ARTICLE IN PRESS

Sustainable Chemistry and Pharmacy (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Sustainable Chemistry and Pharmacy

journal homepage: www.elsevier.com/locate/scp

The concept of sustainable chemistry: Key drivers for the transition towards sustainable development

Christopher Blum[a,*], Dirk Bunke[b], Maximilian Hungsberg[c], Elsbeth Roelofs[d], Anke Joas[e], Reinhard Joas[e], Markus Blepp[b], Hans-Christian Stolzenberg[a]

[a] *Umweltbundesamt, Dessau, Germany*
[b] *Oeko-Institut, Freiburg, Germany*
[c] *TU Darmstadt, Darmstadt, Germany*
[d] *CSR Netherlands, Utrecht, The Netherlands*
[e] *BIPRO GmbH, München, Germany*

A R T I C L E I N F O

Keywords:
Sustainable chemistry
Green chemistry
Chemicals safety
Chemicals management
Sustainable development
Sustainable development goals

A B S T R A C T

To achieve and safeguard the chemicals management “2020 goal” of least possible adverse effects, we need broad and global transformation to a sustainable chemistry, which can provide the most adequate solutions contributing to sustainable development as set out in the Agenda 2030. As a basis for effective progress, a common understanding is required of sustainable chemistry, of its scope, characteristic elements, and specific objectives, as well are guidelines requisite for influencing the speed and direction of this complex and encompassing transformation. This article aims at stimulating this transition process towards a sustainable chemical sector by proposing “100 words for sustainable chemistry”, objectives and guiding principles as well as actions steps towards the further implementation of sustainable chemistry.

1. Executive summary

Producing, using, re-using, disposing, and eliminating chemicals with the least possible adverse effects on human health and the environment is a global goal. This so-called 2020 goal has been initially formulated 2002 by the Johannesburg World Summit for Sustainable Development. Since then, several policy for a have repeatedly endorsed and reinforced the 2020 goal. While rapidly approaching the initial target date, we face globally ongoing progression of production volumes, count, and uses of chemicals. Thus, despite all considerable efforts in chemicals management so far, the need for broad transformation to a sustainable chemistry becomes exigent. Moreover, as humankind has to rely on the chemicals sector for contributions to nearly all Sustainable Development Goals (SDG) of the Agenda 2030, it is even more essential to get the urgently needed sustainable solutions from a thoroughly sustainable chemistry.

The herewith-presented Concept of Sustainable Chemistry describes the understanding of what sustainable chemistry is about in view of the authors. Furthermore, it is setting out the objectives and guiding principles for sustainable chemistry and points out action topics influencing the holistic approach that sustainable chemistry entails.

Sustainable development is a process to ensure the future as well as present potential to meet essential human needs and desires within the ecological and resource limits of our planet. This paradigm is relevant for all areas including those where chemicals are produced, traded, used, processed, incorporated into products, reused and recycled, disposed off and released into the environment. These chemical relevant areas need to reach a common understanding of how to foster sustainability in chemistry since the term sustainable chemistry has been used with different interpretations for many years. In order to guide this process, we propose a description of sustainable chemistry which is building on the sustainable chemistry definition of the OECD, rooted in chemicals management as well as the 12 Principles of Green Chemistry and addresses social, environmental, scientific and economical aspects (Fig. 1).

Sustainable chemistry is a holistic approach where the entire lifecycle of chemical products and the related system of actors, institutions and culture is considered. This implicates that all stakeholders along the life cycle chain of chemicals have responsible roles. Besides health and environment, social conditions, research, science and economic aspects have to be considered and balanced within the capacity-limits of our planet. This holistic approach distinguishes sustainable chemistry from green chemistry and from operational safe

* Corresponding author.
E-mail address: christopher.blum@uba.de (C. Blum).

http://dx.doi.org/10.1016/j.scp.2017.01.001
Received 4 June 2016; Received in revised form 23 December 2016; Accepted 14 January 2017

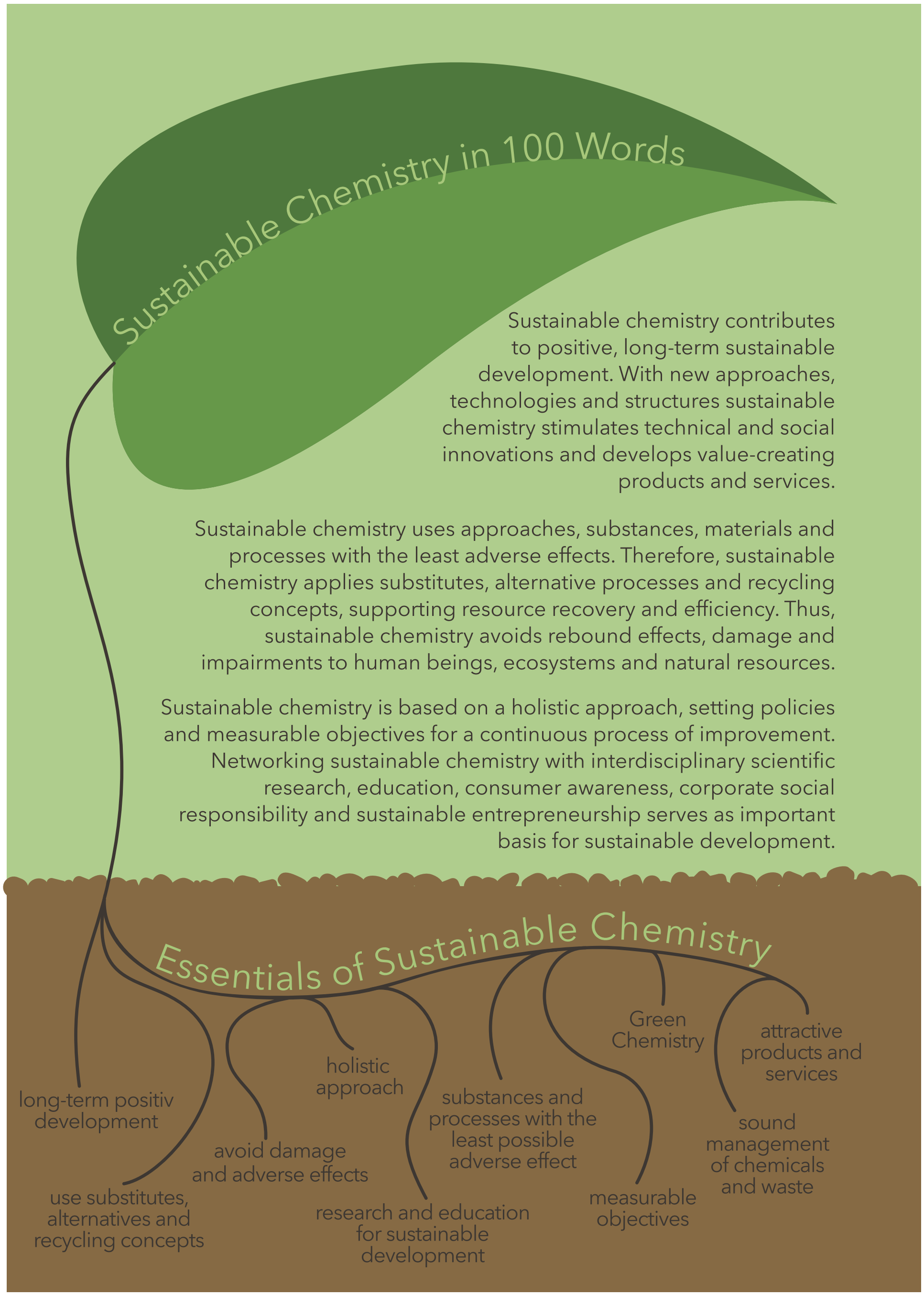

Fig. 1. Sustainable chemistry in 100 words.

use of chemicals. Sustainable chemistry is building on and goes beyond these two concepts. Moreover, this encompasses system innovations which will lead to fundamental changes in both social dimensions (values, regulations, attitudes etc.) and technical dimensions (infrastructure, technology, tools, production processes etc.) and, very importantly, in the relations between them.

Sustainable chemistry thrives innovative solutions, even including non-chemical alternatives, based on knowledge to address serious societal problems and is able to preserve and create jobs and to access new business markets. It generates sustainable products or services which are commercially successful, beneficial to society, and not harmful to humans and environment. This implies the need for sustainable production in which steps before or after production have to be included in sustainable assessment and action.

Sustainable chemistry applies the precautionary principle and uses or applies only products and services that are sustainable and serve sustainable objectives. Based on this assumption, to guard against green washing, to reduce current burdens, and with a view to the SDGs, we propose seven Objectives and Guiding Principles of Sustainable Chemistry to be applied in all chemical relevant areas:

- Design and use of benign chemicals.
- Development and use of alternative solutions for problematic applications.
- Reduction of impacts.
- Conservation of natural resources.
- Promotion of reuse and recycling.
- Increase of market opportunities.
- Application of corporate social responsibility.

For many important applications, chemicals without problematic properties are still not available. In these cases, hazardous substances have to be used. Therefore, safe use and sound management of such chemicals are essential parts of sustainable chemistry. They ensure that exposures and releases are kept as low as possible – while sustainable chemistry implies ongoing efforts to find suitable alternative substances or technologies, which are economically and technically feasible.

To implement these Objectives and Guiding Principles of Sustainable Chemistry into practice, all stakeholders have to make joint efforts to develop common strategies for action and activities.

On international policy level, the United Nations are discussing and fostering sustainable development at the global policy level since 2002. Since 2006, the Strategic Approach to International Chemicals Management (SAICM) is contributing to the management part of global chemical policy. However, sustainable chemistry has not been very visible in these activities so far. This has changed at some extent in 2015 when the Sustainable Develpoment Agenda 2030 was adopted. 17 Sustainable Develpoment Goals (SDGs) and 169 underlying targets offer various connection points to highlight the capabilities of sustainable chemistry. Chemicals are explicitly named in SDG 12 (consumption and production), SDG 6 (water and sanitation) and SDG 3 (healthy lives and well-being). To these and other SDGs we believe sustainable chemistry will be a significant stimulator, generating the most adequate sustainable contributions from the chemicals sector.

In summary, we see a window of opportunity to strengthen the role and visibility of sustainable chemistry in the current policy context. Tapping the full potential of sustainable chemistry will most effectively contribute to the whole sustainable development agenda and will further enhance sound management of chemicals (Fig. 2). To realise this, an important aspect will be the international cooperative action of all stakeholders and organizations dealing with chemical relevant areas, as particularly injected in SAICM and sighted by SDG 17. In our view, the International Sustainable Chemistry Collaborative Centre (ISC_3) will be a fitting institution definitively contributing to this process.

2. Introduction

At the global level, in 2002 the United Nations discussed sustainable development at the World Summit on Sustainable Development (WSSD) in Johannesburg, South Africa. Since 2006, the Strategic Approach to International Chemicals Management (SAICM) bundles the various activities relating to chemical safety in an integrated approach. SAICM is an overarching strategy of a cross-cutting nature, institutionalizing the involvement of stakeholders from all relevant sectors on a voluntary basis. SAICM is a time-limited process; its mandate is currently limited until 2020. SAICM has adopted the “2020 goal” of the World Summit on Sustainable Development in 2002 as part of the Johannesburg Plan of Implementation: ”…to achieve, by 2020, that chemicals are used and produced in ways that lead to minimization of significant adverse effects on human health and the environment (…)”.⟨http://wwwunorg/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImplpdf⟩ (2002).

In this sense, producing, using, re-using, disposing, and eliminating chemicals with the least possible adverse effects on human health and the environment is a global goal. However, while rapidly approaching the initial target date of the 2020-goal, we face globally ongoing progression of production volumes, count, and uses of chemicals. Thus, despite all considerable efforts in chemicals management so far, the need for broad transformation to a sustainable chemistry becomes exigent.

Sustainable chemistry is ready to make contributions in this respect and this has been acknowledged in 2016 when the second United Nations Environment Assembly (UNEA-2) mentioned sustainable chemistry for the first time in a resolution and requested governments and stakeholders to share good practices with UNEP by June 2017. UNEP/EA (2016) Thereby, a basis for exploring sustainable chemistry linkages with and developing options for the implementation of the 2030 Agenda for Sustainable Development shall be provided. Moreover, as humankind has to rely on the chemicals sector for contributions to nearly all Sustainable Development Goals (SDG) of the Agenda 2030, it is even more essential to get the urgently needed sustainable solutions from a thoroughly sustainable chemistry.

The field of green and sustainable chemistry has rapidly grown in the past few decades. Both in science and research as well as in segments of the industry there have been many independent activities. (Cannon and Warner, 2011; Kümmerer and Hempel, 2010; Angrick et al., 2006) Various organizations have launched activities with the goal to foster green and sustainable chemistry (Fig. 2).

Green chemistry is a prerequisite and a core part of sustainable chemistry. Most important for green chemistry are the 12 Principles of Green Chemistry. (Anastas and Warner, 1998; Voutchkova-Kostal et al., 2012) Green chemistry and sustainable chemistry have in common a benign design, manufacture and use of chemical products and services which are efficient, effective, safe and environmentally harmless. However, whereas green chemistry strives primarily at engineering and technical issues, like synthesis, atom economy and use of solvents, and thereby derives from a perspective of design and production, sustainable chemistry encompasses all life cycle stages as well as direct and indirect implications in surrounding areas and addresses different perspectives besides environmental aspects like economy and society.

In 1996 the Annex IV of the directive on integrated pollution prevention and control of pollution (IPPC Directive) (Voutchkova-Kostal et al., 2012) expressed 12 guiding principles on the status of the best available technology describing sustainable production especially for the chemical industry. The IPPC Directive (Council Directive 96/61/EC of 24 September (1996)) was integrated in the industrial emissions directive (IED) in 2010 Directive (2010)/75/EU of the European Parliament and of the Council of 24 November (2010). In 2004 the German Environment Agency (UBA) jointly with the Organization for Economic Cooperation and Development (OECD) developed qualitative and quantitative criteria for sustainable chemistry (German Federal Environment Agency, (2009)).

However, despite these efforts, a commonly shared understanding of what actually constitutes sustainable chemistry is still lacking. Today, several definitions on sustainable chemistry exist. Among these, the OECD description of sustainable chemistry (http://www.oecd.org/chemicalsafety/risk-management/sustainablechemistry.htm) has a strong perception, because of the particular role of this international organization in providing science-based tools for policy-making. However, initiatives like SusChem define sustainable chemistry in slightly different ways (http://www.suschem.org/about-suschem/vision-and-mission-sustainable-chemistry.aspx), whereas the American Chemical Society (http://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/definition.html) and the US EPA (https://www.epa.gov/greenchemistry/basics-green-chemistry) do not differentiate between green and sustainable chemistry.

This situation implies that there is a lack of direction and prioritization of the various activities. A commonly shared understanding of sustainable chemistry and specific objectives are required in order to not transgress the ecological guideline and limits of our planet and to achieve the internationally agreed Agenda 2030 with its 17 Sustainable Development Goals (SDG) and 169 targets (UN document, 2030).

At this point the Concept of Sustainable Chemistry hooks in. A clear presentation of the objectives and guiding principles of sustainable chemistry should serve to guide concrete entrepreneurial, administrative, academic and social actions and, moreover, clarify the meaning of sustainable chemistry. It will assist stakeholders in exploiting chemistry's potentials for the solution of current and future societal challenges in a targeted manner.

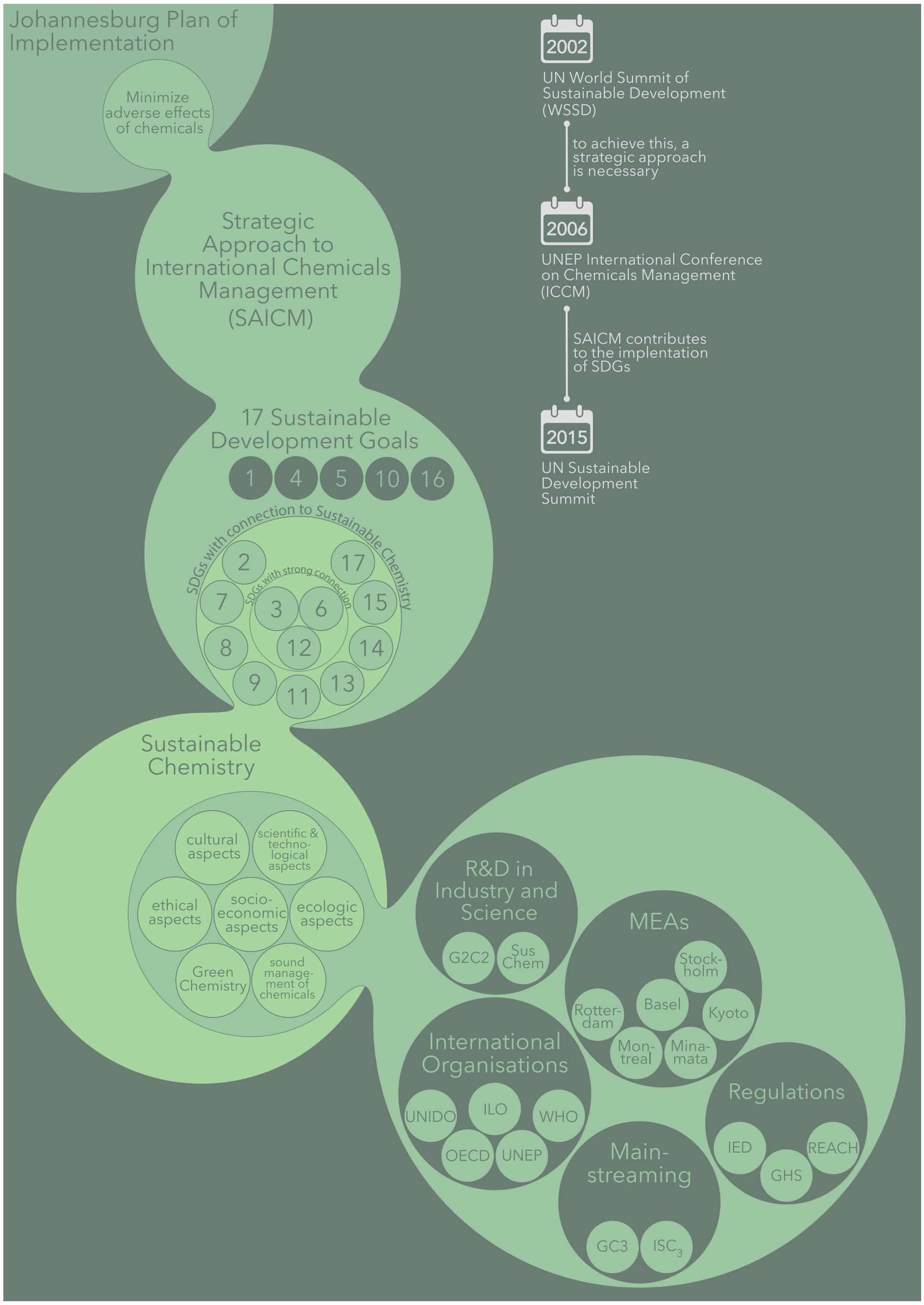

Fig. 2. Sustainable chemistry and surrounding elements.

The concept aims to stimulate future activities in the field of sustainable chemistry and materialize sustainable chemistry for the chemical industry and their user industries as well as related fields such as pharmacy (Kümmerer and Hempel, (2010)). Furthermore, the concept has significant potential to align chemicals and waste management effectively with sustainable development. The concept is also intended to serve as a starting point of reference for the work of the International Sustainable Chemistry Collaborative Centre (ISC_3) as well as for the work of the chemical industry to fulfill the UN SDGs.

In developing our concept it was possible to take advantage of substantial preliminary work already undertaken, including the 12 Principles for Green Chemistry and the work of the OECD on the characterization of sustainable chemistry (German Federal Environment Agency, (2009); http://www.oecd.org/chemicalsafety/risk-management/sustainablechemistry.htm; Environmental Directorate OECD, 2004; Reihlen et al., 2016 ; Moser et al., 2014; Clark and Kümmerer, 2016). These approaches have been integrated, extended to a more holistic view, and specified. Thereby, we have taken into account the effects on environment and health, as well as scientific, cultural, social and economic aspects. When it comes to the next steps, we put precedence to the pursuit of ways to reduce negative impacts on health and the environment. This set of priorities complements the works undertaken by other stakeholders who focus more on economic and societal issues.

3. The challenge of sustainable development

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition by the Brundtland Commission, was made almost 30 years ago and has defined the still valid understanding of sustainability (World Commission on Environment and Development, (1987)). Hence, sustainability needs to be rooted in the societal, environmental, economic and scientific fields as well as in cultural understanding.

Realisation of sustainable chemistry requires a holistic approach. Bearing this in mind, developing sustainable chemistry, i.e. in the chemical industry entails more than innovation of chemical products and processes. It requires the transformation of value chains as well as institutional and financial structures that might hinder sustainability. Therefore, system innovations are important to achieve sustainable supply of products and materials for society.

A systems approach analyses chemistry and the chemical sector as a system that provides the products and materials for society and that has evolved into a tightly interlinked network of actors, technologies and institutions. This network provides reinforcements – e.g. through accumulation of knowledge, economies of scale, network effects, consumer habits – to the preservation and improvement of carbon based products and processes. To overcome this, a system innovation is needed that "... leads to fundamental changes in both social dimensions (values, regulations, attitudes etc.) and technical dimensions (infrastructure, technology, tools, production processes etc.) and, very importantly, in the relations between them" (Suurs and Roelofs, 2014).

However, absolute sustainability will endure as a vision and motivation for further changes. Life cycle analysis can be applied as a tool to assess ecological aspects in a comprehensive manner. In addition, modules for social impacts, costs and benefits have become instruments of sustainability assessment (Kemp, 2011; World Business Council for Sustainable Development, 2016; Antony et al., 2014). Sustainable chemistry has a large potential for fulfilling material and product needs of a modern sustainable society; for instance innovative solutions with chemicals in the area of energy efficiency or the change from fossilized carbon to renewable resources (Collins, 2001). These examples have demonstrated that they have the power to contribute to sustainable development worldwide. However, there have been increasing challenges on a global scale in recent years. Clean water, enough safe food for all, poverty eradication, urbanization, population growth, climate protection, biodiversity, health and environmental protection – these examples illustrate that the world has to face ever growing challenges when striving for a truly sustainable development.

The development and application of new approaches and technologies and the coinciding evolvement of new structures that stimulate transformation is necessary to enable the development of value-creating products and services. Which such development, sustainable chemistry is able to contribute to enduring positive development urgently required for society, economy and environment. In the scope of sustainable chemistry, more emphasis is being placed on the stress limit of humans and the limited carrying capacity of the environment than has been done under previous approaches.

Fig. 2 describes areas of sustainable chemistry and their relations important elements, aspects, initiatives and organizations with regard to sustainable development.

3.1. Organizations influential in sustainability

3.1.1. Governmental and inter-governmental organizations

Over the past twenty years, major progress has been made towards green chemistry, but less towards sustainable chemistry. Various elements have helped to adopt and implement different aspects of sustainability, for example in objectives formulated or in practical solutions.

The policy-framework for implementation of sustainable development has received an immense momentum at the global level by adoption of the UN Sustainable Develpoment Agenda 2030 in 2015, which builds upon 17 Sustainable Develpoment Goals and 169 underlying targets proclaimed as integrated and indivisable. The 2030 Agenda for Sustainable Development offers an overarching framework for enhancing synergies between separate policy areas towards the global sustainability goals (UNEP/EA, 2016). In this regard, sound management of chemicals, explicitly addressed in target 12.4 of Sustainable Development Goal 12 (SDG 12) aims also at bettering conditions for environment (SDG 3, SDG 6) and health (SDG 3) through elimination of negative impacts. However, there are many other SDGs (Nachrichten aus der Chemie 64, 2016) that may have strong linkages with chemicals management, for example agricultural practices regarding hunger elimination (SDG 2), energy efficiency (SDG 7), global resource efficiency in consumption and production (SDG 8), sustainable industrialization (SDG 9), sustainable cities and communities (SDG 11), climate protection (SDG 13), life below water and on land (SDG 14 und 15) and global partnerships (SDG 17). Frequently such linkages are complex and their analysis is not yet thoroughly studied in science and even less visible in policy making.

As stated above, target 12.4 takes over SAICM's "2020 goal" and further coins the key concept of Sound Managements of Chemicals and Waste (SMCW): "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". SMCW refers to tools developed and provided by various actors. It takes into account e.g. the relevant multilateral environmental agreements (MEA), the globally harmonized system (GHS), the aforementioned strategic approach SAICM, as well as various instruments of the Inter-Organization Programme for the Sound Management of Chemicals (IOMC) - particularly from the OECD chemicals programme - and also regional schemes such as the European regulations REACH or those on plant protection products, biocides, the California Proposition 65, specific Japanese chemicals regulations and many others.

In order to contribute to the whole sustainable development agenda there is a need to enhance sound management of chemicals through sustainable chemistry (Fig. 2). Equally, fulfilment of the SDGs through sound management of chemicals can be enhanced by enshrining sustainable chemistry in future chemicals management. Chaperoning aspects essential for successfully influencing direction and speed of sustainable chemistry as a holisitc approach are among others primarily green chemistry, innovation in combination with research and development, cooperative action of international organizations like the OECD or the United Nations Industrial Development Organization (UNIDO), as well as of institutions responsible for implementing regional and national regulations, international MEAs, SAICM and others.

Policy instruments on sound management of chemicals on international and national level, including voluntary programms, particularly SAICM, as well as regulations like the Stockholm Convention (Stockholm Convention on Persistent Organic Pollutants POPs, 2010) or the Rotterdam Convention (Rotterdam Convention, 2013), and other MEAs, have the objective of protecting human health and the environment from hazards and, with more stringency, from evidenced risks. Under this policy regime there are underlying or implicit considerations that take some aspects of the precautionary principle into account. This is the case in particular for the Stockholm Convention (Annex F for risk management evaluation) and the Rotterdam Convention (notifications of final regulatory actions).

However, overarching considerations have not been bundled so far to a comprehensive understanding of what is really important in terms of sustainable development. SAICM has some weak linkages to overarching considerations, e.g. the nomination process for emerging policy issues and UNIDO's Cleaner Production Centers show in an exemplary way the progress achieved in plant and process safety as well as in occupational safety.

REACH, the major component of European chemicals legislation, is a very ambitious regulation. Among other things, it requires taking into account socio-economic considerations when concluding on authorization applications for substances of very high concern. At the level of technical implementation, best available techniques (BATs) and best available techniques reference documents (BREFs) are standards for process optimization, while best environmental practices (BEPs) describe the application of the most appropriate combination of environmental control measures and strategies (Directive (2010)/75/EU of the European Parliament and of the Council of 24 November, 2010). Environmental and consumer protection organizations such as the umbrella organization European Environmental Bureau (EEB) play an important role in encouraging the ambitious elaboration of both legal frameworks as well as voluntary initiatives for sustainable chemistry.

3.1.2. The role of the chemical industry in sustainability

Our society is nowadays faced with a number of persistent problems in domains such as energy, mobility, agriculture, and biodiversity. The persistent nature of these problems is closely related to the fact that the problems arise from patterns and processes that are deeply embedded in and privileged by the institutions of state, science, market and society – as well as their mutual alignment. These persistent problems ask for transitions or system innovations, where societal development breaks away from previous lines of progress. Radical new approaches of production and consumption are necessary to influence societal development processes in such a way that in the long-term sustainability ambitions are met. In this, the chemical industry is essential, since it is a key partner for the all sectors of the manufacturing industry. On a global scale, it provides significant contributions to satisfy the needs of society as far as possible, given the limited resources available.

The chemical industry has indeed undertaken efforts according to its perception of sustainability. The chemical industry's core strength is the development of innovative materials and system solutions as well as the interlinking of social, environmental and economic aspects. In this regard, the chemical industry can provide crucial contributions to sustainable development. However, in many countries and areas of application, production, use and disposal of chemicals are still connected with significant or even increasing exposures to human health and the environment also resulting in damages of those.

The chemical industry created global approaches like the Global Productship Scheme (GPS) and the Responsible Care initiative (RC) (http://www.icca-chem.org/en/Home/Responsible-care/; http://www.globalpsc.net/). The German chemical industry's Chemie[3] initiative drives in its guidelines extensive allowance for social and economic issues (Verband der Chemischen Industrie, 2013). The Dutch MVO QUICKSCAN initiative illustrates the corporate social responsibility in the chemicals industry (Netherland, 2015). The Green Chemistry and Commerce Council (GC3) (http://greenchemistryandcommerce.org/) is a good example of a network of companies, scientists, governmental organizations and environmental and consumer associations which strive to put green chemistry approaches into practice.

3.2. Missing aspects towards increased sustainability

Despite all these activities, globally agreed objectives like SAICM's 2020 goal and the Agenda 2030 target 12.4, (UN document, 2030; UNCSD Outcome document, 2012) will not be realized by 2020. Moreover, there is the enduring need to further develop the ambitions of chemicals management. Globally, we are still continuously facing increasing amounts and numbers of chemicals used. In many countries and fields of application, the use of chemical substances is still connected with considerable burdens or damage to human health and the environment. A vital precondition for attaining the 2020 objective is therefore to abandon the use of hazardous chemicals in as many fields as possible. Where this is not possible, emission levels must be reduced substantially.

Regarding societal aspects different sources of so-called lock-in of the present system of supply of products and materials exist. These sources of lock-in are mechanisms that reinforce the present system of production and consumption, and thus contribute to the present persistent societal problems (Unruh, 2002). They can be of various nature: technological (i.e. dominant design, standard architectures and components, compatibility of designs), industrial (i.e. industry standards, technological inter-relatedness, co-specialized assets), organisational (i.e. routines, departmentalization, customer-supplier relations, training, capacity building), institutional (i.e. policies, legal frameworks, departments/ministries, educational programs) and socio-cultural (i.e. social norms, values, preferences, expectations, behavioral habits) (Suurs and Roelofs, 2014; Unruh, 2002). These lock-ins have to be overcome by a system innovation related to sustainable chemistry.

In general, missing aspects towards increased sustainability require a different handling of chemicals and a new understanding of chemistry as well as the role the chemical sector has to play in society. Therefore, new knowledge and technology as well as a transformation of the structure, culture and approach in the chemical sector is needed. That's where sustainable chemistry as a holisitc approach comes into play.

3.3. The concept of sustainable chemistry

3.3.1. Origin and meaning of the term

30 years ago the Brundtland Commission stated: “Sustainable development is essentially a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent, and increase the future as well as present potential to meet essential human needs and desires” (World Commission on Environment and Development, 1987) This process of change has already begun in the chemical industry. The aim is to reach sustainability in chemistry, but what is in fact sustainable chemistry?

At the international level, the term of sustainable chemistry has been used since more than ten years (Angrick et al., 2006). Criteria for sustainable chemistry have been developed by the German Environment Agency and the OECD in 2004 (Environmental Directorate OECD, 2004). A definition has been given by the OECD in 2014 (German Federal Environment Agency, 2009). According to this definition, sustainable chemistry is a chemistry characterized by increased resource efficiency, safer and less polluting substances, through innovations beyond sector borders, improved performance and increased added value. This definition has also been taken as a basis for the present Concept of Sustainable Chemistry. Bearing this in mind, sustainable chemistry can be described in 100 words (Fig. 1):

3.3.2. Sustainable chemistry: a holistic systems approach

For achieving sustainable chemistry a holistic approach is being adopted which is comprised of several aspects, some of these highlighted here. What does that mean? With sustainable chemistry the entire lifecycle of chemical products is considered. This includes molecular design, resource demand and synthesis over distribution, usage and recycling to end of life issues. Sustainable chemistry is continuous improvement to safer chemicals both through selection of alternatives and through research and development of new chemicals. Sustainable chemistry implicates that in addition to the chemical industry, downstream users of substances and materials, manufacturers of products as well as consumers are important players, who have their roles in a systems innovation approach. Consequently, sustainable chemistry does not only address effects on humans and the environment, but also challenges in terms of social conditions, the inclusion of research, science and culture, and a successful long-term and sustainable way of management respecting the capacity-limits of our planet.

This holistic approach distinguishes sustainable chemistry from green chemistry (Anastas and Warner, 1998; Cui et al., 2011; Beach et al., 2013) (at the same time integrating it) and from operational safe use of chemicals. The latter clearly emphasize the development of chemicals which are less problematic for humans and the environment, occupational health and safety in relation to production, and the protection of users. Both, green chemistry and the operational safe use of chemicals are important building blocks of sustainable chemistry. However, sustainable chemistry goes beyond both.

One key objective of sustainable chemistry is to use chemicals which are benign. This means they do not have any problematic characteristics for humans and the environment and their use or application in products and services are sustainable and serve sustainable objectives. In regards to hazardous substance groups, sustainable chemistry draws on the precautionary principle. This means that for certain groups of substances the hazardous potential of a substance alone is sufficient to trigger the implementation of measures or to not authorize them. Meanwhile, the precautionary principle has been recognized in several international conventions. Among other legal frameworks it is mentioned in the Basel, Rotterdam, Stockholm and Minamata Conventions, in the Montreal Protocol and also in REACH. The precautionary principle allows to address the challenge of adverse effects on human health and the environment by exposure to critical substances even in low dosages and to take into account lessons learnt from earlier releases of related substances (European Environmental Agency, 2012). The Tiered Protocol for Endocrine Disruption (TiPED) can be seen as a recent example for an interdisciplinary research approach from sustainable chemistry to reduce such adverse impacts starting from the source (Schug et al., 2013).

Sustainable chemistry significantly contributes to the reduction of current burdens and to attain the global objectives of sustainability. Fig. 3 shows the central objectives and guiding principles of sustainable chemistry.

In general, a holistic understanding of sustainability implies that the actors examine whether the use or application of a product is sustainable and whether it serves sustainable objectives. Therefore, sustainable chemistry aims at generating sustainable products produced in a sustainable value chain. For example, they should be commercially successful, beneficial to society, and enable the supplied clients to contribute effectively to all aspects of sustainability. Sustainable chemistry also means to establish sustainable production at every local plant. Additional steps taking place either before or after production often play an essential role as well. The evaluation of the use of renewable resources, for example, requires information on whether they were grown under sustainable conditions. For businesses, this implies to include also activities outside their local plants, since these can have a major impact on the overall sustainability of a product or service.

However, for many important applications, chemicals without problematic properties are still not available. In these cases, hazardous substances have to be used. Is this the case, safe use and sound management of such chemicals are essential to ensure that exposures and releases are kept as low as possible.

Sustainable chemistry thrives on finding innovative solutions to serious societal problems. To a very large degree, it is based on knowledge. Thus it enables innovative businesses to tap new markets permanently and to safeguard their company site in a better way. Sustainable chemistry is thereby able to preserve jobs and create new ones which are, inter alia, characterized by a high level of occupational health and safety.

4. Actions steps towards implementation of sustainable chemistry

In order to stimulating a transition process towards a sustainable chemistry we outline necessary and undividable actions steps to be taken on by all stakeholders.

4.1. General aspects of sustainable chemistry

More sustainability in chemistry will not be gained in the short term. In order to further develop sustainable chemistry in collaboration with all stakeholders on a global scale, there is a need for a “Roadmap of Sustainable Chemistry”. In evolving such a document, stakeholders have to agree upon a step-wise approach to attain the ambitious development goals set in terms of content and time schedule. Five elements will catalytically accelerate the growth of sustainable chemistry:

- **Innovative ideas.** Ensure sustainable energy supply and increase efficiency in resource utilization – these and other topics with relevance to the future need inventiveness and new approaches as indispensable preconditions for finding solutions. Therefore, science, research and development need an environment encouraging ideas and innovations as well as conditions and incentives that foster them.
- **New business models.** Further improvements in the performance of products, as achieved by the service-oriented business model of chemical leasing, (Moser et al., 2014; Schwager, 2010) may serve as a door-opener to convince (B2B-) customers of more sustainable products and services.
- **Responsible companies.** Setting of and compliance with demanding environmental and social standards by companies and their supply chain partners, such as long-term business relations and supplier trainings. Be transparent as a company on its own sustainability issues, in the company itself and in the supply chain. Having regular contact with a diversity of stakeholders in order to check the licence to operate as a company. Finally, companies have to perform due diligence on sustainability problems in their value chain to comply with the international guidelines for responsible behaviour (OECD, 2011).
- **Resource recovery.** Life cycle thinking and circularity should be the basic principle when developing new products, services business models and corporations.
- **Reliable, accessible and transparent data.** In order to comprehensively evaluate the sustainability of products, stakeholders need information on the impact of raw materials extraction, production, processing, transportation, use and disposal of substances, materials and products.
- **Demanding and enabling legislation.** In a globalized world, all companies should be compliant with comparably ambitious legislative frameworks and act responsibly. Besides that, regulation should be enabling and rewarding for companies that are frontrunners in terms of sustainability. Governments can also help by acting as launching customers for sustainable products and by creating more experimentation space for sustainable frontrunners (US Department of Agriculture; PIANOo).

In order to achieve greater sustainability in chemistry, the actors need appropriate instruments to comprehensively evaluate approaches or solutions. Sustainability should be measurable. By means of quantifiable indicators which should be workable in practice and which allow for an assessment of measures already during the planning phase.

4.2. Increased collaboration and communication

Sustainable chemistry is a process of change. In addition to the multilateral environmental agreements and the regional and national regulations on chemicals management which are in place, voluntary initiatives and schemes can contribute to this change in different ways and extent at the national and international scale, e.g. the German Blue Angel or the EU Ecolabel, German chemical industry's initiative Chemie[3] or the global Responsible Care scheme, numerous sector-

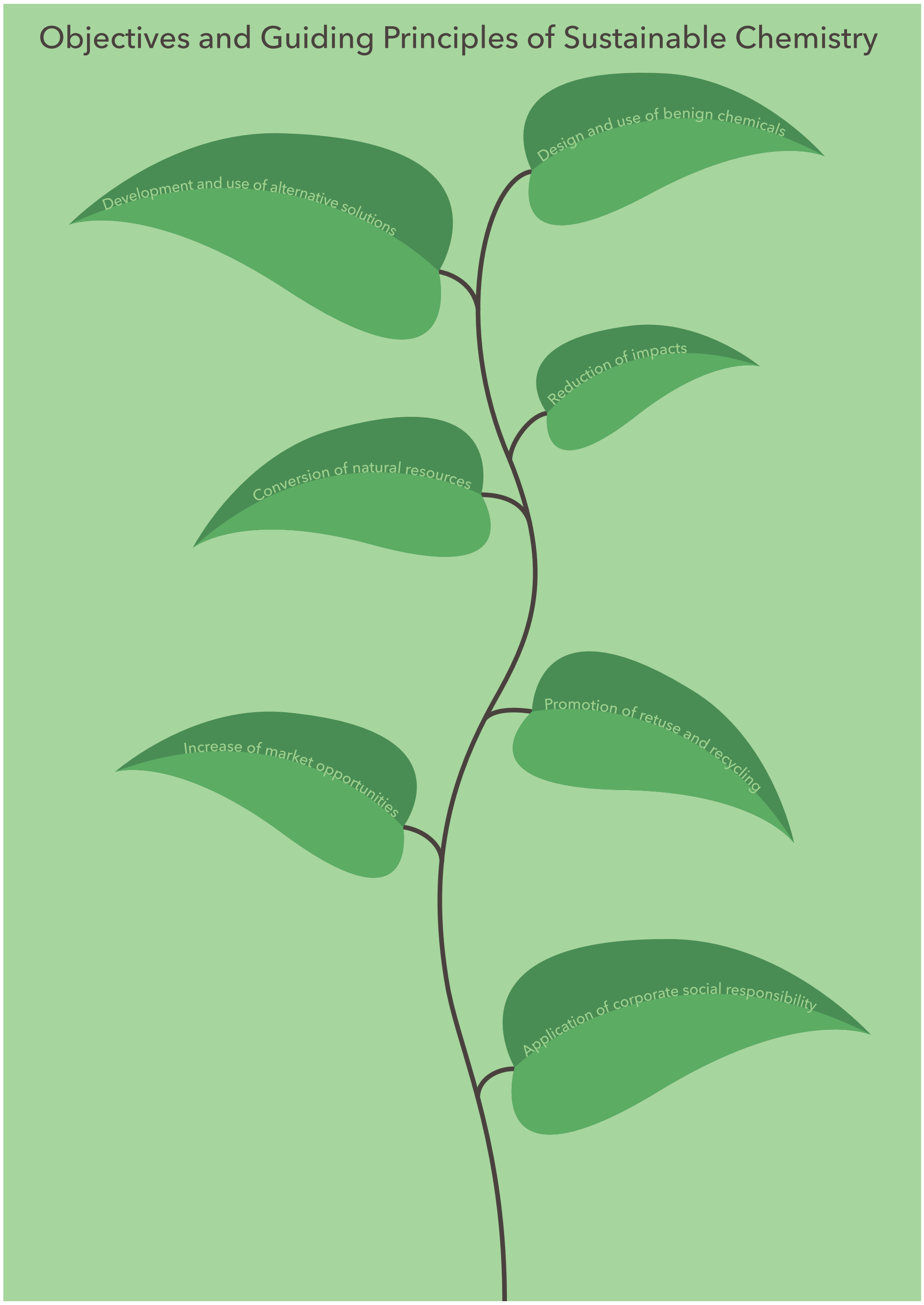

Fig. 3. Objectives and guiding principles of sustainable chemistry.

specific approaches, the global policy platform SAICM, and many others.

The steps towards sustainable chemistry require the cooperation of many stakeholders. The scientific community and companies convert new findings into the creation of innovative products. Public institutions, by means of legislative provisions, set the framework obliging everybody to comply. Often, environmental and consumer organizations provide crucial impetus for development when it comes to detecting problematic health or environmental burdens and boosting more sustainable products.

Globalized production chains increase the need for international cooperation, especially in administrative bodies parallel to the global chemical industry. Many countries still need to support institution and capacity building to capture the trade and use of chemicals, for chemical safety, security and the elimination of the historical sources of danger. Communication regarding safe use and commendable substitutes between stakeholders along the supply chain will have to play a key role in this regard.

4.3. Networking

Knowledge, activities and competencies in the area of sustainable chemistry need to be bundled, networked internationally and developed further. Cooperation between all stakeholders involved needs to be strengthened. Recognizing these needs, the German government currently prepares the establishment of the International Sustainable Chemistry Collaborative Centre (ISC$_3$ – www.isc3.org) with an international network for stakeholders in the field of sustainable chemistry (ISCnet – www.iscnet.org) (Blum et al., 2015). The ISC_3 is an offer to all sustainable chemistry actors around the globe, and it will support the identification, prioritisation and answering of open research questions and other challenges linked to sustainable chemistry.

4.4. Beneficial for humans and the environment and successful in the market

Sustainable products are beneficial for human health, for the protection of the environment and of resources. However, these advantages are only realized if they are economically viable. However, the environmental and social impact of less sustainable products is not incorporated in the price of products. There is no level playing field for sustainable chemical products. Therefore, a key question is whether customers are willing to pay sometimes higher prices for more sustainable chemicals and products produced. Some companies indicate that the willingness of their customers to switch to a more sustainable product is low, even if the performance and costs are the same. The willingness seems to be there only when the performance of the sustainable product is better.

If all objectives and dimensions of sustainability have been taken into account in the assessment, conflicts deriving from different priorities and interests might arise in individual cases. The Product Environmental Footprint (PEF) Initiative has the objective to inform consumers more precise about direct and indirect impacts of products (EU Commission).

The relation between environmental, social, and governmental criteria and corporate financial performance is positive in approximately 50% (40% neutral and only 10% negative) of business cases (Friede et al., 2015) This implicites that products manufactured in a sustainable manner not necessarily have to be more expensive than conventional products. This applies in particular when the costs of damage and its removal are included in the evaluation. By weighing the pros and cons, the limits of capacities of humans and the environment as well as the limited willingness of customers to pay more have to be considered. When it comes to evaluating and assessing chemicals, we need economic instruments which take into account the effects on human health and the environment as well as we need to incorporate social responsibility and CSR. For multinationals this implies inter alia to follow the OECD guidelines for multinational enterprises (Schwager, 2010).

4.5. Prioritization within the chemical industry

It is one of the key tasks of stakeholders in sustainable chemistry to further minimize the releases of problematic substances, not just from processes but also from materials and products. For this purpose, considerable efforts are needed. Therefore, several initiatives have to line up with clear emphasis on the implementation of substance-related requirements. For substances, materials and products the objective must be: benign substances, (DeVito, 2016) easy to recycle and not persistent in humans or environment after the desired use or application. The chemical industry should be encouraged by policy and self-committment to offer sustainable solutions in all areas, also at the substance level.

Additionally, all activities must complement each other, e.g. measures at the substance level should be combined with others like plant- or process-related issues or social or economic questions. In this context, substitution should not be requested at any price. Before the introduction of new chemicals, materials and products a full assessment is needed to avoid unwanted outcomes or rebound effects. Sustainable solutions have also to be socially favorable and allow competitiveness of the chemical industry in the medium and long term. When deciding on a substitute, socio-economic aspects have to be considered. Doing so, it is of high importance that all factors are being conveyed in a transparent manner.

In order to fully implement the objectives and guiding principles of sustainable chemistry as proposed in this paper they should be adopted by industrial and economic activities at a national and international level. This can be achieved by the development of widely accepted sub-criteria and indicators to assess how substances, materials, processes and resource requirements comply with the Concept of Sustainable Chemistry. Additionally, key interfaces of sustainable chemistry with resource protection, health protection, occupational safety, product and plant safety have to be addressed.

The efforts should accompanied by the selection and promotion of best practice examples evaluated with the future set of sub-criteria and indicators. Such examples shall illustrate the benefits of sustainable chemistry and thus advance and mainstream their development. This includes among others the analysis and dissemination of business models promising a successful economic development on the basis of sustainable chemistry as well as a description of the common benefits for resource protection, health protection and occupational safety, product and plant safety.

4.6. More sustainable products in the supply chains

Chemicals are not marketed for their own sake. Many sustainable chemistry products are tailored to the needs of the sectors in which they are used: mechanical engineering companies, automobile or electronic manufacturers, the construction industry and others. Therefore, functionality of chemicals and chemical products is the crucial aspect in terms of sustainability. However, for chemicals with wide application fields such as solvents, cross-sectoral approaches in sustainable product development are needed in order to reach market penetration. Experience clearly shows that sustainable products will be able to attain a leading position on the market only if they perform better than conventional competitive products (Fennelly and Associates, Inc, 2015).

4.7. Fair prices: a shift in the awareness of end-users

Sustainable chemistry will be successful in the mid to long term, if there is demand for their products and if they are bought by consumers and public authorities. This presupposes a change of consumer-attitude, who will then question the lower-priced products that have been produced without respecting sustainability demands, and who demonstrates willingness to pay the price a sustainable product is worth. PEF (Product Environmental Footprint) can be one important tool for this development (EU Commission). A long journey has to be expected, on which also social media and socially critical art might be able to provide important stimuli. Thus, sustainable chemistry will also become a cultural topic.

4.8. Education for a sustainable development

Increasing sustainability in the chemical industry needs increased involvement and enhanced cooperation of various chemical and non-chemical subdisciplines. In this context, the integration of sustainable chemistry into the education for chemistry, pharmacy (UNEP/EA, 2016) and sustainable development in general is an important aspect to enable chemistry contributing significantly to resources conservation, energy savings and strengthened occupational, environmental and consumer protection. Education for sustainable chemistry and sustainable development is the basis for generating an understanding of sustainability in different fields, including chemistry. More than two decades of experience with teaching green and sustainable chemistry in tertiary chemistry education shows the need to enhance the competence of students regarding chemistry and sustainability (Collins, 2017). In future, state-of-the-art knowledge on sustainable chemistry needs to be better integrated into education at school, university training of chemists, engineers, process engineers, product designers, business administration graduates and economists, for example, as well as into the related crafts.

4.9. Societal aspects of sustainable chemistry

Sustainable chemistry as an innovation of a system will generate sustainable products and materials while changing networks of actors, technologies and institutions in the chemical sector. This development is already taking place. To develop towards a sustainable chemistry the technological, industrial, organisational, institutional and socio-cultural sources of lock-in have to be overcome, that are at the root of our persistent environmental and social problems.

At the same time sources of lock-in in the chemical industry have to be overcome to enable sustainable chemistry. Lock-in sources like vested interests in the present chemical plants or the paradigm of innovation at large scale in the chemical industry (high risk - high gain approach) are hindering innovation. The present competition of chemicals, mainly based on price and performance has to be expanded by incorporating the external costs. Thereby, an sustainably produced product will be more economically attractive.

5. Connecting sustainable chemistry and international chemicals management

The Concept of Sustainable Chemistry can help all actors to identify feasible technical alternatives in synthesis and production with less hazardous chemicals by taking into account sustainability criteria in areas beyond the scope of sound management of chemicals, like for instance resource and energy efficiency, the use of renewable feedstock, working conditions and the impact on communities of the production of chemicals. Thus, in all relevant aspects towards sustainable development.

To further evolve management of chemicals towards sustainable chemistry in a holistic manner, it is necessary to address complex chemicals management issues, taking into account ethical and social criteria as well. Whereas there is a lot of ongoing work on indicators of sustainable chemistry there is still no agreed approach for measuring sustainability in chemicals management and its impact on sustainable development. Therefore, there is a need for further methodical developments and mechanisms to use such indicators e.g. in the context of SAICM and a potential follow-up process of SAICM as well as serving the Agenda 2030 for sustainable development.

With a view to the Agenda 2030, application of the Concept of Sustainable Chemistry along the whole value chain will significantly enhance contributions of the chemicals sector to the SDGs, especially to sustainable consumption and production (SDG 12), healthy lives (SDG 3), clean water and sanitation (SDG 6) as well as consumption and production (SDG 8) and sustainable industrialization (SDG 9). It can also make substantial contributions to efforts in areas such as combating poverty, hunger and climate change (SDG 1, 2 and 13) ensuring access to energy and economic growth. Partnerships for the goals (SDG 17) are an inherent aspect of almost any activity following the Concept of Sustainable Chemistry. In order to provide solutions for the area of sustainable chemistry the following aspects have to be implemented:

- establish sustainable chemistry as an overarching concept and holisitc approach to align chemicals and waste management effectively with the global Agenda 2030 for sustainable development and support governmental institutions bi- and multilaterally in this process;
- provide support and guidance beyond formal compliance, especially to emerging and developing countries, inter alia regarding SAICM and international rules and regulations concerning production, handling of chemicals and waste and regarding CSR;
- disseminate and establish synthesis strategies (material flow management and product design), as well as appropriate professional standards;
- enhance and extent the existing knowledge base in study programs, school lessons, vocational training and consumer education;
- encourage companies to get insight in the sustainability issues in their value chain and encourage them to cooperate and innovate with value chain partners and other stakeholders like NGO's to either solve the sustainability issues or turn them into innovation opportunities;
- create an enabling environment by the government for frontrunning chemical companies by creating more experimenting space in regulation (e.g. for pilot or demonstration plants), financial incentives, subsidies and the government as launching customer for sustainable products or mediator to find potential partners or investors;

Concerning SAICM, the prioritization of complex chemicals management issues in a follow-up process of SAICM beyond 2020 will need solid analyses at the policy-science interface. A systematic evaluation of overall sustainability in chemicals management is needed for the multilateral environmental agreements where chemicals are listed in view of their impact on human health and environment on the basis of agreed recommendations by scientific bodies, as well as in SAICM or for regional regulations and frameworks. Following the Concept of Sustainable Chemistry will have a greater impact when it is implemented in the context of multi-actor and multi-sector approaches in the long run. Connecting sustainable chemistry to SAICM and a potential a follow-up process of SAICM will also yield social and economic benefits, e.g. reduced burden of disease and proliferation of best management practices in agriculture.

Acknowledgements

The authors acknowledge Jan Moltmann and all stakeholders involved in the consultation process performed for the development of this concept. Special acknowledgements to Klaus Kümmerer for his valuable suggestions to this work. We highly appreciate the ongoing discussions with many partners, friends, and fellow campaigners in the scientific, regulatory, and policy realms of chemicals management. We need these discussions and we look forward to continue them for the sake of truly sustainable development.

References

⟨http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/WSSD_PlanImpl.pdf⟩.
UNEP/EA, 2016. 2/Res.7 of the United Nations Environment Assembly of the United Nations Environment Programme; Second session; Nairobi, 23–27 May (⟨http://web.unep.org/unea/list-resolutions-adopted-unea-2⟩)
Cannon, A.S., Warner, J.C., 2011. The Science of green chemistry and its role in educational reform. New Solut. 21 (3), 499–517.
Kümmerer, K., Hempel, M., 2010. Green and Sustainable Pharmacy. Springer, Berlin.
Angrick, M., Kümmerer, K., Meinzer, L., 2006. Nachhaltige Chemie: Erfahrungen und Perspektiven, Metropolis Verlag für Ökonomie. Ges. Polit..
Anastas, P.T., Warner, J.C., 1998. Green Chemistry Theory and Practice. Oxford University Press, New York, 30.
Voutchkova-Kostal, A.M., Kostal, J., Connors, K.A., Anastas, B.B.W., P.T., Zimmerman, J.B., 2012. Towards rational molecular design for reduced chronic aquatic toxicity. Green. Chem. 14, 1001–1008.
Council Directive 96/61/EC of 24 September 1996. Concerning Integrated Pollution Prevention and Control
Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010. on industrial emissions (integrated pollution prevention and control)
German Federal Environment Agency, 2009. Sustainable Chemistry: Positions and Criteria of the Federal Environment Agency.
⟨http://www.oecd.org/chemicalsafety/risk-management/sustainablechemistry.htm⟩.
⟨http://www.suschem.org/about-suschem/vision-and-mission-sustainable-chemistry.aspx⟩.
⟨http://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/definition.html⟩.
⟨https://www.epa.gov/greenchemistry/basics-green-chemistry⟩.
UN document, 2030. Transforming our world: the Agenda for Sustainable Development

(A/RES/70/1).
Environmental Directorate OECD, 2004. Sustainable Chemistry Brochure.
Reihlen, A., Bunke, D., Groß, R., Jepsen, D., Blum, C., 2016. Guide on sustainable chemicals – a decision tool for substance manufacturers. (UBA)Formul. End. users Chem., (UBA).
Moser, F., Karavezyris, V., Blum, C., 2014. Chemical leasing in the context of sustainable chemistry. Environ. Sci. Pollut. Res.
Clark, J., Kümmerer, K., 2016. Green and Sustainable Chemistry. In: Textbook on Sustainability Science. Springer, Berlin, 43–59.
World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, Oxford⟨http://www.un-documents.net/our-common-future.pdf⟩.
Suurs, Roelofs, 2014. Systemic Innovation: Concepts and tools for strengthening National and European eco-policies, June 2014, reportnr. TNO R10903.
Kemp, R., 2011. Ten themes of eco-innovation policies in Europe. Surv. Perspect. Integr. Environ. Soc. 4, 2 ⟨http://sapiens.revues.org/1169⟩.
World Business Council for Sustainable Development, 2016. Social Life Cycle Metrics for Chemical Products, ⟨http://www.wbcsd.org/Projects/Chemicals/Resources/Social-Life-Cycle-Metrics-for-Chemical-Products⟩
Antony, F., Grießhammer, R., Speck, T., Speck, O., 2014. Sustainability assessment of a lightweight biomimetic ceiling structure. Bioinspir. Biomim. 9 (15), 016013. http://dx.doi.org/10.1088/1748-3182/9/1/016013.
Collins, T., 2001. Towards sustainable chemistry. Science 291 (5501), 48–49. http://dx.doi.org/10.1126/science.291.5501.48.
Nachrichten aus der Chemie 64, 2016. ⟨www.gdch.de/nachrichten⟩
Stockholm Convention on Persistent Organic Pollutants (POPs), 2010. The Secretariat of the Stockholm Convention.
Rotterdam Convention, 2013. on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade; Rotterdam Convention Secretariat.
⟨http://www.icca-chem.org/en/Home/Responsible-care/⟩.
⟨http://www.globalpsc.net/⟩.
Verband der Chemischen Industrie, 2013. e.V., IG BCE Industriegewerkschaft, Bundesarbeitgeberverband Chemie e.V., Ambitionen.Leistung.Lösungen Nachhaltigkeit in der deutschen Chemie.
Netherland, C.S.R., 2015. Int. CSR Dutch Chem. Sect. Quick..
⟨http://greenchemistryandcommerce.org/⟩.
UNCSD Outcome document, 2012. The Future We Want (A/RES/66/288)
Unruh, G.C., 2002. Escaping carbon lock-In. Energy Policy 30 (4), 317.
Cui, Z., Beach, E.S., Anastas, P.T., 2011. Green chemistry in China. Pure Appl. Chem. 83, 1379–1390.
Beach, E.S., Weeks, B.R., Stern, R., Anastas, P.T., 2013. Plastics additives and green chemistry. Pure Appl. Chem. 85 (8), 1611–1624.
European Environmental Agency, 2012. Late lessons from early warnings: Science, precaution and innovation. EEA. ⟨http://www.eea.europa.eu/publications/late-lessons-2⟩
Schug, T.T., et al., 2013. Designing endocrine disruption out of the next generation of chemicals. Green Chem. 15, 181–198.
Schwager, 2010. Chemical Leasing - A NOVEL and SMART business model for industry and environment; Chemical Industry Digest
OECD, , 2011. OECD guidelines for multinational enterprises, edition, ⟨http://www.oecd.org/corporate/mne/48004323.pdf⟩
US Department of Agriculture, Biopreferred Program; ⟨https://www.biopreferred.gov/BioPreferred/faces/pages/AboutBioPreferred.xhtml⟩
PIANOo, the Dutch Public Procurement Expertise Centre on sustainable public procurement in the Netherlands. ⟨https://www.pianoo.nl/public-procurement-in-the-netherlands⟩
Blum, C., Friege, H., Stolzenberg, H.-C., 2015. Fostering Sustainable Chemistry. Chem. Watch Glob. Bus. Brief. 79, 11–12.
EU Commission, The Product Environmental footprint (PEF) initiative. Guidelines. (⟨http://ec.europa.eu/environment/eussd/smgp/pdf/Comm_bgdoc_v1.1.pdf⟩).
Friede, Gunnar, Busch, Timo, Bassen, Alexander, 2015. ESG and financial performance: aggregated evidence from more than 2000 empirical studies. J. Sustain. Financ. Invest. 5 (4), 210–233. http://dx.doi.org/10.1080/20430795.2015.1118917, (http://dx.doi.org/10.1080/20430795.2015.1118917).
DeVito, S.C., 2016. On the design of safer chemicals: a path forward. Green Chem. 18, 4332–4347. http://dx.doi.org/10.1039/C6GC00526H.
Fennelly, T., Associates, Inc, 2015. Advancing Green Chemistry: Barriers to Adoption & Ways to Accelerate Green Chemistry in Supply Chains. A Report for the Green Chemistry & Commerce Council, March. ⟨http://greenchemistryandcommerce.org/assets/media/images/Publications/Advancing-Green-Chemistry-Report-15-June-2015.pdf⟩
Collins, T., 2017. Review of the twenty-three year evolution of the first university course in green chemistry: teaching future leaders how to create sustainable societies. J. Clean. Prod. J. Clean. Prod. 140, 93–110 , (2016)http://dx.doi.org/10.1016/j.clepro.2015.06.136.