RSC Sustainability

PAPER

View Article Online
View Journal | View Issue

Cite this: *RSC Sustainability*, 2025, **3**, 4724

Metrics are the key: development of criteria and indicators for measuring sustainability in international chemicals management

C. Blum, *[a] B. Zeschmar-Lahl, [b] E. Heidbüchel, [c] H. C. Stolzenberg, [d] K. Kümmerer, [e] A. Becker[f] and H. Friege *[g]

Received 26th February 2025
Accepted 8th August 2025

DOI: 10.1039/d5su00135h

rsc.li/rscsus

Materials and products provided by the chemical industry and related sectors are indispensable for a satisfactory living standard and high standard of health. On the other hand, emissions from resource extraction, production, unsustainable use, and inadequate disposal of chemicals and related products contribute significantly to the pollution of the planet. To address the aforementioned issues on a global level, the "Global Framework on Chemicals" was launched in 2023. It presents a comprehensive plan with 28 targets jointly addressing the lifecycle of chemicals. In addition to efforts to ensure the sound management of chemicals and waste, the targets are partially oriented towards the concept of sustainable chemistry due to its search for innovative and sustainable solutions across the complete value chain of chemicals. To enable and monitor the implementation of this framework, indicators are needed to show progress towards the targets. This paper presents indicators that are based on an internationally established understanding of sustainable chemistry. To consider the target relevance of each indicator as well as its suitability, criteria were developed to assess the viability of the proposed indicators. The criteria as well as the suggested indicators were discussed with international experts and in stakeholder workshops that involved all six UN regions. The evaluation of these meetings ultimately led to a set of 23 indicators based on the previously defined criteria. It is demonstrated that these indicators can be used to measure the progress towards the targets of the Global Framework on Chemicals.

Sustainability spotlight

The concept of sustainable chemistry is used for the development of progress indicators for the Global Framework on Chemicals (GFC). We present criteria for deriving and testing indicators for the international management of chemicals and waste. Although the sound management of chemicals and waste relates to SDG 12, the indicators refer also to numerous other SDGs and thus focus on chemicals and their utilization as part of sustainable development. Due to the interdisciplinary nature of sustainable chemistry, the indicators comprise interfaces with global management of resources, health protection, climate protection, the circular economy and biodiversity.

1. Introduction

Chemicals undeniably contribute to human advancement through innovations *e.g.* in healthcare, agriculture, food security, and the development of new materials, driving economic growth and job creation. The chemical industry is one of the most important industrial branches. Global sales of the chemical sector are projected to reach US$ 6.3 trillion by 2030. At the same time, chemicals cause significant environmental and social harm through resource demands, toxic properties, emissions and waste from their production, incorrect application, excessive use and end of life issues of products, and their release into or application in the environment. Thus, chemicals also cause numerous deaths and diseases, and contribute to biodiversity loss, environmental pollution, and resource depletion.[1] Moreover, there are risks associated with accidents

[a]*Umweltbundesamt (German Environment Agency), Germany. E-mail: christopher.blum@uba.de*
[b]*BZL Kommunikation und Projektsteuerung GmbH, Germany. E-mail: bzl@bzl-gmbh.de*
[c]*Collaborating Center for Consumption and Production, CSCP, Germany. E-mail: esther.heidbuechel@cscp.org*
[d]*Umweltbundesamt (German Environment Agency), Germany. E-mail: hans-christian.stolzenberg@uba.de*
[e]*Leuphana University, Lüneburg, Germany. E-mail: Klaus.kuemmerer@leuphana.de*
[f]*International Sustainable Chemistry Collaborative Center – ISC$_3$, Germany. E-mail: anna.becker@isc3.org*
[g]*N^3 Thinking Ahead, Dr Friege & Partners, Germany. E-mail: Friege@N-hoch-drei.de; Web: **http://www.n-hoch-drei.de***

and resulting disasters in manufacturing plants. Disasters have caused long-lasting environmental and health impacts, underscoring the pressing need for safer chemical practices.[1] The chemical industry is responsible for 7.4% of global greenhouse gas (GHG) emissions and 10% of the world's total energy demand.[2] Thus, the chemical sector contributes significantly to climate change. "Chemical pollution" by non-natural chemicals is grouped together with genetically modified organisms as novel entities in the concept of planetary boundaries.[3] "Novel entities" include not only persistent and toxic organic pollutants and heavy metals, but also microplastics and hazardous nanomaterials.[4] Though it is not possible to assess planetary boundaries for pollution by chemicals in general, "an increasing body of evidence strongly suggests that we need more effective global chemicals management".[5] Recent scientific work assumes that the planetary boundaries have been exceeded by the use of chemicals, polymers, and pharmaceuticals.[6] Ubiquitous chemical contamination by persistent organic pollutants, toxic metals, antibiotics emitted into the environment, the flood of plastic products that are not collected and disposed of correctly *etc.* is widely considered as a contributor to the planetary triple crisis, interlinked with climate change and biodiversity loss.[7] Therefore, it is necessary to consider the interlinkages between threats and benefits from the use of chemical substances in materials and products on the one hand, and climate and biodiversity on the other. This is complex and requires appropriate frameworks, criteria and indicators, and methods and tools that address the interlinked challenges[1,8] mentioned above in an overarching manner.

On the political level, this work is supported by the implementation activities of the "Global Framework on Chemicals" (GFC),[9] which was mandated by the fifth International Conference on Chemicals Management (ICCM5) in 2023. The GFC aims to pave the way for the sustainable management of chemicals and waste, as well as the prevention of pollution. To achieve this, the GFC sets five strategic objectives with 28 targets for the management of chemicals worldwide over their entire life cycle. These strategic objectives and targets are to be implemented across all sectors and within defined deadlines.

In order to measure the progress or setbacks on the road taken, suitable indicators are required, for which the United Nations Environment Programme (UNEP) has set up an open-ended working group.[10] The concept of sustainable chemistry (see Section 2.3) is well suited for the development of indicators, because it not only focuses on the synthesis and properties of chemicals, but also on the interdependencies of the ecological, social and industrial aspects of the production, as well as the use and disposal of chemicals.

This study aims to develop suitable indicators for the GFC. We therefore explain the political background of the international management of chemicals and waste and give a brief outline of the concept of sustainable chemistry (Section 2). The objective of the study is described in detail in Section 3 (Scope). In developing the indicators, previous findings on the benefits and nature of indicators for international chemicals management on the one hand and the scientific basis of sustainable chemistry on the other were brought together (Methods, Section 4). We present a list of potential indicators based on suitable criteria (Section 5) and discuss their value for the GFC (Section 6). In the final section (Conclusion, Section 7), we provide an outlook on the opportunities that this approach offers for the next UN agenda and a science-policy panel that is currently under negotiation.

2. Background

2.1. Strategic approach to international chemicals management (SAICM)

Agenda 21, adopted by the Global Summit in Rio de Janeiro,[11] emphasized the essential crosscutting role of sound chemicals management for sustainable development in the realm of the United Nations. In the following years, some key instruments for the safe handling of substances were developed, such as the Globally Harmonised System (GHS).[12] The Johannesburg World Summit on Sustainable Development in 2002 adopted a "Strategic Approach to International Chemicals Management (SAICM)", with which the goal of "sound management of chemicals throughout their life cycle and of hazardous wastes for sustainable development" was to be realized. The goal was to achieve, by 2020, that "chemicals are produced and used in ways that minimize significant adverse impacts on the environment and human health".[13] It aimed to complement the international chemicals and waste framework by including existing multilateral agreements (Stockholm, Basel and Rotterdam Conventions) and addressing the need for and importance of comprehensive national chemicals management frameworks.[14] SAICM[15] and its successor GFC (see Section 2.2) are "multi-stakeholder, multi-sector, voluntary policy frameworks" under the auspices of UNEP. The Inter-Organization Programme for the Sound Management of Chemicals (IOMC, a cooperation project of ten international institutions, *i.a.* UNEP, WHO, ILO, OECD, UNIDO, World Bank, coordinating their work on chemicals) were thus given a corresponding mandate. After the adoption of Agenda 2030 in 2015,[16] IOMC developed an attempt to spell out the particular relevance of SMCW for reaching other SDGs.[17] Nevertheless, explicit reflections of this essential and cross-cutting relevance of chemicals management remained very sparse in the global indicator framework for the SDGs,[18] often output-oriented rather than outcome- and impact-oriented. A list of indicators described as "a concise set of quantitative indicators from verifiable sources and for which global data are available" was developed by the IOMC in order to contribute to tracking future progress of SAICM.[17] They map, among other things, the number of countries which are party of a convention (*e.g.* Stockholm Convention on POPs) or have established basic facilities for SMCW (*e.g.* GHS, poison centres). But only a few indicators consider interfaces with other issues like health.

SAICM has been instrumental in promoting the sound management of chemicals and waste (SMCW), but many targets were not or were only partially met by 2020.[1] Overall and in spite of the many implementation shortcomings identified, an independent evaluation concluded that SAICM has been an ambitious and unique global policy framework on SMCW and that retaining its strength and character would be highly recommendable in a significantly more effective successor framework.[19]

2.2. Global framework of chemicals (GFC)

International management of chemicals and waste long focused on the mitigation of problems caused by hazardous chemicals. The need for integrating the life cycle of materials and products in the SAICM-successor framework became particularly clear as a result of the 2030 Agenda with its 17 Sustainable Development Goals (SDGs) and 169 underlying targets though "sound management of chemicals and waste" (SMCW) at first sight merely addresses target 12.4.† However, this must be seen in the context of the preamble which states that all SDGs and targets are integrated and indivisible also balancing the three dimensions of sustainable development: economic, social and environmental. The UNEA (United Nations Environmental Assembly) resolutions in 2016 (ref. 20) and 2019 (ref. 21) recognised the concept of sustainable chemistry as an opportunity for further progress in managing the risks and benefits of chemicals. These resolutions influenced the consultations and the work until September 2023, when the ICCM5 adopted the GFC.[9] The GFC aims to pave the way for the sustainable management of chemicals and waste as well as the prevention of pollution. Five strategic objectives with 28 targets are to be implemented across all sectors and within defined deadlines. The targets are time-bound. It is planned to monitor their achievement using suitable indicators. This new framework adds some elements that SAICM lacked that are needed to improve chemical management in a cross-sectoral and multi-stakeholder manner: most importantly, the measurability framework must be concretised by indicators, to track the progress or the delay with respect to the targets. Additionally, there will be specific provisions on capacity building as well as a more active role envisioned for the IOMC participating organizations. Another focus is on initiating and expanding a set of guidance and institutions for the implementation of chemicals management in developing and emerging countries. Finally, a set of implementation programmes will be initiated to spark and guide sector-based initiatives between chemical producers and users such as textiles or pesticides.[22]

2.3. Sustainable chemistry

As a reaction to the increasingly visible pollution of the environment by chemical waste, effluents and exhaust into the air and its impact on health and the environment as well as catastrophes related to production plants, ambitions to prevent such pollution started in the chemical industry in the 1970s and 1980s.[23–25] Improved methods of catalysis to increase the yields of chemical syntheses and the reduction of waste, and design, development and implementation of chemical processes and products to reduce or eliminate substances hazardous to human health and the environment were addressed in the late 1980s and early 1990s.[26–29] In the Rio Declaration within Agenda 21 in 1992 it was stated that it is important for research to intensify the development of safe substitutes for chemicals with long life cycles (#19.21 (ref. 11)). The United Stated Environmental Protection Agency (US EPA) introduced the term "green chemistry" to promote this in the early 1990s. In 1996, the European Commission (EC) Council Directive (96/61/EC) came into force requesting integrated pollution prevention in chemical and other industrial production. It names groups of chemicals which should be avoided in its Annex III and 12 principles in Annex IV addressing a more integrative view.[30–33]

The 12 principles of green chemistry were published in 1998, only "just summarising what was already commercialised in industry".[23] These synthesis related pollution prevention efforts including green chemistry can be summarized as synthesizing less hazardous chemicals in a safer manner using less energy and generating less waste. Whilst there are clear merits of the EC directive, of pollution prevention activities and of the green chemistry concept, products synthesized accordingly are not necessarily greener or more sustainable. These approaches do not consider the basic principles of sustainability.[34] In the 2000s, the circular economy was "re-invented"[35–37] after the basic concept has already been elaborated in 1982.[38–40] In a publication introducing circular chemistry a zero-waste industry was envisaged.[41] This is impossible, however, because of the basic laws of thermodynamics.[42] Nowadays' wasting of resources and products resulted from seemingly endless availability of resources and economic thinking neglecting its own material basis.[43–47] Mainstream circular economy is referring to nature's material cycles without further mentioning the severe limitations of such an analogy, neglecting at the same time the basic laws of nature.[45,46,48]

The concept of sustainable chemistry focuses on the desired function of a substance or material. Therefore, alternative ways of fulfilling the intended function without using chemicals (non-material-based delivery of services and functions) are taken into account first. "Chemical service"[49] is in second place, because this is an important view and approach to making use of chemicals more sustainable. The concept of sustainable chemistry[50–53] addresses the shortcomings of green and circular chemistry and seeks to embed the chemical sector into sustainability (at present based on the SDGs)[54] as well as the planetary boundaries by identifying sustainable contributions by chemistry to sustainable development. This encompasses all three strong sustainability strategies, *i.e.* sufficiency, consistency, and efficiency, and is based on an ethical background.[55] This process engages all stakeholders along the life cycle of products.

Through its holistic approach and "systems thinking",[56,57] sustainable chemistry takes into account important interfaces, especially with the extraction and use of natural resources, waste management and climate protection. It therefore focuses not only on the environmental compatibility of a substance, but also on the opportunities and risks of its use as well as of not

† Target 12.4: "By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment".

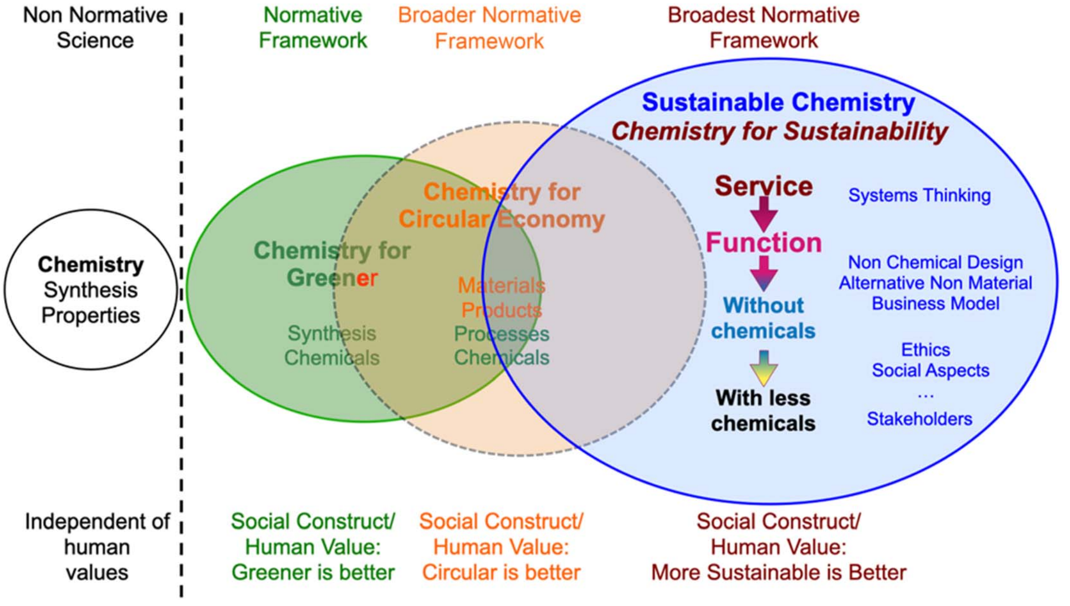

Fig. 1 Development towards sustainable chemistry – from left to right: historical development, from right to left: practical application.

using it, its production, and its recycling or disposal.[58] These relationships are shown in Fig. 1.

Greener chemistry, circular chemistry and sustainable chemistry are neither synonyms, nor in opposition to each other (see Fig. 1). Greener chemistry and circular chemistry both are important tools for greener and more circular products of chemical industries and the whole chemical sector. However, the decisive point is sustainable chemistry using systems and service and function-oriented thinking, thus allowing chemistry to contribute to sustainable development in a sustainable manner. Because of its integrated and holistic approach, the concept of sustainable chemistry provides a conducive basis for developing indicators to measure advancements of chemicals management integration into sustainable development.

3. Scope of the project

The 2023 adopted "Global Framework on Chemicals" (GFC)[59] aims to ensure the sustainable management of chemicals worldwide throughout their entire life cycle, including the products manufactured from them and the waste generated after use (*cf.* Section 2.2). This approach is in line with the concept of sustainable chemistry (*cf.* Section 2.3) that appears to be an excellent overarching guideline to reach the targets of the GFC. In particular, the extensive set of targets under GFC's strategic objective D ("Safer alternatives and innovative and sustainable solutions in product value chains…") provides multiple opportunities for using the concept of sustainable chemistry at the global level. In the follow-up, a set of suitable output- as well as impact-oriented indicators is needed to verify whether or to what extent the targets of the GFC have been achieved.

Ahead of the ICCM5, different actors worked on the development of criteria and/or indicators on tracking progress regarding the three dimensions of sustainability in chemicals management, guided by the concept of sustainable chemistry:

• In 2016, the German Environment Agency (UBA) published its "Guide on sustainable chemicals",[60] which served as a basis for the development of the online application "ChemSelect".[61] This application focuses on characteristics of individual substances as well as the responsibility of suppliers along the value chain. These are depicted by nine sustainability criteria, including, *e.g.*, sub-criteria on (eco-) toxicity, persistence and mobility, circularity, and greenhouse gas potential as well as social aspects. Though the approach of ChemSelect contributes to sustainable chemistry on a practical level, the indicator set seems too specific, not established enough and data very hard to collect on a global level.

• In 2019, the International Pollutants Elimination Network (IPEN), an association of some 600 local and national initiatives, proposed a list of 160 indicators on "Chemical Safety Contributions to the SDGs".[62] Although the focus here is on chemical safety, several proposals go beyond this purpose and address also aspects of sustainable chemistry.

• In 2020, the United Nations Environment Programme (UNEP) published its Framework Manual on Green and Sustainable Chemistry, based on a decision of UNEA 4 (2019, Resolution 4/8) and with broad international participation of experts from academia, international organizations, non-governmental organizations, and industry associations.[63] The manual focuses on ten guiding principles (including "Avoiding regrettable substitutions" or "Maximizing social benefit") and provides numerous examples of how work based on sustainable chemistry can contribute to sustainable development in multiple sectors and what conditions must be met in each case.

• In 2021, the International Sustainable Chemistry Collaborative Centre (ISC_3) published a dialogue paper on "Key Characteristics of Sustainable Chemistry".[58] The authors describe their approach as follows: "Sustainable chemistry is achieved, if chemistry contributes in a sustainable manner to sustainability. In other words, the principles of sustainability are applied to and implemented into the chemical sector" including downstream users of chemical products. The ten key characteristics include holistic and systems thinking, ethical and social responsibility, a life cycle approach, and circularity as well as sustainable and responsible innovation.

Considering the political and scientific background (see Section 2) as well as the sets of indicators already used or proposed (see above), we aimed to develop indicators for the GFC. We focused on the following questions:

• What basic criteria should indicators fulfil to be suitable for an international network?

• Which elements of the concept of sustainable chemistry should be covered by the indicators?

• How should one consider the gaps and deficits in previous policy approaches, especially in SAICM?

• Which indicators can be combined to monitor the achievement of SMCW as a basic objective and show progress towards more sustainable chemistry?

Based on the experience with SAICM described in Section 2, two key aspects must be considered:

• The indicators should be as simple and reliable as possible to measure.

• They must take into account the perspective of economically advanced countries and countries in transition as well.

Commissioned by the German Environment Agency (UBA), the project was executed while the ICCM5 was prepared under the German presidency. As objectives and targets were under discussion till September of 2023, it was necessary to carefully observe their negotiating process to formulate the indicators as closely as possible to the targets as adopted with the GFC at ICCM5. As follow-up, a working group within GFC is currently developing a measurability structure including indicators.[64] Therefore, in a final step, we discuss how the indicators can be assigned to the targets adopted for the GFC.

4. Methods

Our project aimed at a set of yardsticks for environmental and social development. Studies of this kind at the interface between science and politics require a recognized scientific basis, should be comprehensible for social discussion and, if possible, be applied by the responsible political body. In the present case, the body consists of a small number of politicians, but also of high-ranking officials from national and international administrations, experts from industry associations and NGOs. The project did not focus on political objectives, but aimed at metrics that make the level of achievement of the GFC targets measurable. Nevertheless, the result must be politically acceptable. To address the objectives and the constraints outlined above (Section 3), the following methodological decisions were made:

(1) Indicators should meet various requirements, on the one hand formal criteria like measurability, on the other hand relevance criteria, *i.e.* either for targets not yet achieved (SMCW as formulated by SAICM) or for the future orientation towards the concept of sustainable chemistry. The selection of criteria should be completed before the discussion of indicators.

(2) Where possible, indicators should be taken from existing international treaties or be similar to indicators already in use or be easily recordable at the national level.

(3) Because of the links between production, use and disposal of chemicals with global challenges like increasing greenhouse gas emissions, declining biodiversity and pollution, the involvement of experts from outside the chemical sector was considered indispensable.

(4) Given the different perspectives of countries and levels of industrial development, the preliminary results should be discussed with experienced stakeholders from different continents.

4.1. Survey of international treaties, agreements and standards

First, national and international treaties and voluntary agreements, standards, and frameworks were reviewed which intersect with "sound management of chemicals and waste" (SMCW) or the concept of sustainable chemistry, to identify potential indicators for use in the SAICM beyond the 2020 process. This included treaties and programs directly focusing on chemicals and waste (like, *e.g.*, the Minamata Convention, Basel Convention, and Responsible Care®), as well as initiatives on, *e.g.*, sustainability reporting, health, climate action, and biodiversity. A detailed review covered more than 40 global and regional agreements (Table 1) as well as some national programs from industrialized and emerging countries. The sources used for the documents listed in Table 1 are provided in Appendix A (see the SI).

Findings were summarized in detailed fact sheets that followed a standardized format, providing:

• A brief overview of the document,

• An assessment of how well the indicators align with then SAICM's goals,

• Links to broader goals and targets, and

• Possible indicators that could be incorporated into SAICM or its successor.

Additionally, fact sheets offered ideas for new indicators based on each document (*cf.* Table 1) referring to instruments, objectives, and regional implementation where available. Around 200 indicators of interest for "SAICM beyond 2020" were identified.

Moreover, three lists of indicators under discussion were taken into consideration:

• The "global indicator framework" for the 2030 Agenda,[18]

• a list that had been developed by the responsible SAICM Technical Working Group,[65,66] but not adopted until ICCM5,

• the "Chemical Safety Contributions to the SDGs" proposed by the International Pollutants Elimination Network (IPEN).[62]

4.2. Expert dialogues

4.2.1. Dialogue subjects. In the first round of discussions (6–8/2020), six internationally renowned experts were

Table 1 List of documents checked for potential indicators[a]

Type of document	Titles of documents
World-wide (UN) conventions and related resolutions/decisions	**A**ichi Biodiversity Targets, **K**unming-Montreal Global Biodiversity Framework, **B**asel Convention, **N**agoya Protocol, **G**lobally Harmonised System of classification and labelling of chemicals (GHS), **I**LO Chemicals Convention No. 170 (1990), **I**LO Prevention of Major Industrial Accidents Convention No. 174 (1993), **M**inamata Convention, **M**ontreal Protocol, **S**DG indicators, **U**N SDG Compass, **S**tockholm Convention, **W**HO International Health Regulations
World-wide (UN) voluntary and non-binding approaches	**D**ubai Declaration, **I**nternational Panel on Climate Change (IPCC), **I**ntergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), **I**OMC Toolbox, **L**IRA Guidance (legal and institutional infrastructure for the sound management of chemicals), **S**AICM indicators, SAICM **T**WG4 new approaches, Sustainability Framework (World Bank), **U**N System of Environmental Accounting – SEEA
Other international conventions	**O**SPARCOM (convention for the protection of the marine environment of the North-East Atlantic), **P**RTR (pollutant release and transfer registers)
Globally used non-binding reporting systems for governments and corporates	**C**OFOG reporting, UN **G**lobal Compact, **G**lobal Reporting Initiative (GRI)
Sustainability and reporting standards of the chemical industry	**R**esponsible Care©, **C**hemie,[3] **G**lobal Product Stewardship, **T**ogether for Sustainability – TfS, **W**BCSD PSA guideline
Commercial stock and investment indexes	**D**JSI – Dow Jones Sustainability Index, **E**coVadis, **F**TSE 4 good, **M**SCI ACWI sustainable impact index, **M**SCI ESG indexes
Standards and publications by the OECD and related organisations	**I**EA: future of hydrogen, **O**ECD sustainability reporting
Reporting systems of non-profit associations and non-governmental organisations	**C**arbon Disclosure Project (CDP), **C**ircular Economy Approaches (Ellen Mac Arthur Foundation), **E**conomy for the Common Good - ECG (former GWÖ approach), **I**PEN thought starter on milestones and indicators, **S**cience Based Targets for Nature (SBTN), **S**ustainability Accounting Standards Board (SASB)
EU regulations, directives, and programmes	**E**U chemicals strategy for sustainability strategy (EU CSS) **E**U circular economy action plan (EU CEAP) **E**U: corporate social responsibility directive (CSRD) **E**U safe and Sustainable by design (SSbD) chemicals and materials **S**ustainable public procurement (SPP) approaches
Indicators and tools provided/proposed by scientific organisations	**H**uman Bio-Monitoring (HBM)
Other regulations, programmes, and approaches on a national or corporate basis (examples)	**L**ieferkettensorgfaltspflichtengesetz (German Supply chain due diligence Act), **M**alaysia Bioeconomy Corporation, **M**anagement approaches for sustainable corporate governance (*e.g.*, TIMM), **N**ational Hazardous Waste Management Plan (NHWMP) (2014–2020) of Ireland, **S**outh African Bioeconomy Strategy, **U**NITAR national profiles

[a] The sources for these documents are provided in Appendix A (see the SI). To facilitate searching, the keywords are listed alphabetically (letters highlighted in bold in this table).

interviewed on which aspects of sustainable chemistry should be integrated into SAICM, which indicators from existing conventions, statistics of the chemical industry or the like are suitable and how investments in sustainable chemistry can be incentivized.

The second round of interviews (10–12/2020) with another six experts focused on the criteria used to evaluate indicators, especially indicators from conventions, treaties, frameworks, approaches *etc.*, which have proven to be useful, what effort for measuring and controlling is required, recommended modifications of indicators for monitoring progress in shifting investments to sustainable chemicals management, and existing reporting or monitoring systems.

The third round of interviews (5/2021–3/2022) with another nine experts focused on the interfaces between sustainable chemistry and other global problem areas (climate, health, labour, biodiversity, agriculture, *etc.*) and corresponding indicators, with the questions being geared to the respective areas of expertise of the interviewees.

The last round consisted of two interviews (3/2023 and 6/2023). The focus of the first was on the question of how to enforce the application of indicators in the SAICM or its successor process and on waste and its potential links to sustainable chemistry from the viewpoint of an NGO. The other interview was about the use of key performance indicators (for progress in the field of sustainable chemistry and further development of portfolio sustainability assessments (PSA)) by the chemical industry.

4.2.2. Dialogue partners. In sum, the team conducted 24 dialogues, almost exclusively *via* video. The results were recorded in writing and agreed upon with the referring dialogue partner. Table 2 summarizes the distribution of the dialogue

Table 2 Distribution of dialogue partners

Region stakeholder group	Asia + Pacific	Europe	Latin America + Caribbean	North America	Global	Sum
Industry	—	4	1	1	—	6
International organisation	—	—	—	—	3	3
Network (science, economy, politics and society)	—	1	—	1	—	2
NGO	—	1	—	1	—	2
Policy/administration	—	1	—	—	1	2
Academia	1	4.5[a]	2	1	0.5[a]	9
Sum	1	**11.5**[a]	3	4	**4.5**[a]	24

[a] One expert with double function is counted 0.5 twice.

partners regarding stakeholder group and region. The proportion of female dialogue partners was one sixth (4/24). Annex B contains more details concerning the dialogue partners' background. For further details see the project report.[67]

Efforts were made to include experts from all UN regions and to involve persons from academia, research, industry and international as well as non-governmental organizations as evenly as possible. Contacting and scheduling discussions were not always successful, especially in Africa, Asia, the Middle East and Oceania. It is likely that chiefly contacts in national administrations had other work priorities during the COVID-19 pandemic.

4.3. Workshops in the UN regions

Due to the Covid-19 pandemic, most workshops had to take place online. They were scheduled in such a way that all experts were able to participate in daylight hours. Table 3 shows the distribution of workshop participants (besides the project team).

Participants received topic-specific "thought starters" beforehand, which included an overview of the project, relevant indicators, and regional issues presented during the actual workshops in two or three brief impulses. Each workshop featured four one-hour working group sessions to review potential indicators using established criteria. Starting from the second workshop, discussions were documented using a "traffic light" system to streamline the final review and documentation process.

The topics of the workshops were:

- Workshop No. 1, Target Region Europe and International Organizations: criteria for the evaluation of indicators, discussion of first potential indicators.
- Workshop No. 2, Target Region Asia and Pacific: indicators for the interfaces with climate and resource consumption as well as waste management, water management and "chemicals of concern" in consumer products.
- Workshop No. 3, Target Region Latin America and Caribbean: biodiversity interface indicators.
- Workshop No. 4, Target Region North America/NAFTA: economic indicators, climate interface.
- Workshop No. 5, Target Region Africa: indicators for the use of renewable raw materials and energy sources, interfaces with biodiversity, improvement of the economic situation of developing countries.
- Workshop No. 6 (hybrid format) served to present the complete list of indicators and to discuss a possible prioritization with stakeholders from industry, NGOs and international organisations.

4.4. Transparency

During the course of the projects, thought starters, minutes of the workshops, and drafted lists of indicators were available to all involved and interested experts in a read-only cloud. To enable the discussion of the final list of indicators and to support ongoing exchange between the experts, an interactive online platform was introduced in the last phase of the project.

Table 3 Distribution of workshop participants (with the exception of the project team)[a]

Region stakeholder group	Africa	Asia + Pacific	Europe	Latin America	North America	Global	Sum
Industry	1	3	9	8	3	1	25
International organisation	0	0	0	0	0	12	12
Network (science, economy, politics and society)	1	0	2	0	4	0	7
NPO/NGO/CSO	2	1	4	1	0	0	8
Policy/administration	1	3	6	2	4	0	16
Academia	7	8	4	7	1	0	27
Others (expert, consultant, …)	1	3	4	2	0	0	10
Sum	13	18	29	20	12	13	105

[a] No adjustment for participation in more than one workshop.

Experts were invited to provide feedback on the indicators and development process through emails with follow-up questions, and responses were posted and clustered thematically on the platform.

5. Results

As outlined in Section 3, indicators used for future international chemicals management should cover important elements of the concept of sustainable chemistry to measure progress and be suitable for the goals adopted with the GFC.

Experience with the collection of data on target tracking in international environmental agreements (see Section 2.1) shows that the metric must be as simple as possible, even if complex relationships need to be mapped.[1,19] This should be reflected in the criteria for indicators. Therefore, an indicator should not only be relevant in relation to the target in question, but should also be easy to measure, reliable, and comprehensible. "Targets" should – according to the specification of the responsible SAICM working group[68] – be "SMART", *i.e.*, "specific", "measurable", "achievable", "relevant", and "time-bound." This has been applied to the corresponding indicators with few exceptions: the criterion "achievable" was dropped, as it can be meaningfully linked only to a target, but not to an indicator. The criterion "timebound" was substituted by "dynamic", because targets usually include a deadline for their achievement. Indicators, however, should show changes over time. The term "relevant" was changed to "pertinent", as pertinent defines an issue as directly related to the matter at hand and also significant and important, thus being more precise than "relevant", which has a more general meaning. In view of the problems of collecting reliable data at the level of national governments, we recognized the need for two additional criteria:

(1) To minimize the effort required for the collection of data, the indicators should be as easy as possible to determine.

Objectives are developed and agreed by international committees; this is a transparent process. As data for indicators are provided by numerous institutions, it is necessary to verify their source (traceable data collection) and plausibility in case of doubt or dispute.

(2) Therefore, a criterion for reliability and transparency was added.

The general criteria for indicators used in this project are summarized in Table 4.

The discussion following the UNEA resolutions on integration of the concept of sustainable chemistry in the global management of chemicals and waste initialized the formulation of corresponding criteria for identification of indicators reflecting sustainable chemistry. A first draft of criteria was developed and presented for discussion in several interviews with experts as well as in the first consultation workshop. Especially the publications of UNEP (Green and Sustainable Chemistry Framework Manual) and ISC_3 (Key Characteristics of Sustainable Chemistry) were helpful for the development of sustainability criteria.

Discussions with both organisations fed into the selection of a first set of criteria for sustainable chemistry indicators. These criteria were further discussed in each of the second to fifth consultation workshops. This helped to replace formulations that were not very comprehensible; however, changes in content were not necessary. In Table 5, these criteria (called "H-criteria" to complete criteria A to G) are matched with the content of publications of UNEP[63] and ISC_3.[58]

The aspects of sustainable chemistry have been grouped into five criteria in order not to unnecessarily complicate the evaluation of indicators. The overarching criterion H is explained in more detail by the sub-criteria H1 to H5: a major step from the sectoral view of SMCW to sustainable chemistry is the inter-linkage with other demands of sustainable development by systemic thinking and thus avoiding regressions elsewhere as well as to enable net progress in sustainable development. This is reflected especially by the ecological responsibility component of H2 "Inter- and multidisciplinary, holistic approach" as well as in H3 "Social responsibility". H1 "Responsible innovation" links economically successful innovations to the precautionary principle and the rules of green chemistry. It was necessary to broaden the narrower view of SMCW, especially "waste", to include the problem of dwindling non-renewable and wasted renewable resources, thus including the concept of "circular economy" *via* H5 "Resource management and circularity". The sub-criterion H4 "Transparency and information exchange" reflects *i.a.* SDG 17 with respect to chemicals and waste.

The suitability of the indicators from numerous conventions and standards (Table 1), the proposals of the TWG, the considerations of IPEN and the indicators proposed by participants of the workshops or by the project team were then assessed using criteria A–G plus H (Tables 4 and 5). When compiling the list of indicators, it was ensured that all H-criteria

Table 4 General criteria for indicators

	Criteria	Criteria wording
A	Specific	The indicator must be precise and unambiguous
B	Established	The indicator is already in use by other systems, *e.g.*, SAICM, conventions
C	Determinable	The collection of the data needed for reporting in the respective sector is easy and cost-efficient
D	Measurable	Either quantities, thresholds or qualitative properties are applicable
E	Reliable and transparent	The data associated with the indicator are trustable and traceable
F	Dynamic	Progress over time, a difference in the data associated with the indicator, can be measured
G	Pertinent	The indicator covers relevant aspects for the respective sector and/or area of application

Table 5 Criteria for sustainable chemistry indicators related to important sources

ISC_3 key characteristics of sustainable chemistry[58]	Criteria wording for indicators focussing on the concept of sustainable chemistry	Green and sustainable chemistry: framework manual[63]
(1) Holistic (3) Systems thinking (10) Life cycle	(H) Sustainability: systems thinking is the prerequisite to reach the goals of Agenda 2030: potential trade-offs can be identified and managed with systems thinking. Sectors dealing with chemical entities contribute to sustainable development in compliance with the relevant SDG principles and the following sub-criteria (H1–H5)	(10) Developing solutions for sustainability challenges
(2) Precautionary (6) Sustainable and responsible innovation (7) Sound chemicals management (9) Green chemistry	(H1) Responsible innovation: development of sustainable solutions and safe and non-regrettable alternatives for chemicals of concern through cooperation on innovations, non-chemical alternatives, services like chemical leasing, or extended producer responsibility (EPR) mechanisms. Foster collaboration along the value chains to promote circularity	(1) Minimizing chemical hazards (2) Avoiding regrettable substitutions and alternatives (4) Advancing sustainability of production processes (6) Minimizing chemical releases and pollution
(1) Holistic (3) Systems thinking	(H2) Inter- and multidisciplinary, holistic approach: considering interfaces with other urgent issues (health, environment, climate, resources/waste/circularity, biodiversity, nutrition, *etc.*) throughout the entire life cycle of chemical entities, while avoiding transport of problems to other sectors and future legacies	(5) Advancing sustainability of products
(4) Ethical and social responsibility	(H3) Social responsibility: promoting and ensuring health and safety as well as fair, inclusive, and emancipatory labour conditions, complying with human rights and justice in all its fields including education and science. Reduction of inequalities and fair distribution of benefits	(8) Maximizing social benefit (9) Protecting workers, consumers and vulnerable populations
(5) Collaboration and transparency	(H4) Transparency and information exchange: enabling right-to-know throughout the entire life cycle. Promoting knowledge exchange on all levels including all stakeholders (*e.g.*, science, education, business, governments, administration, NGOs)	—
(8) Circularity	(H5) Resource management and circularity: sustainable management of resources, materials, and products (raw materials extraction, production, application, logistics, recycling, and end of life scenario) and energy, to enable circularity without contamination throughout the entire life cycle	(3) Sustainable sourcing of resources and feedstocks (7) Enabling nontoxic circularity

(Table 5) were represented by at least one indicator in order to include the many different aspects of sustainable chemistry. Only a few indicators fulfilled almost all of the general criteria (A through G). Unfortunately, indicators that were particularly specific and/or pertinent often proved difficult to measure.

For the search of indicators, existing international agreements regulating the management and safe use of chemicals were one of the most valuable sources of indicators either directly related to chemistry (highly hazardous pesticides, hazardous substances, hazardous waste) or indirectly addressing interface issues like with biodiversity, climate, occupational health and safety.

As a result, 45 indicators were identified as suitable because they fulfilled at least one H-criterion, and prioritized criteria B, C, D, and E (Appendix C, see the SI). During an extensive discussion at the last workshop with experts from international organisations, industry, and NGOs, it was emphasised that indicators in the sense of an SMCW should be listed along with the future-oriented indicators because of the failure of numerous SAICM reduction targets to be achieved by 2020. On the other hand, a list of about 20 indicators would be far more manageable. This led to a selection of 23 indicators, taking particular account of data availability, measurability and quality (Table 6).

For these indicators (Table 6), the following characteristics have been identified:

• There are relations to all sub-criteria for sustainable chemistry, in many cases also to several criteria out of H1 to H5.

• Some indicators address only the SMCW or the concept of sustainable chemistry, but most address both.

• State, impact, and response indicators as well as driving forces are present.

• Many indicators can be related directly or indirectly to specific SDGs.

• Most indicators are of relevance for industrial, emerging and developing countries and not only to a certain group of countries, *e.g.* economies still under development.

Table 6 Final list of indicators covering relations to GFC objectives and SDGs[a]

No. {# in ref. 67}	Proposed indicator	Assignment to a GFC strategic objective[69]	Origin of the indicator and potential data source, for details see footnotes	Criteria for sustainable chemistry (bracketed = partially applicable)	Relation to SDGs: bold = directly, bracketed = indirectly
1 {# 1}	Share of large/medium/small chemical enterprises of the region (Africa, Asia, Europe…) that report on their sustainability performance using GRI SRS	D, E	Project team	H2, H3, H4, H5	**12.6**
2 {# 2}	Number of new supplier assessments carried out in the year under review, by region, and change compared with the previous year	A, D	Project team (TfS)	[H2], H3	**12.4**, **12.6**
3 {# 6}	Proportion of hazardous waste treated, by type of treatment, *e.g.*, recovered, recycled, incinerated	A, D	SDG indicator 12.4.2	(H2), H3, (H5)	**12.4**
4 {# 8}	Value of fossil-fuel subsidies per unit of GDP (production and consumption) related to Chemical Industry's energy consumption	D, E	Modification of SDG indicator 12.c.1	H2, H5	**12.c**
5 {# 9}	Total value of inward and outward illicit financial flows related to chemicals and waste measured per unit of product detected used for unintended application and volume of illegally disposed waste	A, C, D	Modification of SDG indicator 16.4.1	H3, H4	**16.4**
6 {# 10}	Number of companies certified for environmental management or health, safety, environment management system… within the chemical industry… by an independent auditor	D	Modification of a TWG4 indicator	H3, (H4), (H5)	**12.4**, **12.6** (8.3)
7 {# 12}	Share of the world's largest chemical companies having signed on to the 2014 responsible care global charter	A, D	Project team	H3	**12.4**
8 {# 13}	Number or share of parties that have ensured that the public has appropriate access to information on chemical handling and accident management and on alternatives that are safer for human health or the environment than the chemicals listed in Annex III of the Rotterdam convention	B	Project team	H3, H4	**12.4**
9 {# 16}	CO_2eq. Scope 1 & 2 per unit of value added (*e.g.*, gross output [Mg per year]) of the chemical industry	C, D	Modification of SDG indicator 9.4.1	H2, H5	**9.4**
10 {# 19}	Share of chemical production based on renewable materials in relation to the global production which is based on renewable materials…[%]	D	Modification of a TWG4 indicator	H5	**12.2**
11 {# 20}	Reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by *x*%	A, D	Modification of IPEN indicator D.5-2	H1, H3	**12.4** (6.3)
12 {# 22}	Amount of post-consumer plastic waste generated/recycled/incinerated/landfilled/not collected per country	B, C, D	Project team (based on a suggestion by the participants of workshop #2)	(H2), (H5)	**12.5**
13 {# 24}	Material footprint, material footprint per capita, and per GDP	D	SDG indicator 12.2.1	(H2), H5	**12.2**

Table 6 (*Contd.*)

No. {# in ref. 67}	Proposed indicator	Assignment to a GFC strategic objective[69]	Origin of the indicator and potential data source, for details see footnotes	Criteria for sustainable chemistry (bracketed = partially applicable)	Relation to SDGs: bold = directly, bracketed = indirectly
14 {# 28}	Number of countries that adopt policies and instruments that implement agroecological strategies and practices that reduce synthetic input such as pesticides and fertilizers and are based on biodiversity and integrated soil nutrition…	D	IPEN indicator A.1-6	H2, (H5)	**2.4, 2.5**
15 {# 31}	Number of PRTRs with publicly accessible data established	A, B, D	IPEN indicator A.5-1	(H1), H4	(12.4, 16.10)
16 {# 33}	The percentage of companies with human rights (HR) due diligence procedures for toxic substances used, produced and released in their activities	D	Modification of IPEN indicator D.6-2	H3, (H4)	(12.4, 10.3)
17 {# 34}	Change in water-use efficiency in the chemical industry ("water footprint")	A	Modification of SDG indicator 6.4.1	(H2), H5	**6.4**
18 {# 35}	Renewable energy share in the total final energy consumption of the chemical industry	A, D	Modification of SDG indicator 7.2.1	(H2), H5	**7.2**
19 {# 36}	Number of countries that have implemented pesticide legislation based on the FAO/WHO international code of conduct	A, B, C	TWG4 (IOMC indicator)	(H2), H5	**12.4**
20 {# 37}	Number/percentage of countries where the legal framework demands risk assessment and registration/authorization of new chemicals before putting them on the market	A, C	Project team (with reference to the IOMC toolbox)	H1, H3	**12.4**
21 {# 38}	Number of (share of) countries reducing the emission of reactive N compounds (waste water, exhaust air, agriculture) by legislation	A, C	Project team	(H1), H2, H3	**2.4, 6.3, 13.2**
22 {# 44}	Number of companies conducting an environmental cost–benefit analysis	D	Project team	H4, H5	(12.6)
23 {# 45}	Sum of resource taxes on non-renewable natural resources and their extraction collected by countries	D, E	Project team	(H4), H5	(8.4, 9.4, 12.2)

[a] Numbers of indicators in the first column are related to the final list of 23 indicators whereas numbers in brackets (*e.g.* {#1}) belong to the long list of 45 indicators presented in Appendix C (see the SI).[67] Origin of the indicators: IPEN: (2019): thought starter on beyond 2020 indicators and milestones…[62] IOMC toolbox: ref. 70 and 75. SDG indicator: indicator for Sustainable Development Goal No.…[18] TfS: Together for Sustainability.[71] TWG4: mapping exercise: existing global and regional data and indicators relevant to the beyond 2020 framework.[65]

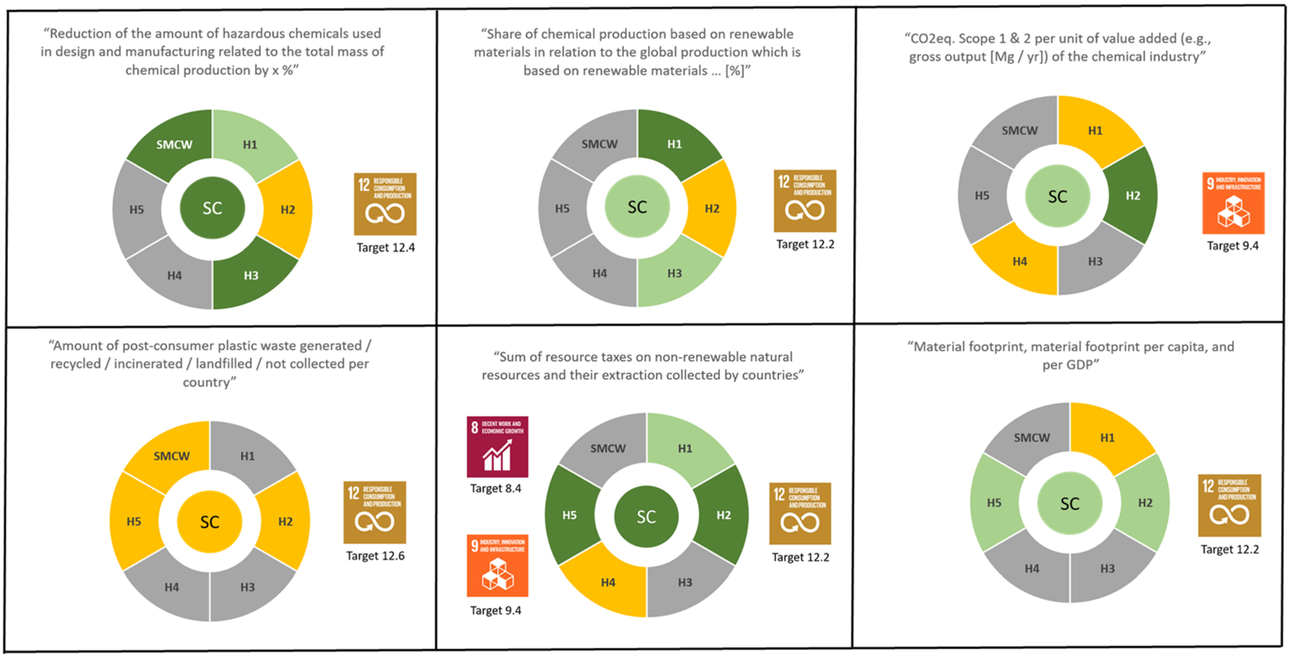

Fig. 2 Relevance of six indicators to Sustainable Chemistry criteria and SMCW as well as their most relevant SDG target(s). Depicted indicators (clockwise): top left: "reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by *x*%". Top middle: "share of chemical production based on renewable materials in relation to the global production which is based on renewable materials…[%]". Top right: "CO_2eq. Scope 1 & 2 per unit of value added (*e.g.*, gross output [Mg per year]) of the chemical industry". Bottom right: "material footprint, material footprint per capita, and per GDP". Bottom middle: "sum of resource taxes on non-renewable natural resources and their extraction collected by countries". Bottom left: "amount of post-consumer plastic waste generated/recycled/incinerated/landfilled/not collected per country". The colours depict the connection (dark green = very strong; light green = strong; yellow = moderate; grey = none) of the indicator to the highlighted sustainability criteria H1–H5 and to SMCW (all outer circle) as well as to Sustainable Chemistry (SC; inner circle) in total. The depiction of SDG targets is based on the highest relevance for the indicator.

• All GFC objectives are covered by at least three indicators (for details see ch. 6).

In the following, we present six indicators in detail which cover most important aspects of sound management of chemicals and waste (SMCW) and/or the concept of sustainable chemistry.

Indicator No. 11: "Reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by *x*%": this (response) indicator can be very strongly related to the overarching goal of the SMCW, but is also linked to H1 "Responsible innovation" (strong) and H3 "Social responsibility" (very strong). Its over-all correlation to sustainable chemistry is very strong, as it touches various aspects of three sustainability criteria. The indicator contributes most to SDG target 12.4 (Fig. 2; top left). Based on the original suggestion by IPEN[62] the indicator was modified to make it more specific and targeted (criteria A and G). It is designed to check a dynamic development (criterion F), but it will not be easy to install data mining and management (criteria C–E) because it is not established in multilateral environmental agreements.

Indicator No. 10: "Share of chemical production based on renewable materials in relation to the global production which is based on renewable materials…[%]": this specific and pertinent indicator is closely related to SDG target 12.2 and reflects a dynamic status in the chemical industry with respect to responsible innovation (sustainability criterion H5). Its over-all correlation to sustainable chemistry is very strong, as it touches another two aspects of three sustainability criteria (H2 "Inter- and multidisciplinary, holistic approach" moderately and H3 "Social responsibility" strongly; Fig. 2; top middle). It was based on a proposal by TWG4 (ref. 65 and 66) ("Number of companies that use natural products as a source…") but modified as the mere number of companies can be misleading. It is assumed that data can be provided by the chemical industry and national governments (criteria C and D) though the proof of reliability will be difficult.

Indicator No. 9 "CO_2eq. Scope 1 & 2 per unit of value added (*e.g.*, gross output [Mg per year]) of the chemical industry" is a modification of the SDG impact indicator 9.4.1 that focuses on the chemical industry and is more precise (scope 1 and 2) with respect to the data to be collected. As this indicator is already established in a similar form, data mining should not be complicated. The indicator fulfils criterion H2 "Inter- and multidisciplinary, holistic approach" (very strong) and partially also H1 "Responsible innovation" as well as H4 "Transparency and information exchange" (both moderately). Its overall correlation to sustainable chemistry is very strong. The indicator contributes most to SDG target 9.4 (Fig. 2; top right).

Indicator No. 12 "Amount of post-consumer plastic waste generated/recycled/incinerated/landfilled/not collected per country" is based on a suggestion from the 2nd workshop.

Though the negotiations on a plastics treaty[72] are still going on, it seemed necessary to include this indicator which is specific, dynamic and pertinent. Obviously, the management of waste plastics in most countries and some uses of plastics are not environmentally sound. There is only a moderate connection to SMCW. Alignment with the principles of sustainable chemistry would reduce the problem. However, its connection to H2 "Inter- and multidisciplinary, holistic approach" and H5 "Resource management and circularity" is only moderate, like its overall correlation to sustainable chemistry. The indicator contributes most to SDG target 12.6 (Fig. 2; bottom left). Due to numerous scientific investigations, there is a feasible basis for data mining of the status that can be broadened by the UN (criteria C to E).

For indicator No. 23: "Sum of resource taxes on non-renewable natural resources and their extraction collected by countries" the criteria of data availability as well as the ability to unambiguously define certain aspects are either lacking or only partially met. Additionally, there is an ongoing debate about the precise definition of "renewable" resources — such as whether water qualifies as "renewable". Not all countries collect taxes on resources, and such an indicator is not yet part of an international agreement, but once such an indicator would be established, it could help measure the impact of cost increase for or related to resource consumption and the shift towards renewable resources. While taxes can influence behaviour, they may fail to achieve a guiding effect and be primarily used for revenue generation. Therefore, alternative economic tools such as fees, charges, or similar instruments should be considered in addition. The indicator contributes very strongly to H2 "Inter- and multidisciplinary, holistic approach" as well as H5 "Resource management and circularity", strongly to H1 "Responsible innovation" and even moderately to H4 "Transparency and information exchange". It differs from the other indicators analysed, as it contributes to the targets of the three SDGs (8, 9, and 12; Fig. 2; bottom middle). Transitioning to a more sustainable system will also require innovative business models aligned with the principles of a circular economy, such as chemical leasing,[49] which can be promoted through targeted financial incentives.

Indicator No. 13 "Material footprint, material footprint per capita, and per GDP" (SDG indicator 12.2.1) is an established indicator (criterion B). Though it can be easily determined (criterion C) data for its calculation are often difficult to obtain and might be unreliable (criteria D, E). As to sustainable chemistry, it is strongly related to H5 "Resource management and circularity" and H2 "Inter- and multidisciplinary, holistic approach", but also to H1 "Responsible innovation" (moderately). Its overall correlation to sustainable chemistry is strong; however, it touches various aspects of three sustainability criteria. The indicator contributes mostly to SDG target 12.2 (Fig. 2; bottom right).

6. Discussion

The concept of sustainable chemistry as an integrative approach includes not only the use phase of chemicals, but rather their full life cycle. Additionally, social aspects, approaches for innovation and a view on global resource problems are characteristics for sustainability in chemistry, as can be taken from the criteria presented in Table 5.

6.1. Indicators related to the SDGs

The three most suitable sources for potential indicators turned out to be the "global indicator framework" developed for measuring progress on the 2030 Agenda (originally adopted in 2017, but continuously refined),[73] a list that had been developed by the responsible SAICM Technical Working Group,[65,74] and a list of 160 potential indicators on "Chemical Safety Contributions to the SDGs" introduced into the discussion by IPEN in 2019.[62]

It would certainly be misguided to consider the entire 2030 Agenda from the perspective of sustainable chemistry. However, the approach used in this study leads to indicators that are applicable not only to SDG target 12.4, which is particularly relevant to SAICM and its successor, the Global Framework on Chemicals (GFC), but also to other targets of SDG 12, *e.g.*

- 12.2 – resource consumption,
- 12.5 – municipal waste reduction,
- 12.6 – steps towards sustainable development and corresponding reporting in companies.

Some SDG indicators that refer to entire economies can be used in the context of this study if they are narrowed down to the chemical industry or chemical products. (*e.g.* indicator No. 17). On the other hand, indicators such as No. 21 ("…reducing the emissions of active N compounds…"), which are not addressed as a topic in SDG 12, have numerous cross-connections to SDGs 2, 6, and 13.

The entries in the last column of Table 6 (reference to the SDGs) are presented graphically in Fig. 3. The graph highlights the value of the integrative approach of sustainable chemistry for achieving the SDGs. Moreover, though most of the indicators are related to SDG 12, there are several indicators that make references between SDG 12 and other SDGs (*e.g.*, indicator No. 6 on SDG 8). Furthermore, numerous indicators relate to one or more of the other SDGs.

In addition to Fig. 3, numerous indicators can also reflect indirect effects, *e.g.* indicator No. 6 ("Number of companies certified for Environmental Management or Health, Safety, Environment (HSE) Management System… within the chemical industry… by an independent auditor"). It relates directly to SDG targets 12.4 and 12.6, respectively, and partly to SDG target 8.3 ("Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation…"). Companies that are audited in terms of HSE standards will also take measures for occupational health and safety (SDG 3) and reducing emissions into the environment (SDG 13–15), or continuously improve their standards in this regard. The overarching approach of the SDGs is thus reinforced by these indicators.

In the coming years, the international community will have to negotiate a 2030 Agenda successor. As outlined, the indicators selected or developed in this study are parameters integrating aspects of sustainable chemistry in advancement of the

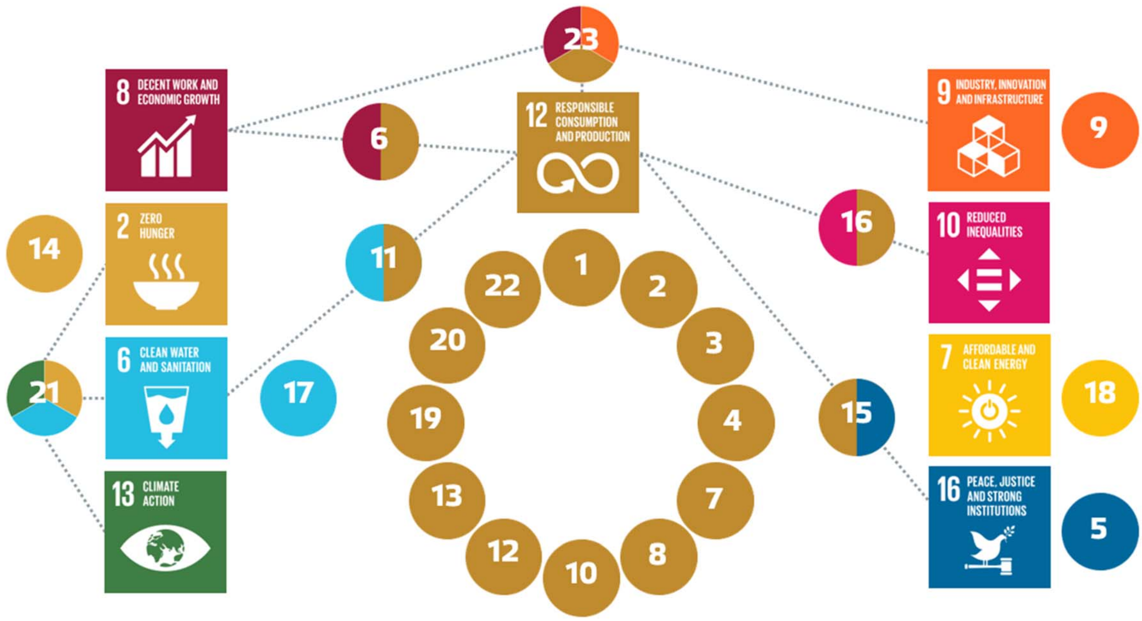

Fig. 3 Indicators related to SDGs. The indicators (circles) are each assigned to an SDG (squares) with their number (see the first column of Table 6) and color-coded accordingly. Connecting lines indicate the applicability of indicators to further SDGs.

global management of chemicals and waste. On the one hand, the indicators focus on open problems and unachieved goals of the Dubai Declaration and, on the other hand, they depict developments that are conducive to sustainable chemistry or that also stand in its way. The indicators not only monitor and support the objective of the Dubai Declaration, which is essentially re-emphasized by SDG 12.4, but they also address the achievement of numerous other SDGs.

In this project, several indicators were chosen with strong connections to the SDGs (see Table 6). Some indicators, like No. 18 "Renewable energy share in the total final energy consumption of the chemical industry", derive from the current SDG indicator set. Except one (No. 13), all proposed indicators have been amended by a specification towards the chemical sector serving the goals of sustainable chemistry. Several proposed indicators have a striving character as process indicators for sustainable chemistry, *e.g.* No. 22 "Number of companies conducting an environmental cost–benefit analysis". Another group of indicators relate to SMCW including No. 12 "Amount of post-consumer plastic waste generated/recycled/incinerated/landfilled/not collected per country". Last but not least, we identified impact indicators for sustainable chemistry, like No. 9 "Reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by x%". It is an important fact that so far, sufficient and reliable data are available for only some of the potential indicators. Therefore, to stimulate data generation and access, these indicators would be predestined to contribute to an ambitious set of indicators for a future 2030 Agenda successor.

6.2. Indicators developed by the IOMC

As outlined in Section 2, IOMC developed an indicator set to monitor the progress of SAICM towards "sound management of chemicals and waste" (SMCW), *e.g.* "the number of parties to important multilateral environmental agreements" or the "number of countries with legislation in place to manage industrial and consumer chemicals".[70] After the concept of sustainable chemistry was recognized as an additional instrument by UNEA, IOMC proposed (on occasion of the 4th meeting of the intersessional process, 2022, Bucharest) three groups of indicators to measure progress toward the SAICM 2020 target.[75] These indicators additionally focused on the implementation of SMCW objectives like legislation and enforcement mechanisms that address the life cycle of chemicals (target group: national governments). Furthermore, indicators for sustainable chemistry strategies (target group: industry and retailers) and the integration of chemicals and waste policy into a general sustainability policy were added. An advanced set of indicators was presented by IOMC on occasion of the ICCM5 (ref. 76) that is now available to the GFC as part of the basis for further negotiations. While IOMC concentrates again mainly on SMCW objectives, the list of indicators presented here (Table 6) leaves more space for specifically monitoring developments towards sustainable chemistry and sustainable development. The lists have intersections on the following aspects (see Table 6):

• Two IOMC indicators of the list published in 2015 were adopted unchanged in this project: No. 19, 20.

• Indicators No. 3, 4, 15, and 21 are similar to indicators proposed in the IOMC list of 2023, *e.g.* "Trends in nitrogen deposition" *vs.* "Trends in loss of reactive nitrogen to the environment".

• Other indicators could serve to complement the list presented here, particularly on biodiversity, *e.g.*: "Water Quality Index for Biodiversity (trends in ecosystems affected by pollution)" and waste ("number of parties that have developed and implemented national strategies, plans or programs for hazardous waste minimization").

In general, the IOMC list and the indicators presented here partially overlap and partially complement each other.‡ This observation does not surprise: IOMC focuses on SMCW, but SMCW is among the preconditions for sustainable chemistry and sustainable development.

The comparison between the two sets of indicators reveals a major dilemma: the IOMC preferred – more or less exclusively – indicators with easily available global data and suitable "custodians", *i.e.* the IOMC member organisations. This was not possible in this work because of the far broader integration of stakeholders. In terms of data availability, there is a dilemma when measurability is prioritised over all other criteria in the selection of indicators. Often, countries are counted that have introduced certain regulatory measures. However, their associated impacts cannot be assessed as it is difficult to track their implementation. On the other hand, relying on global sectoral indicators such as the amount of renewable resources bears risks of producing less reliable figures due to potential data scarcity. Theoretically, data of this type can be provided by the national governments as part of the data mining of the UN Statistics Division. As the statistical data from numerous countries will not be sufficient for this purpose, the chemical industry would have to be recruited as a further custodian of data. As indicators are supposed to be established, determinable, and measurable, as well as reliable and transparent, involvement of an additional custodian from the private sector increases the difficulty of data acquisition. Nonetheless, commitment of the chemical industry is a necessary step as sustainable chemistry is part of industrial development; legislative approaches are complementary.

6.3. Proposals by TWG4

Proposals made by TWG4 were analysed for their suitability for monitoring progress towards sustainable chemistry using the criteria developed. The following indicators were adopted by the project team, in two cases (No. 6, 10) after modification:

6 "Number of companies certified for Environmental Management or Health, Safety, Environment Management System… within the chemical industry… by an independent auditor".

10 "Share of chemical production based on renewable materials in relation to the global production which is based on renewable materials…[%]".

19 "Number of countries that have implemented pesticide legislation based on the FAO/WHO International Code of Conduct".

Other proposals, even if they met at least one criterion for sustainable chemistry, were not adopted to the final list due to a lack of reliable data, difficulty in collecting data or were not meaningful (C, D and/or E) such as "Share of product categories (in relation to all product categories) to which extended producer responsibility applies".

6.4. Proposals by IPEN

The International Pollutants Elimination Network (IPEN), an association of some 600 local and national initiatives, submitted its own proposals for potential indicators in the SAICM intersessional process in 2019.[62] This list was analysed for its suitability for monitoring progress towards sustainable chemistry using the criteria developed. The following indicators were adopted by the project team into the list of priority indicators, in two cases (No. 11 and 16) after modification:

11 "Reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by *x*%".

14 "Number of countries that adopt policies and instruments that implement agro-ecological strategies and practices that reduce synthetic input such as pesticides and fertilizers and are based on biodiversity and integrated soil nutrition…".

15 "Number of PRTRs with publicly accessible data established".

16 "The percentage of companies with human rights (HR) due diligence procedures for toxic substances used, produced and released in their activities".

Other proposals, even if they met at least one criterion for sustainable chemistry, were not adopted due to a lack of reliable data or difficulty in collecting data (C, D and/or E) or were not meaningful, such as "Number of countries that implement Circular Economy/cradle to cradle systems without toxic chemicals recycling".

Data for another highly ranked indicator ("Number of countries that phased out the manufacture, import, sale and use of HHP") could have been collected with some effort. However, the indicator was not adopted as indicator 14 (agroecology…) also covers this target and goes beyond it.

6.5. Gaps and shortcomings

Considerable gaps remain in the economic indicators with a focus on innovations as well as investments in plants and processes that promote development in the sense of sustainable chemistry. Similar problems apply to social indicators. This problem is also seen by other institutions and stakeholders, as the evaluation of the sixth workshop and the discussion with members of the IOMC working group showed.

As already discussed in Sections 6.1 and 6.2, the measurability of several indicators is not possible on a global scale at present (*e.g.* indicators No. 1, 2, 9, 10, 11). For these indicators, existing sustainability reports or aggregated HSE data of the chemical industry could be summarized and provided to the UN Statistics Bureau by national members of ICCA, large chemical companies or TfS. For example, CEFIC already publishes aggregated data from the European chemical industry on its website to demonstrate progress towards more sustainable practices.[77]

The measurability and reliability of indicators are discussed here using two examples, namely indicator No 13 and No 19. We

‡ On occasion of a discussion between members of the IOMC and the authors of this study (1.2.23, summary by Henning Friege sent on 13.2.23), it was agreed that the lists are complementary and that both lists have gaps in terms of innovation towards sustainability, equality and financial aspects.

Table 7 Indicator No. 13 as an example for the measurability and reliability in two countries

Country	Availability of data	Quality of data	Data sources
Developed country	High: regular, annual data; multiple years; high granularity (by sector, material, *etc.*)	High: harmonized, verified by standardized economy-wide material flow analysis (EW-MFA) methods; follows international guidelines	INSEE (national), Eurostat MFA, UN SDG data portal, global footprint network, Eora MRIO
Lower-income country	Low–moderate: some data available but with gaps; often aggregated; less frequent and less granular; partially modelled	Moderate–low: often relies on estimation/models (Eora MRIO) rather than complete national accounts; less consistency, often delayed	Eora MRIO, national statistical service (with limitations), international estimates (*e.g.*, global footprint network, UN SDG data portal)

Table 8 Indicator No. 19 as an example for the measurability and reliability in two countries

Country	Status of implementation	Quality of legislation/ Alignment	Key features and gaps	Data sources/references
Developed country	Yes: comprehensive pesticide legislation established and regularly updated in alignment with both EU and FAO/WHO codes	High: strict, incorporates latest EU directives and FAO/ WHO code. Regular updates and enforcement; strong regulatory capacity	Coverage extends across the pesticides' life cycle; strong enforcement, but occasional controversy on scope (*e.g.*, reauthorization); monitoring infrastructure	FAO indicator map, national regulation resources, EU documentation
Lower-income country	Yes: national pesticide act implements legislation based on FAO/WHO code; acknowledges international standards	Moderate: recognizes and uses FAO/WHO code as the basis but faces gaps in regulation and enforcement. Law governs registration, import, labelling, use and disposal	Law covers key aspects, but implementation faces resource and over-sight challenges; gaps in covering transport, disposal, public health pesticides, and enforcement; harmonization and capacity still under development	FAO indicator map, policy analyses, national EPA and agriculture ministry reports

describe the situation in an industrialised country (EU member state) and in a lower-income country in the Global South, both unnamed and exemplary. We searched for corresponding information in international and national databases (national databases not disclosed) and in the literature.

Indicator 13: material footprint, material footprint per capita, and per GDP (SDG 12.2.1): Generally, the impact of material use can have different levels of impact on ecosystems.[78] For tracking resource use and progress toward sustainable consumption and production on a global level, material footprint is an important metric for which data must be collected at the country level. Table 7 depicts the characterisation for this indicator in both countries.

In terms of comparability and trustworthiness, due to standardized methods, dedicated institutions, and mandatory reporting, data for a developed country could be qualified as much more reliable and comparable at the international level. For lower-income countries, there exist uncertainties and reduced capacity to make precise assessments or confidential track of year-on-year progress, due to modelled or estimated data often substituting for actual measured data. Because of gaps in temporal and/or spatial coverage as well as greater modelling assumptions, results for lower-income countries are useful but should be interpreted more cautiously. Many lower-income countries rely on international initiatives like the EU's resource efficiency projects or UN environment programs to support data collection.[79] In general, material footprint data for a developed country can be confidently used for indicator-based policies, whereas for lower-income countries the data is less robust, more reliant on estimation, and subject to higher uncertainty, limiting its use for precise comparison unless these data limitations are made explicit.

Indicator 19: number of countries that have implemented pesticide legislation based on the FAO/WHO International Code of Conduct: This is a key global indicator focusing on the regulation of pesticides.[80,81] This means robust national legislation aligned with international standards. Since only the number of countries that have introduced such legislation is measured here, this is initially a reliable figure. But the devil is in the details, *i.e.* it is difficult to measure the implementation status and the enforcement of the regulation. Table 8 highlights significant disparities in regulatory capacity and effectiveness, which influence the reliability and utility of this indicator for global progress tracking.

For global benchmarking, developed countries can provide a high-confidence data point which can be reliably cited when they have full implementation. In lower-income countries there is less resourcing, some enforcement challenges, and partial coverage as well as caveats on effective implementation and coverage of FAO/WHO code elements. Additionally, concerning highly hazardous pesticides or newer risk mitigation measures, the FAO/WHO indicator status does not guarantee that legislation is fully comprehensive, enforced, or up-to-date. Especially in the global South, countries may still face gaps in specific areas like public health pesticides, enforcement, or monitoring infrastructure. This affects the comparability and policy robustness when using this indicator for global tracking. The indicator cannot substitute for in-depth assessment of coverage and practicality of enforcement at the national level. However, the indicator is a good starting point to signal progress.

Difficulties due to different definitions of key words (*e.g.*: "recycling") could not be solved within the scope of this study. Since the indicators are partially based on existing regulations and treaties, practical implementation will have to rely on the definitions used there.

6.6. Suitability of the indicators with the GFC targets and beyond

At last, the suitability of the indicators proposed in this study for measuring progress towards the objectives and targets of the

Table 9 Suitability of indicators (as described in Table 6) for selected targets of the GFC[a]

Selected GFC targets	Suitable indicators	Example
A1 – by 2030, governments have adopted and are implementing and enforcing legal frameworks, and have established appropriate institutional capacity to prevent or, where prevention is not feasible, minimize adverse effects from chemicals and waste as appropriate for their national circumstances	3, 8, 19, 20	20: Number/percentage of countries where the legal framework demands risk assessment and registration/authorization of new chemicals before putting them on the market
A3 – by 2030, companies implement measures identified to prevent or, where prevention is not feasible, minimize adverse effects from chemicals throughout their life cycle	6, 7, 8, 11	11: Reduction of the amount of hazardous chemicals used in design and manufacturing related to the total mass of chemical production by x%
A4: by 2030, stakeholders have effectively prevented all illegal trade and traffic of chemicals and waste	5	5: Total value of inward and outward illicit financial flows related to chemicals and waste… and volume of illegally disposed waste
D1 – by 2030, companies consistently invest in and achieve innovations towards advancing sustainable chemistry and resource efficiency throughout the life cycle of chemicals	6, 9, 10, 11, 18	10: Share of chemical production based on renewable materials in relation to the global production which is based on renewable materials…[%]
D2 – by 2035, governments implement policies that encourage production using safer alternatives and sustainable approaches throughout the life cycle, including the best available techniques, green procurement and circular economy approaches	4, 15, 17, 19, 20, 21, 23	15: Number of PRTRs with publicly accessible data established
D3 – by 2030, the private sector, including the finance sector, incorporates strategies and policies to implement the sound management of chemicals and waste in its finance approaches and business models and applies internationally recognized or equivalent reporting standards	1, 7, 8	1: Share of large/medium/small chemical enterprises of the region (Africa, Asia, Europe…) that report on their sustainability performance using GRI SRS
D4 – by 2030, relevant stakeholders give priority to sustainable solutions and safer alternatives to harmful substances in products and mixtures, including in consumer products, in their research and innovation programmes	11, 16	16: The percentage of companies with human rights (HR) due diligence procedures for toxic substances used, produced and released in their activities
D5 – by 2030, governments implement policies and programmes to increase support to safer and more sustainable agricultural practices, including agroecology, integrated pest management and the use of non-chemical alternatives, as appropriate	14, 19	14: Number of countries that adopt policies and instruments that implement agroecological strategies and practices that reduce synthetic input such as pesticides and fertilizers and are based on biodiversity and integrated soil nutrition…
D7 – by 2030, stakeholders implement measures and strive to ensure effective occupational health and safety practices as well as environmental protection measures in all relevant sectors and throughout the supply chain	2, 7, 16	2: Number of new supplier assessments carried out in the year under review, by region, and change compared with the previous year

[a] Numbers of indicators refer to the first column of Table 6.

GFC must be checked. GFC "Objective A" aiming at "the safe and sustainable management of chemicals throughout their life cycle" takes up the former SAICM goal ("sound management of chemicals throughout their life cycle and of hazardous wastes for sustainable development"). As our approach included SMCW, it is reasonable that many indicators fulfil the demand for suitable indicators for Objective A.

GFC "Objective D" with its seven targets is aiming at "safer alternatives and innovative and sustainable solutions in product value chains". Many of the indicators listed in Table 6 can be assigned to these targets. Important links between the GFC Objectives A and D and the indicators presented in this study are summarized in Table 7.

The ICCM5's approach to sustainable chemistry can be measured using the set of indicators proposed here. This can be shown using the example of the GFC target D1: the corresponding innovations within the chemical industry can be achieved particularly by switching to renewable raw materials (indicator No. 10), reducing GHG emissions (No. 9), using renewable energy sources (No. 18), and eliminating hazardous substances in production (No. 11) and internally by consistently expanding the HSE policy (No. 6). This must be supported by the government, as mentioned in objectives D2 and D5. Suitable indicators for this can also be found in Table 6.

Furthermore, some indicators can be used when the 'Global Plastics Treaty' becomes more concrete. The way towards a treaty was paced by a resolution by UNEA5 (ref. 72) which aims to combat global plastic pollution and regulate the handling of plastic waste and therefore, has strong connections to SMCW. The negotiations are currently focusing on reducing the use of single-use plastics, promoting recycling systems and reducing plastic pollution in oceans and ecosystems worldwide. Additionally, chemicals in plastics are also being addressed in the negotiations on the agreement. Indicator No. 12 addresses the generation of plastic waste and all forms of its disposal ("Amount of post-consumer plastic waste generated/recycled/incinerated/landfilled/not collected per country"). In particular, illegal or unintentional dumping of plastic waste is one of the major causes of plastic pollution, thus it would be useful to require reporting on the international level on what happens with plastic consumer goods at their end-of-life. Also, the sources of plastic waste first need to be quantified to deduce meaningful measures limiting the production of plastic products or reducing and mitigating the impact of landfilled and not collected plastic waste. Indicator No. 5 covers the "Total value of inward and outward illicit financial flows related to chemicals and waste…" (see Table 6). Plastic waste remains a business – which is a two-sided sword, as recycling is an important market lever for the transition to a circular economy. On the other hand, as recycling facilities are not yet able to process all plastic waste, the export of such waste to countries with weaker legislation and less control mechanisms is a lucrative illegal business. Therefore, an indicator to measure illicit transport of waste is of outstanding importance to monitor progress towards sound management of plastic waste (Table 9).

7. Conclusion

Our goal was to develop proposals for indicators that are suitable for a future-oriented international chemicals policy. As demonstrated in the foregoing section, these indicators can be used to monitor progress of targets that were approved for the GFC by the ICCM5 in 2023. In line with our scope, the indicators are particularly suited to goals on the global scale that aim at the necessary standard of sound management of chemicals and waste (SMCW), progress towards sustainable chemistry and, in general, innovations for sustainable development. For the first time, this study developed criteria for deriving and testing indicators for international chemicals management. These criteria made the selection of suitable indicators considerably easier. The elaboration of criteria was greatly facilitated by fundamental publications within the framework of a UNEP approach[63] and the ISC_3.[58] The criteria were unanimously accepted by renowned experts from all UN Regions in our workshops as a yardstick for evaluating indicators. The combination of formal test criteria and content requirements for the indicators proved to be very helpful for the discussion. Our criteria A to G and H1 to H5 were literally adopted by an industry association[82] as well as by an NGO[83] as an important example for approaches towards sustainable chemistry. We therefore assume that the criteria will be established at the international level during future discussions on indicators. This could also be the case for a future approach developing a 2030 Agenda successor. Due to the interdisciplinary nature of the concept of sustainable chemistry, numerous interfaces can be included, like with global management of resources, health protection, climate protection, circular economy or biodiversity. We also see great potential in the operationalization of the indicators by the "global intergovernmental science-policy panel on chemicals, waste, and pollution prevention"[84] that is currently under negotiation. Due to the alignment of the indicator set to sustainable chemistry, a future panel could supplement these indicators with benchmarks for the evaluation of political initiatives in the chemicals sector.

Considerable gaps remain in the economic indicators with a focus on innovations as well as investments in plants and processes that promote development in the sense of sustainable chemistry. Similar problems apply to social indicators. This problem is also seen by other institutions and stakeholders, as the evaluation of the sixth workshop and the discussion with members of the IOMC working group showed.

An important impulse for the development of chemicals management comes from the Chemicals Strategy for Sustainability (CSS)[85] published in 2020 as part of the so-called Green Deal of the EU Commission. CSS includes an action plan that addresses not only numerous amendments to REACH, improvements to the framework legislation for waste *etc.*, but also topics that are important at the UN level including for SAICM and the GFC, such as the implementation of the GHS and the development of indicators ("establish… Key Performance Indicators to measure the industrial transition towards the production of safe and sustainable chemicals") or a framework on Safe-and-Sustainable-by-Design.[86] We will discuss the suitability of our set of indicators for the European context in a following publication.

The participation process designed for the study resembled the usual procedures for SAICM and GFC in the sense of a multinational and multi-sectoral approach including relevant stakeholders. Free from certain requirements of processes at the UNEP level, we involved independent experts with additional expertise in the discussions. Due to the holistic approach of the concept of sustainable chemistry, numerous experts in other fields, such as biodiversity, resource management and human rights, were invited in addition to experts on chemicals and waste. This proved to be an excellent prerequisite for addressing issues relating to the management of chemicals in the wider context of sustainable development. Since the process took place in parallel with and outside of the negotiations for ICCM5, the discussion was not affected by political representatives of rogue states, who are critical of multinational environmental agreements anyway. Based on the experience gained in this project at the interface between policy and science, it is often timesaving to conclude the factually necessary consultations as far as possible and then present politically decisive alternatives, instead of mixing the political arguments with the scientific debate. This is just an observation – we do not presume giving advice to international bodies without being asked. Nevertheless, we would highly appreciate the inclusion of this study's results into their work and are ready to offer explanations, where considered pertinent.

Author contributions

Conceptualization: Henning Friege, Christopher Blum; background: Klaus Kümmerer, Christopher Blum, Hans-Christian Stolzenberg, Anna Becker; methodology, investigation and results: Henning Friege, Barbara Zeschmar-Lahl, Esther Heidbüchel, Christopher Blum; original draft preparation: Henning Friege; writing—review and editing: Christopher Blum, Henning Friege; supervision: Barbara Zeschmar-Lahl. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Data availability

The data supporting this article have been included in the paper or as part of the SI. SI available: Appendix A – sources/URL's of the documents evaluated. Appendix B – names and affiliations of discussion partners. Appendix C – long list of indicators. Appendix D – list of abbreviations. See DOI: https://doi.org/10.1039/d5su00135h.

Acknowledgements

The results presented here were obtained as part of a study commissioned by the German Environment Agency (as the National Focal Point of SAICM). Anna Becker thanks Juanita Halblaub, ISC_3, for her valuable support. Many thanks to Myra Rednoss, ISC_3, for the redesign of Fig. 3.

References

1 UNEP, Global Chemicals Outlook (GCO) II – From Legacies to Innovative Solutions: Implementing the 2030 Agenda for Sustainable Development, 2019, https://www.unep.org/resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions, accessed 23-08-2019.
2 IPCC, IPCC Report, Working Group 3-Chapter 10, 2022. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter10.pdf, (taken from the CAPCI flyer).
3 J. Rockström, W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. deWit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley, A safe operating space for humanity, *Nature*, 2009, **461**, 472–475. https://www.nature.com/articles/461472a.pdf.
4 W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers and S. Sorlin, Planetary Boundaries: guiding human development on a changing planet, *Science*, 2015, **347**(6223), 1259855. https://www.science.org/doi/10.1126/science.1259855.
5 M. L. Diamond, C. A. de Wit, S. Molander, M. Scheringer, T. Backhaus, R. Lohmann, R. Arvidsson, Å. Bergman, M. Hauschild, I. Holoubek, L. Persson, N. Suzuki, M. Vighi and C. Zetzsch, Exploring the planetary boundaries for chemical pollution, *Environ. Int.*, 2015, **78**, 8–15, DOI: 10.1016/j.envint.2015.02.001.
6 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. S. Jørgensen, P. Villarrubia-Gómez, Z. Wang and M. Zwicky Hauschild, Outside the Safe Operating Space of the Planetary Boundary for Novel Entities, *Environ. Sci. Technol.*, 2022, **56**, 1510–1521. https://pubs.acs.org/doi/10.1021/acs.est.1c04158.
7 UNFCCC, What is the triple planetary crisis?, 2022, https://unfccc.int/news/what-is-the-triple-planetary-crisis, accessed 16-09-2024.
8 S. Hellweg, E. Benetto, M. A. J. Huijbregts, *et al.*). Life-cycle assessment to guide solutions for the triple planetary crisis, *Nat. Rev. Earth Environ.*, 2023, **4**, 471–486, DOI: 10.1038/s43017-023-00449-2.
9 SAICM, Global Framework on Chemicals – For a Planet Free of Harm from Chemicals and Waste, 2023. https://

www.chemicalsframework.org/page/text-global-framework-chemicals.
10 UNEP, Global Framework on Chemicals, Resolution V/9: Measurability structure, 2023. https://www.chemicalsframework.org/page/resolution-v9-measurability-structure.
11 UN Conference on Environment & Development Rio de Janeiro, 1992, AGENDA 21, https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf cf. preambular text paragraphs 1.1-1.6 and particularly on chemicals management section II.19 with paragraphs 19.1–19.76, accessed 26-10-2024.
12 UNECE, Globally Harmonized System of Classification and Labelling of Chemicals (GHS Rev. 9), 2021, https://unece.org/transport/standards/transport/dangerous-goods/ghs-rev9-2021, accessed 15.11.2024.
13 SAICM: Overview. https://www.saicm.org/about/overview.
14 SAICM Knowledge, Policy Document. Overall Orientation and Guidance for achieving the 2020 goal of sound management of chemicals. https://saicmknowledge.org/library/overall-orientation-and-guidance-achieving-2020-goal-sound-management-chemicals, accessed 01-10-2024.
15 SAICM, SAICM texts and resolutions of the International Conference on Chemicals Management, 2006, Geneva, 2006, http://www.saicm.org/Portals/12/documents/saicmtexts/SAICM-publication-EN.pdf, accessed 25-02-2020.
16 UN, Transforming our World: The 2030 Agenda for Sustainable Development, 2015, https://sdgs.un.org/2030agenda, accessed 26-10-2024.
17 IOMC, Chemicals and Waste management: Essential to achieving the Sustainable Development Goals (SDGs), 2018, https://partnership.who.int/docs/librariesprovider14/default-document-library/iomc/chemicals_sdgs_interactive_feb2018.pdf, accessed 26-10-2024.
18 UN, Global indicator framework for the Sustainable Development Goals and Targets of the 2030 Agenda for Sustainable Development, 2017, https://unstats.un.org/sdgs/indicators/indicators-list/, accessed 26-10-2024.
19 R. Nurick, Independent Evaluation of the Strategic Approach from 2006 – 2015, 2019, https://www.saicm.org/Portals/12/Documents/reporting/FinalReport_Independent-Evaluation-SAICM-2006-2015.pdf, accessed 26-10-2024.
20 UNEA - United Nations Environment Assembly, Sound Management of Chemicals and Waste, UNEP/EA.2/Res.7, 2016. https://wedocs.unep.org/bitstream/handle/20.500.11822/11183/K1607167_UNEPEA2_RES7E.pdf?sequence=1&isAllowed=y, accessed 15-01-2020.
21 UNEA - United Nations Environment Assembly, Sound Management of Chemicals and Waste, UNEP/EA.4/Res.8, 2019. https://wedocs.unep.org/bitstream/handle/20.500.11822/28518/English.pdf, accessed 15-01-2020.
22 IISD, ICCM5 report, Earth Negotiations Bulletin, 2023, vol. **15**, No. 311, pp. 2–19. https://enb.iisd.org/sites/default/files/2023-10/enb15311e.pdf, accessed 04-10-2023.
23 M. A. Murphy, Early industrial roots of green chemistry. International "Pollution Prevention" efforts during the 1970s and 1980s, *Chem. Int.*, 2021, 21–25. https://www.degruyterbrill.com/document/doi/10.1515/ci-2021-0105/pdf.
24 United Nations, Non-Waste Technology and Production. A Seminar of the United Nations Economic Commission for Europe, 1979, Pergamon 1978, DOI: 10.1016/C2013-0-02935-0.
25 M. G. Royston, *Pollution Prevention Pays*, Pergamon Press, Oxford (UK), 1979, ISBN 978-0080235974.
26 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, 1998.
27 R. A. Sheldon, Organic Synthesis – Past, Present and Future, *Chem. Ind.*, 1992, 903–906.
28 J. H. Clark, A. P. Kybett, D. J. Macquarrie, S. J. Barlow and P. Landon, Montmorillonite supported transition metal salts as Friedel-Crafts alkylation catalysts, *Chem. Commun.*, 1989, **18**, 1353–1354.
29 F. Trotta, P. Tundo and G. Moraglio, Selective mono-N-alkylation of aromatic amines by di alkyl carbonate under gas-liquid phase-transfer catalysis (GL-PTC) conditions, *J. Org. Chem.*, 1987, **52**, 1300–1304.
30 EU Council, Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control, 1996, http://data.europa.eu/eli/dir/1996/61/oj, accessed 11-01-2025.
31 K. Kümmerer, J. Clark and V. G. Zuin, Rethinking chemistry for a circular economy, *Science*, 2020, **367**(6476), 369–370, DOI: 10.1126/science.aba4979.
32 J. H. Clark, T. J. Farmer, L. Herrero-Davila and J. Sherwood, Circular economy design considerations for research and process development in the chemical sciences, *Green Chem.*, 2016, **18**, 3914–3934. https://pubs.rsc.org/en/content/articlelanding/2016/gc/c6gc00501b.
33 H. Friege, Sustainable Chemistry – a Concept with Important Links to Waste Management, *Sustainable Chem. Pharm.*, 2017, **6**, 57–60, DOI: 10.1016/j.scp.2017.08.001.
34 C. A. Marques and A. A. S. C. Machado, Environmental Sustainability: implications and limitations to Green Chemistry, *Found. Chem.*, 2014, **16**, 125–147, DOI: 10.1007/s10698-013-9189-x.
35 Ellen MacArthur Foundation (EMF), https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview, accessed 09-10-2024.
36 W. McDonough and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things*, North Point Press, 2002, New York, ISBN 0-86547-587-3.
37 M. Braungart, W. McDonough and A. Bollinger, Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design, *J. Cleaner Prod.*, 2007, **15**, 1337–1348.
38 B. Commoner, *The Closing Circle: Nature, Man and Technology, Alfred A. Knopf*, New York, Rodale Press Book Club Edition, 1971, 1972.
39 W. R. Stahel, The product-life factor, in *An Inquiry into the Nature of Sustainable Societies: The Role of the Private Sector*, ed, Grinton Orr, S., 1982, pp. 72–104, HARC

(Houston Area research Center). https://www.quebeccirculaire.org/data/sources/users/4/32217.pdf.

40 W. R. Stahel, The circular economy, *Nature*, 2016, **531**, 435–438, DOI: 10.1038/531435a.

41 T. Keijer, V. Bakker and J. C. Slootweg, Circular chemistry to enable a circular economy, *Nat. Chem.*, 2019, **11**, 190–195, DOI: 10.1038/s41557-019-0226-9.

42 R. De Man, Circularity dreams. Denying physical realities, in *The Impossibilities of the Circular Economy*, ed. Lehmann, H., Hinske, C., de Margerie, V. and Slaveikova Nikolova, A., Routledge, 2023, pp. 3–10, DOI: 10.4324/9781003244196-2.

43 F. Soddy, *Wealth, Virtual Wealth and Debt: the Solution of the Economic Paradox*, George Allen & Unwin Ltd, London, 1926, https://archive.org/details/soddy-f.-wealth-virtual-wealth-and-debt-1925/mode/.

44 K. Polanyi, *The Great Transformation*, Farrar & Rinehart, New York/Toronto, 1944.

45 N. Georgescu-Roegen, *The Entropy Law and the Economic Process*, Harvard University Press, 1971, https://content.csbs.utah.edu/~lozada/Adv_Resource_Econ/En_Law_Econ_Proc_Cropped_Optimized_Clearscan.pdf.

46 *Toward a Steady-State Economy*, ed. Daly, H. E., W.H. Freeman & Company, 1973, ISBN 0-7167-0793-4. https://archive.org/details/towardsteadystat0000daly/towardsteadystat0000daly.

47 M. Faber, How to be an ecological economist, *Ecol. Econ.*, 2008, **66**(1), 1–7, DOI: 10.1016/j.ecolecon.2008.01.017.

48 M. Giampietro, The entropic nature of the economic process: A scientific explanation of the blunder of circular economy, in *The Impossibilities of the Circular Economy*, Lehmann, H., Hinske, C., de Margerie, V. and Slaveikova Nikolova, A., Routledge, 2023, pp. 37–47, DOI: 10.4324/9781003244196-5.

49 UNIDO – United Nations Industrial Development Organization, Global promotion and implementation of chemical leasing business models in industry, Ten years outlook, Vienna, 2016, https://downloads.unido.org/ot/46/86/4686100/SCHWAGER_ENV_IRE_GLO_2016_100035.pdf, accessed 23-07-2025.

50 S. Böschen, D. Lenoir and M. Scheringer, Sustainable chemistry: Starting points and prospects, *Naturwissenschaften*, 2003, **90**, 93–102, DOI: 10.1007/s00114-002-0397-9.

51 O. Hutzinger, The Greening of Chemistry – Is it sustainable?, *Environ. Sci. Pollut. Res.*, 1999, **6**, 123, DOI: 10.1007/BF02987605.

52 K. Kümmerer, Sustainable Chemistry: A Future Guiding Principle, *Angew. Chem., Int. Ed.*, 2017, **56**(52), 16420–16421, DOI: 10.1002/anie.201709949.

53 K. Kümmerer and J. Clark, Green and Sustainable Chemistry, in *Sustainability Science* ed. Heinrichs, H., Martens, P., Michelsen, G. and Wiek, A., Springer, Dordrecht, 2016, pp. 43–59, DOI: 10.1007/978-94-017-7242-6_4.

54 World Commission on Environment and Development (WCED), Our Common Future ("Brundtland Report"), https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

55 H. Jonas, *The Imperative of Responsibility: in Search of an Ethics for the Technological Age*, The University of Chicago Press, 1984, https://press.uchicago.edu/ucp/books/book/chicago/I/bo5953283.html.

56 S. Matlin, G. Mehta, H. Hopf and A. Krief, One-world chemistry and systems thinking, *Nat. Chem.*, 2016, **8**, 393–398, DOI: 10.1038/nchem.2498.

57 C. Blum, D. Bunke, M. Hungsberg, E. Roelofs, A. Joas, R. Joas, M. Blepp and H. C. Stolzenberg, The concept of sustainable chemistry: key drivers for the transition towards sustainable development, *Sustainable Chem. Pharm.*, 2017, **5**, 94–104, DOI: 10.1016/j.scp.2017.01.001.

58 K. Kümmerer, A. K. Amsel, D. Bartkowiak, C. Blum and C. Cinquemani, Key Characteristics of Sustainable Chemistry, *Dialogue Paper by the International Sustainable Chemistry Collaborative Centre (ISC3)*, Bonn, Germany, 2021, https://www.isc3.org/cms/wp-content/uploads/2022/06/ISC3_Sustainable_Chemistry_key_characteristics_20210113.pdf, accessed 07-07-2023.

59 UNEP, 2023, Global Framework of Chemicals – For a Planet Free of Harm from Chemicals and Waste, *Texts and resolutions of the Fifth International Conference on Chemicals Management*, https://www.chemicalsframework.org/sites/default/files/documents/GFC_Main_Brochure__6_March_2024.pdf.

60 UBA, Guide on Sustainable Chemicals, 2016, https://www.umweltbundesamt.de/publikationen/guide-on-sustainable-chemicals, accessed 30-10-2024.

61 UBA, ChemSelect. Selection of more sustainable chemicals for processes and products, 2024, https://chemselect.uba.de/, accessed 30-10-2024.

62 IPEN, *Thought Starter on Beyond 2020 Indicators and Milestones: Chemical Safety Contributions to the SDGs*, Sept. 2019 17, https://ipen.org/news/thought-starter-beyond-2020-indicators-and-milestones-chemical-safety-contributions-sdgs, accessed 24-03-2022.

63 UNEP, *Green and Sustainable Chemistry: Framework Manual*, 2020, https://wedocs.unep.org/bitstream/handle/20.500.11822/34338/GSCF.pdf.

64 UNEP, Global Framework of Chemicals – Open-Ended Ad Hoc Group on Measurability and Indicators, 2024, https://www.chemicalsframework.org/page/open-ended-ad-hoc-group-measurability-and-indicators.

65 SAICM, First e-meeting of the Technical Working Group, 10 January 2020. Meeting Reference Documents, TWG/Document/4 – Mapping exercise: existing global and regional data and indicators relevant to the Beyond 2020 Framework, 2019, https://www.saicm.org/Portals/12/Documents/meetings/TGW/TWG-Doc-4_Mapping_Exercise.docx, accessed 10-10-2019.

66 SAICM, Proposed targets prepared by the Technical Working Group on targets, indicators and milestones for SAICM and the sound management of chemicals and waste beyond 2020, 2020, SAICM/IP.4/3, 21-02-2020, https://www.saicm.org/Portals/12/documents/meetings/IP4/old/

(old)SAICM_IP4_3_Proposed-targets-TWG-SAICM-smcw-beyond-2020.pdf, accessed 10-09-2023.
67 H. Friege, E. Heidbüchel and B. Zeschmar-Lahl, Indicators for sustainable management of chemicals. Contributions to upcoming development work under the new Global Framework for Chemicals, Umweltbundesamt, 2024, UBA-texte 79/2024, https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/79_2024_texte_sustainable_management_of_chemicals_0.pdf.
68 SAICM, TWG/document/3: Proposal by TWG Co-Chairs: Suggested framework to support the development of targets & indicators, 2020, http://www.saicm.org/Portals/12/Documents/meetings/TGW/TWG-Doc-3_Suggested_framework.pdf, accessed 06-09-2023.
69 GFC, Strategic objectives and targets, https://www.chemicalsframework.org/page/strategic-objectives-and-targets.
70 IOMC, Indicators of progress in implementing SAICM, 2015, https://partnership.who.int/iomc/iomc-indicators-of-progress-in-implementing-saicm, accessed 24-03-2022.
71 TfS – Together for Sustainability: 2018 ANNUAL ACTIVITY REPORT. https://tfs-initiative.com/audit-process/#1472630050074-10b9365f-40ca, Third Party Audit Program, Version 3.1, 28.08.2019 https://tfs-initiative.com/dl/TfS_Audit_Program_V3-0.pdf, Audit Preparation Document. https://tfs-initiative.com/dl/Audit-Preparation-Document-V3-0.xlsx.
72 UNEP, End plastic pollution: towards an international legally binding instrument, 2022, UNEP/EA.5/Res.14. https://digitallibrary.un.org/record/3999257?ln=en&v=pdf, accessed 25-09-2024.
73 UN, Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development, 2024, https://unstats.un.org/sdgs/indicators/Global-Indicator-Framework-after-2024-refinement-English.pdf, accessed 25-09-2024.
74 SAICM, Proposed targets prepared by the Technical Working Group on targets, indicators and milestones for SAICM and the sound management of chemicals and waste beyond 2020, 2020, SAICM/IP.4/3, 21-02-2020, https://www.saicm.org/Portals/12/documents/meetings/IP4/old/(old)SAICM_IP4_3_Proposed-targets-TWG-SAICM-smcw-beyond-2020.pdf, accessed 10-09-2023.
75 IOMC, Strengthening integrated chemicals and waste management: An IOMC contribution to the intersessional process on the "Strategic Approach and sound management of chemicals and waste beyond 2020", SAICM/IP.4/INF/18, 2022, https://www.saicm.org/Portals/12/documents/meetings/IP4/2022/SAICM_IP4_INF_18_IOMCIntegratedchemicalsandwastemanagement__.pdf.
76 SAICM, Inventory and analysis report: existing indicators on chemicals and waste management, 2023, SAICM/IP.4/INF/39/Rev.1, 08/08/2023, Annex: IOMC Indicators Project Working Group: IOMC: Update to the Inventory and analysis report: existing indicators on chemicals and waste management. 17/07/2023, https://www.saicm.org/Portals/12/documents/meetings/IP4_3/SAICM_IP.4_INF_39_Rev.1.pdf, accessed 09-06-2023.
77 CEFIC, Sustainability development indicators, 2025, https://cefic.org/a-solution-provider-for-sustainability/cefic-sustainable-development-indicators/, accessed 12-12-2024.
78 https://data.footprintnetwork.org/#/, accessed 28-07-2025.
79 A. K. Osei-Owusu, M. Danquah and E. Towa, *Unravelling Africa's Raw Material Footprints and Their Drivers*, WIDER Working Paper, No. 2022/115, ISBN 978-92-9267-249-2, UNU-WIDER, Helsinki, 2022, https://www.econstor.eu/bitstream/10419/273906/1/1818354136.pdf, accessed 28-07-2025.
80 https://www.fao.org/pest-and-pesticide-management/pesticide-risk-reduction/code-conduct/policy-and-legislation/en/, accessed 28-07-2025.
81 https://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/code/it/, accessed 28-07-2025.
82 Presentation by Dr Eric de Deckere (CEFIC) on occasion of the 6th workshop of this project.
83 BUND/Friends of the Earth Germany and Federal Working Group on Environmental Chemicals/Toxicology, Challenges for a Sustainable Chemicals and Materials Policy. The need for transformation in a global context, 2023, BUND position paper No. 69, 2nd updated edition, status 16.06.2023. https://www.bund.net/fileadmin/user_upload_bund/publikationen/chemie/chemie_stoffpolitik-position_engl.pdf, accessed 23-11-2024.
84 UNEP, UNEP/EA.5/Res.8. Science-policy panel to contribute further to the sound management of chemicals and waste and to prevent pollution, 2022. https://digitallibrary.un.org/record/3999276?ln=en&v=pdf, accessed 22-10-2024.
85 European Commission, 2020, Chemicals Strategy for Sustainability – Towards a Toxic-Free Environment, COM (2020) 667 final, 14.10.2020, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0667, accessed 10-09-2023.
86 C. Caldeira, R. Farcal, I. Garmendia Aguirre, L. Mancini, D. Tosches, A. Amelio, K. Rasmussen, H. Rauscher, J. Riego Sintes and S. Sala, Safe and Sustainable by Design chemicals and materials – Framework for the definition of criteria and evaluation procedure for chemicals and materials, EUR 31100 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-53264-4, JRC128591, DOI: 10.2760/487955.