientific and economic asset spanning multiple supply chains and consequently the whole life cycle can comply with the principles of sustainability for the betterment of our planet"
2022	OECD	Sustainable chemistry	Sustainable chemistry	"Sustainable chemistry is a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes" "Sustainable chemistry is also a process that stimulates innovation across all sectors to design and discover new chemicals, production processes, and product stewardship practices that will provide increased performance and increased value while meeting the goals of protecting and enhancing human health and the environment"

criteria, and other elements of the forty-five sources reviewed as part of this project can be viewed in ESI Table S1.†

Thematic analysis of key documents for committee work. Of the eleven documents in the thematic analysis (Table 1), the most common theme was the protection of human health and the environment (Fig. 1), which is not surprising given concerns about the impacts of chemicals on health and ecosystems as a key driver for sustainable chemistry. Other common themes among the definitions were circularity, sustainable development, and resource conservation. A full explanation of all the themes and how definitions addressed them can be viewed in ESI file S1,† which was submitted in June 2022 as an official comment to the U.S. Office of Science and Technology Policy in response to their Request for Information seeking "input from interested parties on sustainable chemistry to guide future federal efforts".[31]

Consensus definition and criteria for sustainable chemistry. Based on the landscape review, the ECOSChem group determined that there was no one existing definition that truly aligned with a definition as envisioned by the committee. Instead, ECOSChem used the thematic analysis and their collective experience to develop a draft definition and accompanying criteria encompassing aspects of green chemistry, safer chemicals, sustainability, business processes, product design, and environmental justice. After several discussions, iterations, and with input from external engagement efforts, the definition and criteria were refined. The goal was to create a definition and criteria that sets clear direction towards safer and sustainable chemicals, enables concrete action, avoids the potential for greenwashing, and is also adaptable for different contexts. Additionally, the definition and criteria were created to complement and "protect" existing well-defined concepts such as "green chemistry" and "alternatives assessment" and to not contradict previous definitions related to sustainable chemistry.

The definition for sustainable chemistry as developed by ECOSChem (Fig. 2) reads: "Sustainable chemistry is the development and application of chemicals, chemical processes, and products that benefit current and future generations without harmful impacts to humans or ecosystems".[40] The definition was created to be both aspirational as well as practical and was also intended to be succinct so that it would be memorable. It was created to stand alone, but as noted above, was also created in the context of five criteria categories: "Equity and Justice", "Transparency", "Health and Safety Impacts", "Climate and Ecosystem Impacts", and "Circularity". For each of the five categories, specific criteria were developed, with the intention that a chemical, material, process, product, or service would need to meet all the criteria for all categories in order to ultimately be deemed "sustainable chemistry". The rationale for this determination was heavily debated but the goal was to avoid situations where only one set of criteria are followed, potentially leading to regrettable trade-offs or solutions that only address part of the problem. The criteria can be seen in Table 2 and were developed with language broad enough to capture key aspects that would need to be fulfilled while not being so specific as to be metrics (the development of which were outside the scope of this project but will necessarily form part of the next stage of this work).

Criterion #1: Equity and Justice. This first category focuses on the authentic engagement and protection of marginalized communities and the prioritization of products that either remediate past harms in these communities and/or that strengthen local economies. Acknowledging and addressing social impacts was a critical focal point throughout this project, with attention to how environmental justice concerns and considerations can be integrated into chemistry practices. The criteria in this category aim to draw attention to communities, including workers, that could be negatively impacted by chemistry practices and the chemical supply chain, and to highlight the thinking and actions required to protect these groups while not shifting burdens to others.

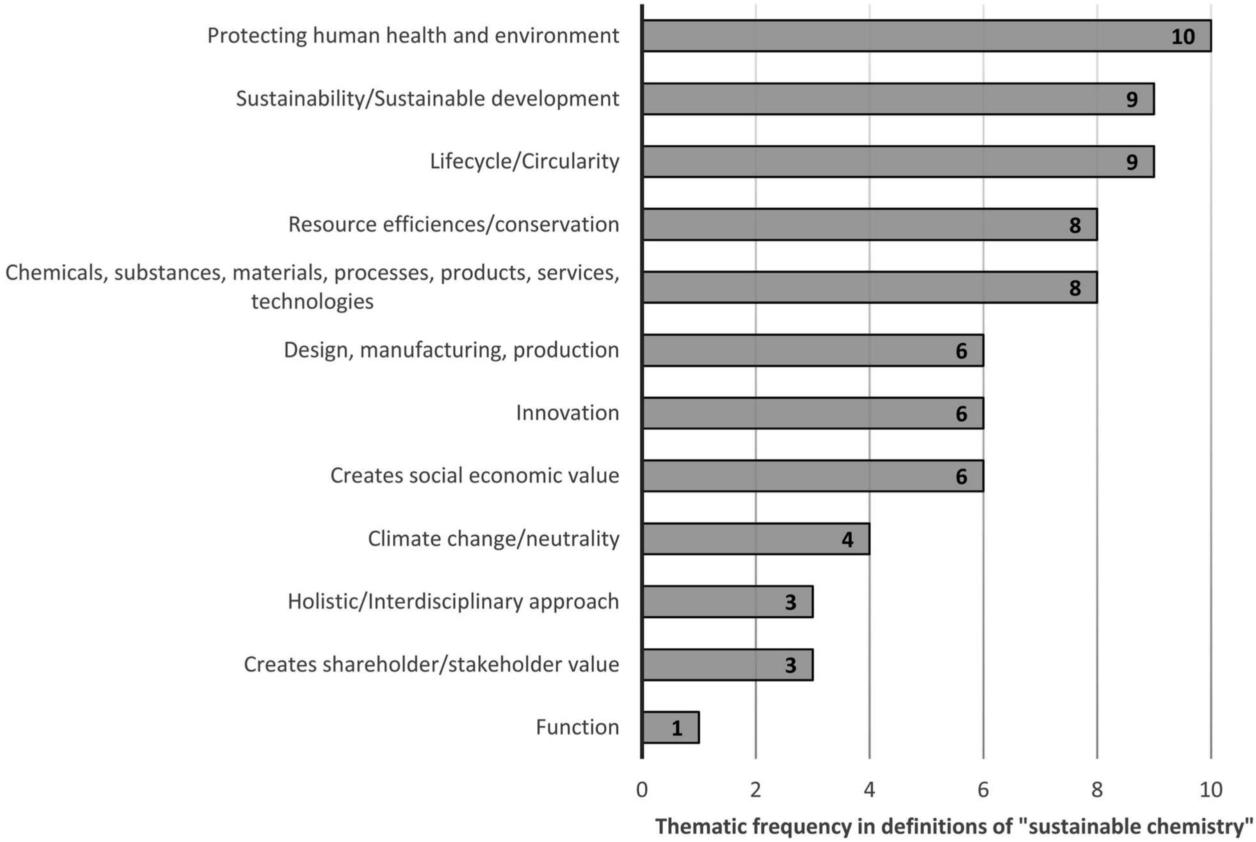

Fig. 1 Thematic analysis of the most common concepts present among eleven sources identified as having an explicit definition related to "sustainable chemistry."

Criterion #2: Transparency. This category is about information disclosure, verification of sustainability claims, and having chain-of-custody information. Access to information about chemical ingredients, how products are made, and overall lifecycle information was discussed as a major barrier for achieving sustainable chemistry, and this concern was voiced both from members of ECOSChem in internal meetings as well as from individuals and organizations participating in the external engagement sessions. The criteria in this category are designed to make information more transparent to customers for informed purchasing. They also allow companies along the supply chain to make informed choices and comply with demands for safer products, ecolabelling standards, or more sustainably managed manufacturing processes.

Criterion #3: Health and Safety Impacts. This category emphasizes that the full lifecycle of materials used to make products should be non-hazardous and neither persist nor bioaccumulate, including for byproducts and breakdown products. The criteria in this category focus on minimizing the toxicological impacts that chemical ingredients can have on people and the environment, taking a hazard-focused approach to reduce the risk of potentially harmful outcomes. In this way, hazardous properties of chemicals and processes are "designed out" from the start, rather than relying on control measures to manage risks. This category overlaps somewhat with the "Equity and Justice" criterion, acknowledging that harmful exposures can occur in communities where raw ingredients are extracted or refined, to workers during the production or use phase, to consumers during the use phase, or in communities where products are ultimately disposed of or recycled.

Criterion #4: Climate and Ecosystem Impacts. This category focuses on the resources and energy used to make and transport products, with the intention of minimizing their impact on the climate and on ecosystems. The chemical industry is the largest industrial energy user and third largest carbon dioxide emitter[41] and chemical exposures have been linked to significant declines in biodiversity.[42] This category overlaps somewhat with the "Health and Safety Impacts" criterion, addressing the harmful effects that can occur on the climate and on ecosystems from material extraction and use and emphasizing the importance of using chemical ingredients and materials that are non-hazardous. Conversations within ECOSChem while shaping this category acknowledged that it is not possible to fully eliminate material or energy use or greenhouse gas emissions, but the focus should be on responsible extraction and use of materials, their minimization, and on preserving non-renewable resources and biodiversity.

Criterion #5: Circularity. The last category focuses on the efficient design of chemicals, materials, processes, products, and services to reduce waste and impact on the environment. This category draws on several of the other criteria, such as the use of non-hazardous chemical ingredients ("Health and Safety

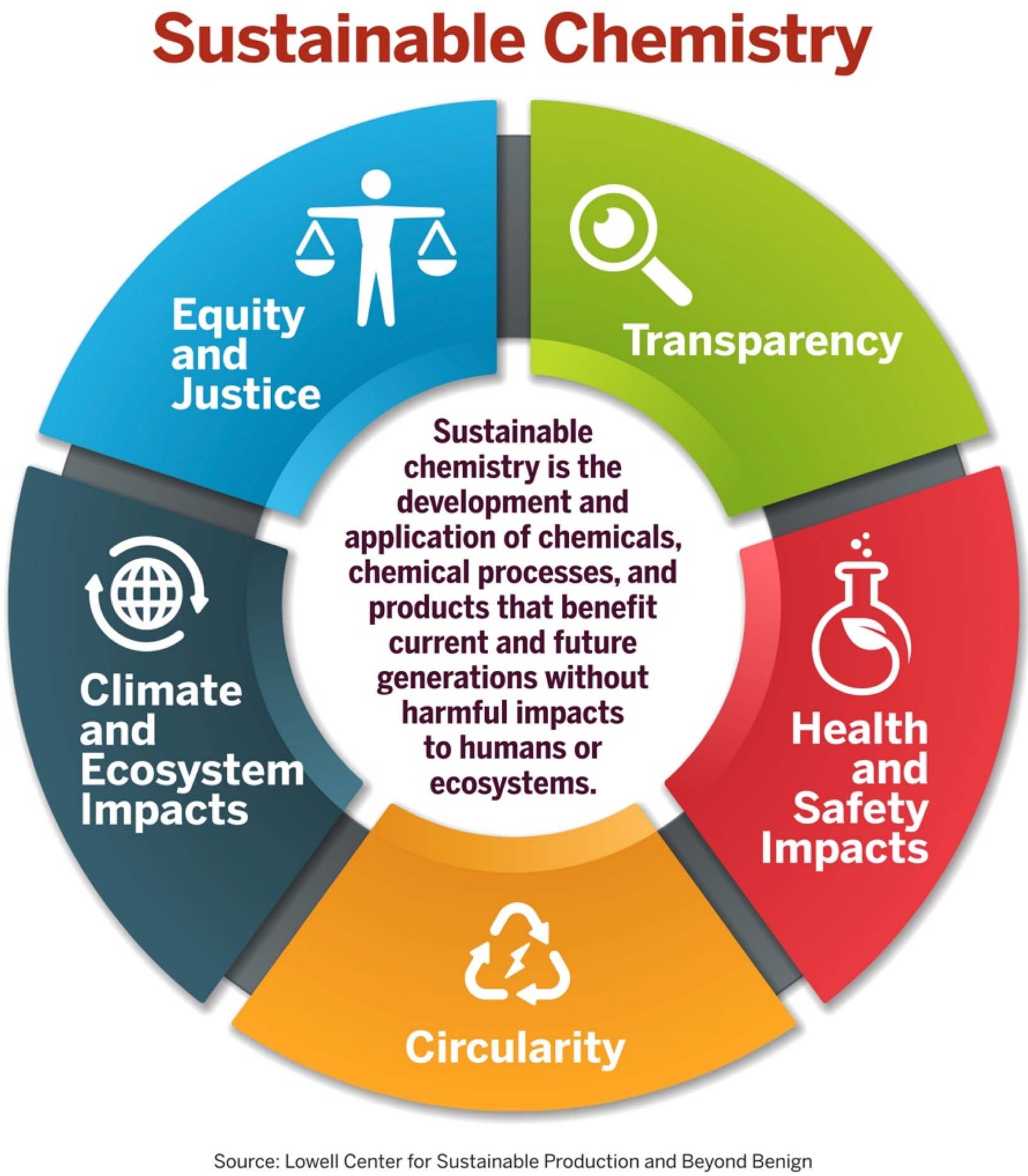

Fig. 2 A graphic depicting the definition and five criteria categories (reprinted with permission from the Lowell Center for Sustainable Production and Beyond Benign).

Impacts") and minimizing resource use ("Climate and Ecosystem Impacts") but is specifically about making chemical products as efficient as possible, aligning with circularity principles to reduce waste and increase reuse. This category addresses efficiency and circularity, but with the understanding that the other criteria categories must be met for the resulting product to be safer for consumer, workers, communities, and the environment.

For both the definition and criteria, there were important discussions around specific language. The word "eliminates" was the subject of much discussion. For example, in earlier drafts, language around sustainable chemistry "eliminating the impacts of harmful chemicals on people and the environment", was used with the intention of setting a very high aspirational bar. Discussion in ECOSChem meetings as well as in the external engagement meetings revealed that the use of this word may not only be impractical but may also deter efforts moving towards sustainable chemistry. Subsequent drafts considered using the word "minimizes" or the phrase "eliminates or minimizes" to allow for more flexibility, but this language was viewed as not strong enough for progress. In the final version, the word "without" was used, which indicates a goal but does not imply specific actions to eliminate impacts.

In addition to the definition and criteria that were developed, the project team and ECOSChem members created a preamble that provides additional context for the work and outlines the importance of the definition and criteria.[40] In

Table 2 Sustainable chemistry criteria categories and specific criteria. Clarifying footnotes are at the bottom

Equity and Justice	• Be designed or implemented with the authentic engagement of potentially impacted communities to help avoid negative social impacts[b]
A sustainable chemical, material, process, product, or service[a] will…	• Be designed or implemented in a way that does no harm and, when feasible, prioritizes sustainable chemistry innovations on the remediation of harms to communities and societies[c] that have been disproportionately impacted at any stage of the lifecycle of the chemical process or product lifecycle
	• Protect workers, marginalized groups (*e.g.*, indigenous, immigrant, frontline, and low-income communities, and communities of color), and vulnerable groups (*e.g.*, children, those who are pregnant, and the elderly)
	• Be designed or implemented in a way that does not create new problems or shift harms across the value chain[d] or to other communities, societies, countries, or generations
	• Be designed or implemented in a way that supports local economies and ensures product access and affordability for marginalized groups
Transparency	• Have had its health, safety, and environmental data[e] disclosed in an accessible[f] format to individuals, workers, communities, policy makers, and the public
A sustainable chemical, material, process, product, or service will…	• Include scientifically defensible verification for sustainability, health, safety, and other claims. The sources for verification should be openly accessible
	• As much as possible, include a chain of custody so that chemicals and materials used in the product and process are traceable throughout their lifecycle
Health and Safety Impacts	• Be without hazards[g], including hazardous components, emissions, and toxic byproducts and breakdown products, to people and ecosystems across its existence[h]
A sustainable chemical, material, process, product, or service will…	• Not result in releases, including releases of byproducts or breakdown products, that persist or bioaccumulate
Climate and Ecosystem Impacts	• Utilize renewable, non-toxic chemical building blocks[i]
A sustainable chemical, material, process, product, or service will…	• Be without negative impacts on climate and biodiversity, including impacts on habitat and resource degradation
	• Be without harmful releases to air, water, and land across its lifecycle, including for transportation and distribution
	• Minimize energy use and greenhouse gas emissions across its lifecycle, including for transportation and distribution
Circularity[j]	• Be designed to have a lifetime appropriate to its use and enable safe reuse and non-toxic recycling[k]
A sustainable chemical, material, process, product, or service will…	• Prioritize resource and energy efficiency, conservation, and reclamation, reduced consumption of finite resources, and waste prevention, minimization, and elimination[l]

[a] A chemical service "involve(s) a strategic, long-term relationship in which a customer contracts with a service provider to supply and manage the customer's chemicals and related services." Chemical Strategies Partnership. [b] Social impacts may include, but are not limited to, chemical-related illness and stress to workers, communities, and societies, impacts from the process or product on cultural resources, and impacts on livelihoods of communities and societies, including access to jobs, natural resources, property values, and other human needs. [c] Historically disproportionately impacted communities and societies may be located where chemicals, materials, and products are extracted, produced, transported, sold, used/consumed, and/or disposed of. [d] The value chain describes the full range of activities that firms and workers do to bring a product from its conception to its end use and beyond. This includes activities such as design, production, marketing, distribution, and support to the final consumer. [e] These data include information on chemical ingredients, resource and energy use, emissions, and other sector-specific information. [f] Accessibility refers to materials that are free of charge and easy to understand by those that speak different languages, are accessing materials in non-digital formats, or have other differing abilities (*e.g.*, are hard of hearing, seeing, *etc.*). [g] Hazards can include toxicological, physical, and other types of hazards. Eliminating hazards is the operational trajectory of sustainable chemistry while risk reduction is a short-term and incomplete strategy. A product or process that achieves only risk reduction cannot be considered sustainable. [h] Existence refers to both product and process lifecycles. The product lifecycle includes design, extraction, production, transportation, use/re-use, recycling, and end-of-life. The process lifecycle includes design, initial research and development, testing, piloting, scale-up, implementation, functional lifetime, and decommissioning/scale-down. [i] Chemical building blocks refer to molecular units or compounds that can be used as ingredients to synthesize more complex chemical materials or products. [j] A circular economy is a "model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended." The European Parliament. [k] Recycling can include mechanical and chemical recycling. Chemical recycling and other emerging technologies for recycling and recovery should be closely evaluated for their hazards to avoid shifting negative impacts. [l] Waste minimization and elimination should be practiced across the supply chain, including for extraction, development, production, use, reuse, and disposal.

addition to environmental justice, the preamble introduces concepts like "lifecycle", "planetary boundaries", and "essential uses", concepts relevant for chemicals management and that are actively being discussed worldwide. The preamble positions the relevance of the definition and criteria amongst these global discussions and needs, supporting its communication to a broad set of audiences. The preamble also notes that sustainable chemistry in some cases may involve the elimination of a chemical or material function or use or its functional replacement with a service (which should also be sustainable).

Discussion

Context and relevance

Defining sustainable chemistry raises questions about its relationship with other fields, such as green chemistry, which is well-established and guided by 12 Principles developed in the 1990s.[26] Green chemistry is a toolkit for chemists to practice chemistry more sustainably, incorporating considerations of atom economy, less hazardous synthesis, energy efficiency, the use of renewable feedstocks, and designing for degradation, among others, into chemical and chemical process design. The concept of sustainable chemistry incorporates the design practices of green chemistry but also connects chemistry more broadly to its impacts in the world, including global resource use, health and environmental impacts, connections to communities impacted by any part of the chemical product lifecycle, and societal needs. It describes a bold vision for the future of chemistry that demands a larger stakeholder view across business value and supply chains.

The process and outputs of the present efforts are relevant for different sectors and contexts. For example, business sectors consisting of chemical manufacturers, formulators, product manufacturers, and retailers are in need of a definition and criteria of sustainable chemistry to guide their efforts towards sustainability. Change Chemistry (formerly known as the Green Chemistry & Commerce Council or GC3) is a cross sectoral network of such companies that guides efforts in the innovation and commercialization of safer and more sustainable chemicals, materials, processes, products, and services.[43] Change Chemistry's member companies can influence the way other companies understand and integrate sustainable chemistry into their practices, including clear metrics for customers, investors, and others to demonstrate progress.[44] The sustainable chemistry definition and criteria could also support efforts such as Clean Production Action's Chemical Footprint Project, which benchmarks companies for their chemicals management systems and recognizes corporate leadership in the use of safer chemicals.[45]

For the investment community, the sustainable chemistry definition and criteria can help to guide financial resources towards companies that demonstrate they can meet or are actively working towards achieving sustainable chemistry in their business practices. For example, the Investor Environmental Health Network, administered by Clean Production Action, brings together socially responsible investors representing nearly $3 trillion in assets under management, that want to leverage the economic value of safer and more sustainable products to drive reductions in chemical pollution and their associated financial risks.[46] The sustainable chemistry definition could also help guide revisions to tools already developed, such as the Portfolio Sustainability Assessment tool developed by the World Business Council for Sustainable Development, which helps chemical manufacturers assess their portfolios against sustainability criteria for annual disclosure to investors.[47]

Environmental health non-governmental organizations have played key roles in advocating for higher standards of chemicals management that protect communities, especially those that have been disproportionately impacted by chemical exposures. These organizations have supported communities in different ways, such as through direct support, education initiatives, product testing, acting as watchdogs, and in amplifying community needs at a policy level. The sustainable chemistry definition and criteria provide a vision for chemical production and end-of-life that could be used as a clear reference to ensure that already impacted communities are not further harmed and ideally benefit from future developments in chemistry. The definition and criteria also include considerations of transparency and engagement, that communities potentially impacted by manufacturing, use, or disposal could refer to in supporting their voice in decision-making. Coming Clean, a non-profit coalition that created the Louisville Charter for Safer Chemicals,[48] a vision for a future chemicals industry, is in a position to catalyze conversations across impacted communities around how to drive a future chemicals industry that is safe and sustainable for those communities.

Chemistry education is immensely important in shaping the way that students think about how chemistry interacts with resource use, human health and safety, environmental impacts, and the global climate. The growth of the sustainable chemistry field has the potential to reshape the way chemistry is taught in schools, orient students towards more systems thinking about sustainable chemistry solutions, and equip them with tools and resources to develop those solutions. Beyond Benign actively works to provide educators with the tools, training, and support to make green chemistry an integral part of chemistry education[49] and has the network to integrate aspects of the sustainable chemistry definition and criteria into its curriculum. Likewise, centers and organizations, such as the Berkeley Center for Green Chemistry,[50] could incorporate the sustainable chemistry definition and criteria directly into their curriculum for learning and discussion.

The definition and set of criteria for sustainable chemistry will be useful in government contexts. In the U.S., these will be used to prioritize federal investments that support innovation toward sustainable chemistry, for example under the Bipartisan Infrastructure Law and Inflation Reduction Act. It can shape investments towards decarbonization – a major priority of the Biden Administration – in ways that minimize potential trade-offs to health and ecosystems. In the future, it will be important for the U.S. Office of Science and Technology Policy to determine how to measure the success and effectiveness of sustainable chemistry investments and what policies, or changes in policy the federal government could make to improve and/or promote sustainable chemistry.

On a broader level, the consensus definition and criteria for sustainable chemistry will be important in influencing and implementing parallel frameworks, roadmaps, and concepts discussed above, such as the Sustainable Chemistry R&D Act, the EU Chemicals Strategy for Sustainability, Safe and Sustainable by Design, the UN SDGs, and others, especially regarding social impacts considerations.

Limitations and lessons learned

As noted in the preamble to the ECOSChem definition and criteria for sustainable chemistry, few, if any, chemistries today meet the criteria. The current chemical industry – particularly for organic chemicals – is built on a small number of fossil-fuel based petrochemicals, many of which are inherently toxic.[1] Likewise, the systems that recover, dispose of, and neutralize toxic chemicals, as well as collect data on impacts along the lifecycles of these chemical or chemical products, may be limited.

An important challenge will be to outline what the developed criteria mean in practice for different sectors and sub-fields, as well as to identify what metrics or indicators will be useful for measuring fulfilment of the criteria or progress towards them. Some criteria are more straightforward to put into practice than others. For instance, metrics have already been developed for measuring energy efficiency and lifecycle impacts, whereas determining metrics to meet the Equity and Justice criteria are more challenging (*e.g.*, measuring authentic engagement with communities or the strengthening of local economies). It was critical for this project to acknowledge and embed the environmental and social justice impacts related to chemistry practices into the criteria. As such, it will be important in subsequent work to define metrics for the Equity and Justice criterion that are feasible for companies and other organizations to apply and that also are seen as valid by the communities impacted by chemistry.

Recognizably, not all chemicals, materials, processes, products, or services are made the same and companies are not involved with all aspects of the production chain. Some companies may play a small role, such as producing a basic chemical or transporting product ingredients. Other companies may be more involved with the manufacturing of a product but face other barriers, such as a lack of transparency of its ingredients. Future work for this project may include exploring case studies for what the sustainable chemistry criteria look like for different actors along the value chain in practice. One option is to develop a tiered system to allow for progress, similar to the Leadership in Energy and Environmental Design (LEED) certification for buildings (*e.g.*, bronze, silver, gold, and platinum levels). However, such a system would have to be designed in a way where potential tradeoffs are transparent and minimized.

As mentioned above, many discussions took place within ECOSChem on the meaning of words for the definition and criteria, and it was evident that further clarification or guidance may be required in later efforts to develop the criteria. For instance, a chemical "service" in one field may signify the function that a chemical serves in an application but in another sector may refer to "a strategic, long-term relationship in which a customer contracts with a service provider to supply and manage the customer's chemicals and related services".[51] Likewise, "hazards" in one field may refer more to toxicological hazards but in another may refer more to physical hazards. The final project briefing clarifies wording around these and other words and phrases. The external engagement process also incorporated external feedback that provided additional perspectives on wording.

Lastly, and as briefly described in the Methods section, the definition and criteria were formed from perspectives mainly from North America and Europe, which could potentially limit the acceptance and use of the definition and criteria from those outside of these areas. Despite this limitation, input was sought during the formation of the definition and criteria from individuals and organizations representing communities disproportionately impacted by harmful chemical exposures. While some funding was available to compensate the time for ECOSChem members representing impacted communities, an important limitation was a lack of funding to enable greater participation and engagement from a broader range of impacted communities. Further efforts related to this work to develop more specific criteria and metrics should ensure reasonable compensation for representatives in sectors that are less able to donate time to such initiatives.

Future work

In the U.S., a briefing document with the ECOSChem group's preamble, definition, and criteria was submitted to the U.S. Office of Science and Technology Policy in January 2023 and soon after was publicly released (ESI file S2†) through a webinar attended by more than 150 people in March 2023 and that included a panel of ECOSChem members who reflected on the process and meaning of the definition and criteria for their sectors. The goal of the ongoing dissemination effort is to present and socialize the definition and criteria to a range of audiences and contexts and to ensure its broad dissemination in policy, education, and practice. To achieve this, ECOSChem members and the networks of the Sustainable Chemistry Catalyst, Beyond Benign, and ECOSChem members are being leveraged. For example, the definition was highlighted in a resolution on "Advancing safer chemical products and processes" passed by the U.S. Environmental Council of the States (representing state environmental agency directors).[52] The definition and criteria framed two meetings on growing investment in sustainable chemistry, one held with the U.S. Department of Energy in March 2023 and one in collaboration with the Investor Environmental Health Network in April 2023. The definition was later featured in a blog hosted by one of the largest banks in the world, UBS.[53] The definition and criteria have been presented to members of Change Chemistry and will serve as the foundation for a discussion on criteria for assessing sustainable chemicals and materials.

In August 2023, the U.S. Office of Science and Technology Policy (OSTP) released its interagency committee report "Sustainable Chemistry Report: Framing the Federal Landscape" which contains a definition of sustainable chemistry. It states, "Sustainable chemistry is the chemistry that produces compounds or materials from building blocks, reagents, and catalysts that are readily-available and renewable, operates at optimal efficiency, and employs renewable energy sources; this includes the intentional design, manufacture, use, and end-of-life management of chemicals, materials, and products across their lifecycle that do not adversely impact human health and the environment, while promoting circularity, meeting societal needs, contributing to economic resilience, and aspiring to perpetually use elements, compounds, and materials without depletion of resources or accumulation of waste".[54] The report also contains "Attributes and considerations to operationalize the definition of sustainable chemistry" with the categories of: Efficiency, Energy, Circularity, Hazard, Social, and Economic. While the OSTP definition is longer and perhaps less actionable than that of ECOSChem, there are points of overlap between them in terms of criteria categories, and the report includes the consideration of environmental justice concerns. A challenge for both will be determining metrics for measuring progress or fulfilment of sustainable chemistry.

A next phase of this project may include advocacy to advance public and private sector investments in sustainable chemistry that meet the areas of criteria and collaborating with organizations such as OSTP on efforts to develop metrics and assessment tools for different sectors and contexts further, as well as case examples of chemistries and applications that meet the definition. Additionally, bringing the ECOSChem definition into global efforts such as the United Nations Sound Management of Chemicals and Waste Beyond 2020 process would advance and help adopt the definition and criteria globally, including how metrics might shift given different cultural and economic perspectives.

Conclusions

Chemistry and the chemical industry have played a critical role in advancing the quality of human life and sustainable development, but those benefits have come at a price. The Expert Committee on Sustainable Chemistry (ECOSChem) was established to create a consensus definition and criteria for sustainable chemistry that represented a broad range of perspectives, that was actionable, and that built upon previous definitions. The definition developed added new concepts such as equity and transparency, which are critical to ensuring that chemistry innovation not only avoids harm, but restores past damage and provides opportunities for those who have not previously benefited from chemistry. The effort, including external engagement sessions, demonstrated that while there may be differences of opinion as to the scope and magnitude of the problem (*e.g.*, which chemicals are problematic, who is responsible for past harms, *etc.*), common ground can be found in defining a vision for the future. The challenge now lies in the implementation of this definition and criteria – not only into new chemical and material designs, but also in prioritizing the chemicals and materials where innovation and transition are urgently needed. Progress will be made if the core elements of the definition and criteria are infused into considerations for government, investment, and corporate decision-making on chemicals and materials, as well as in the training of the next generation of chemists and materials scientists. Ultimately, to have their maximum impact, metrics and tools to evaluate and disclose information on whether chemicals, materials, processes, products, and services meet or are progressing towards the definition and criteria will be needed to ensure that policies, investments, and decisions are accountable to moving towards sustainable chemistry, understanding that this journey will be one of continuous improvement over the coming decades.

Author contributions

Amy Cannon: conceptualization, writing – review & editing, funding acquisition. Sally Edwards: conceptualization, methodology, writing – review & editing, visualization. Molly Jacobs: conceptualization, methodology, investigation, Jonathon W. Moir: conceptualization, methodology, investigation, formal analysis, writing – original draft, writing – review & editing, visualization. Monika A. Roy: conceptualization, methodology, investigation, formal analysis, writing – original draft, writing – review & editing, visualization. Joel A. Tickner: conceptualization, writing – review & editing, visualization, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was funded by the New York Community Trust. The authors would like to thank ECOSChem members for their time, feedback, and contributions to this development of this work, and in particular Ryan Bouldin, Abigail Noble, and Saskia van Bergen for their careful review of this manuscript. The authors would also like to thank all those who participated in the external engagement sessions or who provided feedback on the draft definition and criteria *via* email or survey response. This feedback was crucial for the final revisions process.

References

1 L. Persson, B. M. Carney Almroth, C. D. Collins, S. Cornell, C. A. de Wit, M. L. Diamond, P. Fantke, M. Hassellöv, M. MacLeod, M. W. Ryberg, P. Søgaard Jørgensen, P. Villarrubia-Gómez, Z. Wang and M. Z. Hauschild, *Environ. Sci. Technol.*, 2022, **56**, 1510–1521.
2 J. Tickner, K. Geiser and S. Baima, *Environment: Science and Policy for Sustainable Development*, 2021, 63, pp. 4–15.
3 *Global Chemicals Outlook II: from Legacies to Innovative Solutions*, United Nations Environment Programme, 2019.
4 SystemIQ and Center for Global Commons and University of Tokyo, *Planet Positive Chemicals: Pathways for the Chemical Industry to Enable a Sustainable Global Economy*, 2022.
5 J. A. Tickner, K. Geiser and S. Baima, *Environment: Science and Policy for Sustainable Development*, 2022, 64, pp. 22–36.
6 European Commission, *Transition Pathway for the Chemical Industry*, European Commission, Luxembourg, 2023.
7 J. J. MacKellar, D. J. C. Constable, M. M. Kirchhoff, J. E. Hutchison and E. Beckman, *J. Chem. Educ.*, 2020, **97**, 2104–2113.
8 Green Chemistry and Commerce Council, *Advancing Green Chemistry: Barriers to Adoption & Ways to Accelerate Green*

Chemistry in Supply Chains, T. Fennelly & Associates, Inc., 2015.
9 I. T. Horváth, *Chem. Rev.*, 2018, **118**, 369–371.
10 G. H. Brundtland, *Our Common Future: Report of the World Commission on Environment and Development*, Geneva, UN-Dokument A/42/427, 1987, **http://www.un-documents.net/ocf-ov.htm**.
11 K. Kümmerer and J. Clark, in *Sustainability Science*, Springer, 2016, pp. 43–59.
12 J. Hill, D. D. Kumar and R. K. Verma, *Journal of the American Institute of Chemists*, 2013, **86**, 24–31.
13 P. Marion, B. Bernela, A. Piccirilli, B. Estrine, N. Patouillard, J. Guilbot and F. Jérôme, *Green Chem.*, 2017, **19**, 4973–4989.
14 C. Blum, D. Bunke, M. Hungsberg, E. Roelofs, A. Joas, R. Joas, M. Blepp and H.-C. Stolzenberg, *Sustainable Chem. Pharm.*, 2017, **5**, 94–104.
15 European Commission. Joint Research Centre, *Safe and Sustainable by Design Chemicals and Materials: Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials.*, Publications Office, LU, 2022.
16 *Key Issues in Chemicals Policy on the Road to a Non-toxic Environment*, Council of the European Union, Brussels, Belgium, 2014.
17 G. Goldenman, M. Holland, J. Lietzmann, L. Meura, M. Camboni, A. Reihlen and J. Bakker, *Study for the Strategy for the Non-toxic Environment of the 7th Environment Action Programme (EAP)*, European Commission, Brussels, Belgium, 2017.
18 A. Halpaap and J. Dittkrist, *Curr. Opin. Green Sustainable Chem.*, 2018, **9**, 25–29.
19 United Nations Environment Programme, *Green and Sustainable Chemistry: Framework Manual*, United Nations Environment Programme, 2021.
20 Organization for Economic Cooperation and Development, *Proceedings of the OECD Workshop on Sustainable Chemistry*, Environment Directorate, Organization for Economic Cooperation and Development, 1999.
21 Organization for Economic Cooperation and Development, *Sustainable Chemistry Brochure, Environment Directorate*, 2004, Organization for Economic Cooperation and Development, **https://www.oecd.org/env/ehs/risk-management/29361016.pdf**.
22 German Environment Agency, *Guide on Sustainable Chemicals A decision tool for substance manufacturers, formulators and end users of chemicals*, Umweltbundesamt, 2016, ISSN 2363-832X, **https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/161221_uba_fb_chemikalien_engl_bf.pdf**.
23 A. Bazzanella, H. Friege and B. Zeschmar-Lahl, *Identification of Priority Topics in the Field of Sustainable Chemistry*, Umweltbundesamt, 2017, **https://www.umweltbundesamt.de/publikationen/identification-of-priority-topics-in-the-field-of**.
24 CEFIC, *Input Paper on the Chemicals Strategy for Sustainability*, European Chemical Industry Council - CEFIC, 2020, **https://cefic.org/app/uploads/2020/09/Cefic-Input-Paper-Chemical-Strategy-for-Sustainability-CSS.pdf**.
25 CEFIC, *Safe and Sustainable by Design Report: Boosting Innovation and Growth within the European Chemical Industry*, Cefic, 2021.
26 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford [England]; New York, 1998.
27 United Nations General Assembly, *Transforming Our World: the 2030* Agenda for Sustainable Development, 2015.
28 American Chemical Society, *Chemistry & Sustainable Development Goals: Which SDGs Are Most Relevant to Chemistry?*, **https://www.acs.org/sustainability/chemistry-sustainable-development-goals.html**.
29 European Commission, *Chemicals Strategy for Sustainability: towards a Toxic-free Environment*, European Commission, Brussels, Belgium, 2020.
30 *116th Congress (2019–2020), 2nd Session, Sustainable Chemistry Research and Development Act of 2019. S. 999*.
31 *Office of Science and Technology Policy*, Request for Information, **https://www.federalregister.gov/documents/2022/04/04/2022-07043/request-for-information-sustainable-chemistry**, accessed 21 February 2023.
32 United States Environmental Protection Agency, *Environmental Justice*, **https://www.epa.gov/environmentaljustice**.
33 European Council, Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control**https://wayback.archive-it.org/12090/20151024070420/http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31996L0061**, accessed 21 August 2023.
34 A. van Roon, H. A. J. Govers, R. John and H. van Weenen, *International Journal of Sustainability in Higher Education*, 2001, **2**, 161–180.
35 Dow Chemical, *Sustainable Chemistry: The Sustainable Chemistry Index*, 2015, **http://storage.dow.com.edgesuite.net/dow.com/sustainability/goals/50409-SustainableChemistry-WPaper-Digital.pdf**.
36 Green Chemistry and Commerce Council, *Joint statement on using green chemistry and safer alternatives to advance sustainable products*, 2016, **https://greenchemistryandcommerce.org/documents/RLC-JointStatement.pdf**.
37 Government Accountability Office (GAO), *Chemical Innovation: Technologies to Make Processes and Products More Sustainable*, 2018.
38 United Nations Environment Programme (UNEP), *Analysis of Stakeholder Submissions on Sustainable Chemistry Pursuant to UNEA Resolution* 2/7, Nairobi, 2019.
39 United Nations Environment Programme (UNEP), *Advancing Entrepreneurship and Start-Up Initiatives for Sustainable Chemistry*: Learning from Case Studies, Berlin, Germany, 2017.
40 Expert Committee on Sustainable Chemistry (ECOSChem), *Definition and Criteria for Sustainable Chemistry: Created by the Expert Committee on Sustainable Chemistry (ECOSChem)*, 2023.
41 International Energy Agency (IEA), *Chemicals*, International Energy Agency (IEA), Paris, 2022.

42 K. Groh, C. vom Berg, K. Schirmer and A. Tlili, *Environ. Sci. Technol.*, 2022, **56**, 707–710.
43 Green Chemistry and Commerce Council, *Green Chemistry & Commerce Council (GC3)*, https://greenchemistryandcommerce.org/.
44 *Green Chemistry and Commerce Council (GC3)*, 2015.
45 Clean Production Action, *The Chemical Footprint Project*, https://chemicalfootprint.org/.
46 Investor Environmental Health Network, *A Leadership Network of Investors Reducing the Financial Risks of Chemical Pollution while Leveraging the Economic Value of Green Chemistry*, https://iehn.org/, accessed 22 February 2023.
47 World Business Council for Sustainable Development (WBCSD), *Chemical Industry Methodology for Portfolio Sustainability Assessments (PSA)*, World Business Council for Sustainable Development (WBCSD), 2018.
48 Coming Clean, Inc., *The Louisville Charter for Safer Chemicals*, https://comingcleaninc.org/louisville-charter/endorse, accessed 22 February 2023.
49 Beyond Benign, *Beyond Benign Provides Educators with the Tools, Training and Support to Make Green Chemistry an Integral Part of Chemistry Education.*, https://www.beyondbenign.org/, accessed 22 February 2023.
50 Berkeley Center for Green Chemistry, Berkeley Center for Green Chemistry: Innovation for Safer Materialshttps://bcgc.berkeley.edu/, accessed 22 February 2023.
51 *Chemical Strategies Partnership*, Implement CMS, http://www.chemicalstrategies.org/implement.php, accessed 22 February 2023.
52 U.S. Environmental Council, *Of the States, Resolution 17-1: Advancing Safer Chemical Products and Processes*, https://www.ecos.org/documents/resolution-17-1-advancing-safer-chemical-products-and-processes/.
53 UBS Sustainability and Impact, *Chemical Pollution and the Need to Transition to Sustainable Chemistry: the True Cost of Toxic Chemical Substances Is Not Captured by a GDP-Driven Economy*, https://www.ubs.com/global/en/sustainability-impact/sustainability-insights/2023/sustainable-chemistry.html.
54 Sustainable Chemistry Strategy Team of the National Science and Technology Council, *Sustainable Chemistry Report: Framing the Federal Landscape*, Joint Committee on Environment, Innovation, and Public Health, 2023, https://www.whitehouse.gov/wp-content/uploads/2023/08/NSTC-JCEIPH-SCST-Sustainable-Chemistry-Federal-Landscape-Report-to-Congress.pdf.