Chapter 6
Sustainable Chemistry—Path and Goal for a More Sustainable Textile Sector

Lisa Keßler and Klaus Kümmerer

Abstract This chapter aims to portray the concepts of green chemistry (GC) and sustainable chemistry (SC) with regard to the textile sector and in response to the increasing challenges of the sector in terms of sustainability. It highlights potentials and pitfalls and offers concrete examples and practices of SC relevant for the textile industry. The textile sector is one of the most polluting industries in the world, contributing 20% to total industrial pollution of the water resources. In total, 5 billion kg of dyes, pigments and finishing chemicals are currently in use in the textile industry, adding up to more than 8000 different chemicals utilized for garment production. Moreover, extensive resource use (e.g., fossil fuels, processing chemicals, water etc.) in combination with unhealthy, exploitative working conditions pose a myriad of challenges involving all dimensions of sustainability. Once introduced into a process or product, chemicals and their products of unwanted side reactions and of incomplete mineralization in effluent treatment, so-called transformation products (TPs), are likely to remain a concern throughout the product's lifecycle and even beyond. For example, textiles at their life's end, so-called post-consumer textiles, still contain up to 90% of the chemicals that were initially introduced during manufacturing or finishing. This high amount of chemical residues on textiles (only partly washed out during laundry) is not only problematic in terms of resource use, but it is also an environmental threat. Residues are continuously released due to limitations in conventional wastewater treatment and form waste and dump sites affecting human health and well-being. The aforementioned sustainability issues arising during textile production, distribution, use and disposal are inextricably linked to societal and cultural systems. The complex, dynamic and highly intertwined nature of these

L. Keßler (✉) · K. Kümmerer
Institute of Sustainable and Environmental Chemistry (ISEC),
Leuphana University of Lüneburg, Lüneburg, Germany
e-mail: lisa.kessler@leuphana.de

K. Kümmerer
e-mail: klaus.kuemmerer@leuphana.de

K. Kümmerer
Institute of Sustainable and Environmental Chemistry (ISEC) and International Sustainable Chemistry Collaborative Center (ISC3), Research and Education Hub Leuphana University of Lüneburg, Lüneburg, Germany

A. Matthes et al. (eds.), *Sustainable Textile and Fashion Value Chains*,
https://doi.org/10.1007/978-3-030-22018-1_6

sustainability challenges in the textile sector calls for both a focus on input prevention of chemicals and a strong normative premise of intentionally beneficial design of chemicals that are not harmful to the environment and human health. Sustainable chemistry has become an emerging concept in response to various sustainability challenges associated with the production, distribution, use and discharge of chemicals and products. It has been acknowledged by UNEP as an important cornerstone in achieving the Sustainable Development Goals (SDGs) and servers as a core concept within the Global Chemical Outlook II. Whilst green chemistry mainly addresses the synthesis of chemicals and some of their properties, SC reaches beyond the disciplinary boundaries of chemicals and their usage by a systems thinking approach. Being both a path and a goal, SC can act a beneficial umbrella concept for addressing the highly complex sustainability challenges regarding chemicals in the textile sector. Its specific potentials for the textile sector have not been studied hitherto and lie in its focus on input prevention, which influences not only production or wet processing of textiles, but the entire supply chain—including up- and downstream users—even beyond the product's end of life. Practiced of SC within the textile industry addresses spatial as well as temporal scales, flows and dynamics of chemicals, materials and products and hence addresses drivers of highly complex and currently unsustainable practices. Specific examples and practices of SC within the textile sector will be described in-depth such as new business models (e.g. chemical leasing).

Keywords Textile sector · Chemicals management · Green chemistry · Sustainable chemistry · Sustainability challenges

List of Acronyms

APEO(s)	Alkylphenol ethoxylate(s)
BAT(s)	Best available technique(s)
BFR(s)	Brominated flame retardant(s)
CEFIC	Conseil Européen des Fédérations de l'Industrie Chimique; European Chemical Industry Council
COD	Chemical Oxygen Demand
DWR(s)	Durable Water Repellent(s)
EPA	Environmental Protection Agency
GDCh	Gesellschaft Deutscher Chemiker
GHS	Globally Harmonized System of Classification, Labelling and Packaging of Chemicals
GPS	Global Product Strategy
HPV	High Production Volume (Chemicals Programme)
ICCM	International Conference on Chemicals Management
IED	Industrial Emissions Directive
IPPC	Integrated Pollution Prevention and Control
IUPAC	International Union of Pure and Applied Chemistry

IVU	Integrierte Vermeidung und Verminderung der Umweltverschmutzung (English: Integrated Pollution Prevention and Control, IPPC)
LCA	Lifecycle Assessment
LRI	Long-Range Research Initiative
MEA(s)	Multilateral Environmental Agreement(s)
MRSL(s)	Manufacturing Restricted Substance List(s)
NGO(s)	Non-Governmental Organisation(s)
NSF	National Science Foundation
OECD	Organisation for Economic Co-operation and Development
PFAS(s)	Per- and/or Polyfluoroalkyl Substance(s)
PVA	Polyvinylalcohol
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RSL(s)	Restricted Substance List(s)
SAICM	Strategic Approach to International Chemicals Management
SDGs	Sustainable Development Goals
SVOC(s)	Semi-Volatile Organic Compound(s)
TP(s)	Transformation Product(s)
USA	United States of America
UBA	German Environment Agency
UK	United Kingdom of Great Britain
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNSDS	United Nations Sustainable Development Summit
VOC(s)	Volatile Organic Compound(s)
WSSD	World Summit of Sustainable Development
ZDHC	Zero Discharge of Hazardous Chemicals

6.1 Introduction

The textile sector is growing and producing more and more articles. Along with that, volumes and diversity of substances used as building blocks, processing chemicals or for functionalisation of products are increasing. While this development has more than ever a global dimension, it leads to socio-economic development in the Global South and to huge sustainability challenges over different scales of space and time alike. The importance of chemicals for the textile sector and current chemical risk management approaches will be presented and discussed in this chapter including specific characteristics of the sector that constitute the current sustainability challenges associated with chemicals in textile production. A special focus will be placed on the concepts of Green and Sustainable Chemistry, which offer new perspectives for production, use and management of chemicals within the textile sector. The characteristics of Green Chemistry and Sustainable Chemistry as well as their respective specific potential for application in the field of textile chemicals will be described and highlighted. Last, but not least, different practices are presented to shed light on current efforts from the sector itself and academia aligning with the principles of Green Chemistry and Sustainable Chemistry in order to provide tangible examples on the one hand and entry points for further innovations on the other hand.

6.2 Use and Management of Chemicals Within the Textile Sector

In the following section, different types of chemicals used in the textile sector and their respective volumes will be described. Furthermore, a closer look will be taken on potential release and exposure routes concerning environmental compartments and human beings. Finally, past and current management actions will be presented.

6.2.1 Types and Volumes of Chemicals and Processes Involving Chemicals

The textile sector is one of the most polluting industries in the world, contributing 20% to total industrial pollution of water resources (Kant 2012). Whereas the Swedish Chemicals Agency compiled a non-exhaustive list of more than 1900 chemicals (KEMI—Swedish Chemicals Agency 2013), Scott (2015) states that more than 8000 different chemicals are used for today's garment production. Since some of the chemicals in use are considered confidential and, hence, remain unknown to the public, differing numbers may occur (KEMI—Swedish Chemicals Agency 2013). Nevertheless, it has been estimated that in total 5 billion kg of dyes, pigments and finishing chemicals are currently in use per year in the textile industry (Nimkar 2018). Among them are at least 165 substances which have been classified in the EU as hazardous to human health, for being either carcinogenic, mutagenic or toxic to the reproductive system, or for showing sensitising effects either onto the respiratory tract or the skin. Others have long-term adverse effects on the environment, e.g. the aquatic system (KEMI—Swedish Chemicals Agency 2013). In addition to the risk posed by those parent compounds products of incomplete degradation of chemicals, so-called transformation products (TPs), can be formed in common wastewater treatment processes, like UV irradiation, ozonation and clorination (Kümmerer et al. 2019; Leder et al. 2015).

Since textiles comprise a huge variety of different products, the chemical substances included in the article itself or its production processes and their respective impact vary accordingly, as do their individual properties (EEA—European Environmental Agengy 2014). This in turn impairs a proper risk assessment and handling along the supply chain—or even renders it impossible. The following factors identified in the Environmental Indicator Report (EEA—European Environmental Agengy 2014) may determine and influence the set of chemicals and their properties associated with a textile article and its production process:

- fibre type and chemical properties of the fibre(s) itself
- production method
- performance requirements of the product
- use-phase characteristics
- end-of-life treatment.

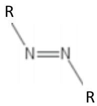
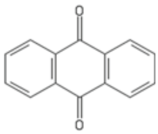
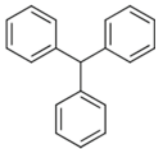
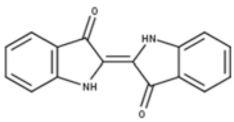
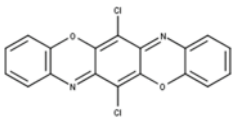
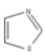
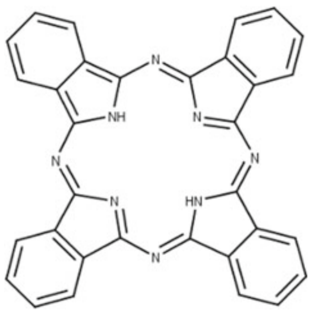
Starting with the fibre type, chemicals are involved from the very beginning of the textile supply chain. Petroleum-based man-made fibres require chemicals in fibre production and processing and finishing chemicals later on. Even natural fibres such as cotton require apart from enormous amounts of water for growing—additional chemicals such as pesticides and fertilisers during conventional fibre production. The majority of chemicals—both in terms of volumes and diversity—is used during wet processing. This phase involves different pre-treatment processes such as desizing, scouring, bleaching and mercerising, followed by dyeing or printing. Depending on performance requirements and desired use-phase characteristics, textile products finally undergo a finishing process, e.g. biocidal, anti-wrinkle or flame-retardant equipment.

Depending on the occurrence and combination of the aforementioned factors and the resulting wet processing steps, many different functional chemicals, auxiliaries and also unintended chemical substances, being present as impurities or degradation products, can either be part of a textile product or its respective production process including effluent and air treatment.

Functional substances mostly remain in the fabric or on top of the fabric's surface after the production process and comprise different functional classes of chemicals such as dyes and pigments (see Table 6.1), oil and water repellents, flame retardants, anti-creasing agents, anti-shrinking agents, plasticisers, biocidal substances, stabilisers, etc.

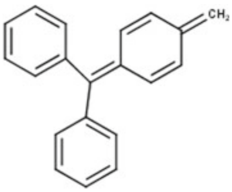
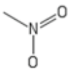
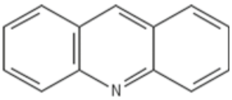
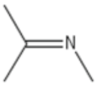
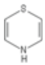
Auxiliaries are intended to only be present at a certain step in the production process where they exert their facilitating function. Organic solvents, surfactants, salts, softeners, acids and bases are used as auxiliary substances as well as biocides when used as preservatives during storage or transport of the textile products. Nevertheless, some auxiliaries can at the same time represent contaminations if their residues or their degradation products still occur in the final textile product (e.g. biocides used as preservatives or residues of processing chemicals since they remain on the fabric at least until the first laundry). Some reactive resins used for finishing treatments of textiles release formaldehyde or other volatile or semi-volatile organic compounds (VOCs/SVOCs) into the indoor air or directly onto the skin (Aldag et al. 2017; Piccinini et al. 2007). Azo dyes and pigments, for example, have been found to degrade into toxic arylamines (Le Marechal et al. 2012). The large diversity and quantity of chemicals, processes and their interconnectedness in textile manufacturing lead to an **individual chemical fingerprint** for each textile product. This makes it even more difficult to establish a proper risk assessment and to increase

Table 6.1 Examples of different functional groups of chemical classes of dyes used in textile manufacturing illustrating the high diversity within a single group of chemicals used (within each chemical class there are several different individual compounds)

Chemical class	Structural chemical formula	Method of application	Example
Azo		Direct, Reactive, Acid, Mordant, Disperse	Disperse Yellow 241
Anthraquinone		Reactive, Vat, Acid, Mordant, Disperse	Acid Blue 25
Triphenylmethane		Acid	Malachite Green
Indigo		Vat	Vat Blue 1 (Indigo)
(Di-)Oxazine		Direct, Reactive, Mordant, Basic	Pigment Violet 23
Thiazole		Direct	Indanthren Blue CLG
Phthalocyanine		Direct, Reactive	Pigment Green 7

(continued)

Table 6.1 (continued)

Chemical class	Structural chemical formula	Method of application	Example
Di-/Triarylmethane		Mordant, Basic	Methyl Violet 2B
Nitro		Disperse	Acid Orange 3
Acridine		Basic	Acridine Orange
Methine		Basic	Basic Yellow 11
Thiazine		Basic	Methylene Blue
Sulphuric	Different structures		Sulphur Red 6

sustainability of textiles. In combination with long and complex supply chains on a global level, this leads to a high level of uncertainty about the substances in textile articles and their respective concentration ranges (KEMI—Swedish Chemicals Agency 2014). Hence, once introduced into a process or product, chemicals or their transformation products are likely to remain a concern throughout the product's life cycle, and even beyond.

6.2.2 Release of Chemicals into the Environment and Exposure Routes

Possible release mechanisms and exposure routes along the textile supply chain are shown in Fig. 6.1. Unintended or intended release occurs at the production site into water and sediment, air or soil (sludge) or from the final product during storage, transport, distribution and use, and at the end of the products life after disposal by dissolution, desorption, volatilisation, incomplete degradation, etc. Potential release patterns of chemicals highly depend on their physico-chemical properties like

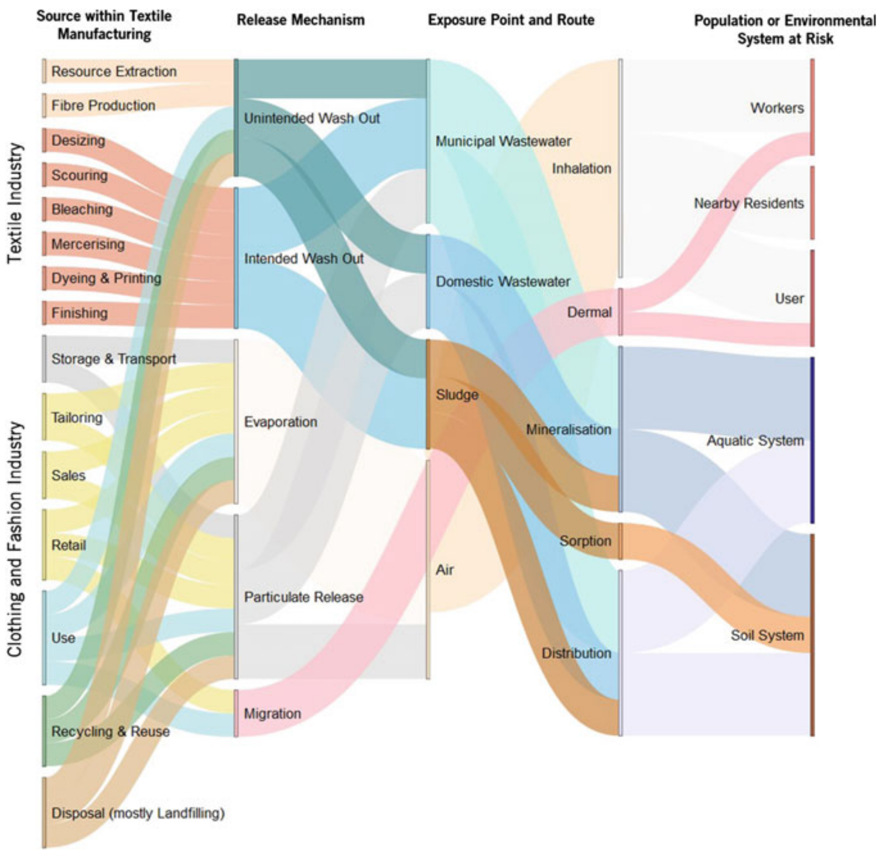


Fig. 6.1 Sources, release mechanisms, exposure points and routes and populations and environmental systems at risk along the textile supply chain regarding chemicals

vapour pressure, polarity, partition coefficients, e.g. *n*-Octanol/Water (P_{OW}), solubility, stability, etc. Therefore, release patterns and exposure routes are substance- and product-specific.

In the following section, three exemplary release patterns and subsequent exposure routes along the textile supply chain will be described in detail, even though other complex release patterns are also relevant for textile chemicals (see Fig. 6.1).

(a) Release from production processes or textile products during textile manufacturing

Release from textile production includes resource extraction, raw material production such as fibres and basic chemicals, and textile production itself. Direct release of untreated effluents or insufficient effluent treatment processes (either in-house or municipal) can create serious environmental and health-related risks by chemicals and their degradation products (Kümmerer et al. 2019, 2018). Since textile production mostly occurs in countries of the Global South, and hence in the absence or under conditions of insufficient enforcement of strict environmental legislations, measures for proper and effective effluent treatment are lacking (Busi et al. 2016; KEMI—Swedish Chemicals Agency 2014; Kümmerer and Clark 2016). Moreover, transformation products as the result of incomplete mineralisation of chemicals in effluent treatment can pose in some cases even greater risks than the parent compounds, e.g. *N*-nitrosodimethylamine (NDMA) formation by oxidative treatment (Kümmerer et al. 2019). Via the release of untreated or insufficiently treated wastewater into the aquatic environment, effluents containing potential micro-pollutants can reach the agricultural soil system and subsequently the food web either unintended or by water reuse practices (Kümmerer et al. 2018, 2019). While effluent treatment is currently in the focus of textile companies, the large amounts of sludge generated and the resulting air emissions are not yet (Nimkar 2018).

(b) Release from textile products during storage, transport, distribution and use

During storage of unpacked textile articles, particulate release of fibres containing chemicals and evaporation of volatile compounds may occur. Both dust and gaseous emissions pose a considerable exposure risk for people working in storage and packaging facilities. When transported and distributed to the consumer, additional (chemical) waste is created by using packaging material which contains chemicals itself, and contributes to environmental pollution due to resource extraction and production of plastic, paper and card board packaging. During retail, employees also have a considerable exposure risk due to evaporation, particulate release, and also dermal exposure of the hands, especially during unpacking and sorting of textile products (KEMI—Swedish Chemicals Agency 2014). Once textile articles are in use, fibres and containing chemicals are subject to unique conditions and stresses like exposure to sun light, abrasion, high temperatures, exposure to body warmth, sweat, and saliva, and exposure to water and detergents during laundry. Some textile articles, like clothes and bed linen, are used in close skin contact for many hours. Depending on different factors (e.g. type of material; properties and concentration of chemicals; skin characteristics), migration and penetration into the skin can occur (KEMI—Swedish Chemicals Agency 2014; Zhong et al. 2011).

(c) Release from textile products at the end-of-life during disposal

In the EU, only a small share of textiles at their life's end, so-called post-consumer textiles, is collected and sorted for reuse (8%) or recycling (10%), whereas 24.9% are incinerated (with or without energy recovery), and the largest part of 57.1% is ultimately disposed by landfilling (KEMI—Swedish Chemicals Agency 2014). This practice creates enormous amounts of solid textile waste, and is hence highly problematic in terms of resource and material use both from a fibre perspective and a chemical perspective, since chemical synthesis usually has a high energy and material demand. Moreover, 90% of the chemicals that were initially introduced during manufacturing are still present in post-consumer textiles (Nimkar 2018). Those residues can subsequently be released into soil and water bodies by leaching from waste and dump sites, and consequently threaten human health and well-being as well as the environment due to limitations in wastewater treatment and the often either non-biodegradable and/or persistent and/or bioaccumulative, and sometimes even toxic nature of follow-up products of those substances (Kümmerer 2017).

6.2.3 *Chemical Risk Management in the Textile Sector as Important Sustainability Challenge*

In order to prevent release or at least minimise exposure risks for the environment and human beings, sound chemicals management measures need to be applied at every step in the textile supply chain. Due to global dissipation of chemicals—both raw materials and functional chemicals, auxiliaries or contaminations within the textile product (see Fig. 6.2)—chemical risks are neither limited to the actual supply chain nor to distinct places and times, but exceed beyond the textile article's life and beyond production sites (e.g. resource extraction, production and manufacturing, consumption, waste).

Therefore, current attempts of managing chemical risks by governments or the industry itself operate on a global or at least European policy level (see Fig. 6.3). Recent years have witnessed a growing number of voluntary associations in the textile sector like ZDHC (Zero Discharge of Hazardous Chemicals, https://www.

Fig. 6.2 Global trade of textile products and subsequent dissipation of contained functional chemicals, auxiliaries and contaminations between the EU-27 and other world regions, 2012 (from EEA—European Environmental Agency 2014, p. 110)

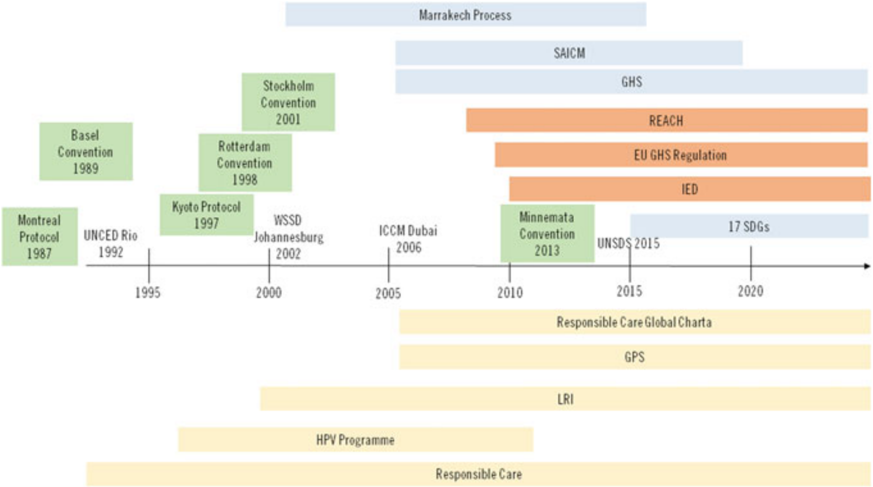


Fig. 6.3 Overview of different frameworks for chemicals management (green—MEAs; orange—regulations; blue—policy frameworks, processes or standards on international level; yellow—industry initiatives)

roadmaptozero.com/), Partnership for Sustainable Textiles (https://www.textilbuendnis.com/en/), use of RSLs/MRSLs (Restricted Substance List(s)/Manufacturing Restricted Substance List(s)) and the DETOX campaign of Greenpeace, etc., started off by different actors like companies, brands, NGOs or governments. The DETOX campaign, for example, focusses on the complete phase-out of eleven groups of chemicals (e.g. APEOs, PFASs, heavy metals, chlorophenols, BFRs) until 2020 rather than on compliance with threshold levels in wastewater or sludge.

6.3 Green Chemistry and Sustainable Chemistry

In the following part of the chapter, two concepts—Green Chemistry and Sustainable Chemistry—relevant for current sustainability challenges regarding chemicals in the textile industry, their origins and the relation between them will be introduced.

6.3.1 The Concept of Green Chemistry

In 1990, the U.S. Environmental Protection Agency (EPA) passed a law to reduce or prevent pollution at the source rather than treating and disposing unwanted toxic substances in industrial processes. With this so-called Pollution Prevention Act, the EPA—although being designed as a classical regulatory agency—created a national policy focusing no longer on conventional control approaches and end-of-pipe solutions but rather increasing interest of industry, government and public attention in pollution prevention and improved design in first place (Anastas and Warner 1998). Building on this legislation and other numerous efforts from regulatory bodies and academia (e.g. Richtlinie 96/61/EG 1996; OECD—Organisation for Economic Co-operation and Development 1998; Cathcart 1990), Paul Anastas and John Warner published in 1998 the following 12 principles of Green Chemistry as a summarising conceptual list to characterise a green chemical substance, product or process and to establish guidelines for the new research field.

The 12 Principles of Green Chemistry

1. Prevention
2. Atom Economy
3. Less Hazardous Chemical Syntheses
4. Designing Safer Chemicals
5. Safer Solvents and Auxiliaries
6. Design for Energy Efficiency
7. Use of Renewable Feedstocks
8. Reduce Derivatives
9. Catalysis
10. Design for Degradation
11. Real-time Analysis for Pollution Prevention
12. Inherently Safer Chemistry for Accident Prevention

(Anastas and Warner 1998).

A recent definition of Green Chemistry is provided by the EPA:

> Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal. (https://www.epa.gov/greenchemistry/basics-green-chemistry)

Despite these seemingly straightforward 12 principles, it remains ambiguous how many of them need to be fulfilled in order to design a green product or process or if they are equally weighted (Kümmerer 2017). In case of the definition provided by the EPA, the characteristics of a substance classified as "hazardous" also leave room for interpretation—this might be a substance exerting acute and/or (sub-) chronic effects, being persistent and/or bioaccumulative or all together. Other than that, we argue that Green Chemistry does not sufficiently address aspects of why we use chemicals in the first place, how we could reduce substance, material and product flows and how rebound effects and entropic losses can be minimised. Addressing those fundamental questions do require a broader perspective on, e.g. competitive demands for resources and energy, alternative business models, economics and last, but not least, ethics. One telling example here is the enthusiasm about digitisation which often lacks a thorough consideration of the material basis. Not only the gadgets themselves are manufactured by using materials (e.g. non-renewable metals), but the enormous energy demand requires a material basis as well—even renewable energy technology (e.g. solar panels containing silicon).

6.3.2 *From Green Chemistry to Sustainable Chemistry*

In 1999, Hutzinger published an editorial in response to a controversial debate around the terms "Green Chemistry" versus "Sustainable Chemistry" within the Federation of European Chemical Societies, Division for Chemistry and the Environment. On the one hand, he affirmed the shared understanding that "dilution is not the solution to pollution, which led to the end-of-pipe mentality" (Hutzinger 1999, p. 123). On the other hand, he emphasised the different cultural-sociological factors that influence the meaning and connotation of terms—even in the scientific discourse held in English (Hutzinger 1999). While in the USA and UK, the term "green" received support both from funding bodies and scientific communities, organisations headed by German-speaking members at that time like IUPAC, OECD, CEFIC and GDCh were reluctant to adopt the term, as it elicited misleading political associations with the Green Party in Germany (Hutzinger 1999).

In addition to the more implicit cultural-sociological associations, Hutzinger (1999) clearly pointed out a fundamental difference between the two concepts: Whereas Sustainable Chemistry represents the "maintenance and continuation of an ecologically sound development" (Hutzinger 1999, p. 123), Green Chemistry covers the "design, manufacture, and use of chemicals and chemical processes that have little or no pollution potential or environmental risk" (Hutzinger 1999, p. 123). This early conceptual delimitation attributes the development of society within the ecological boundaries to Sustainable Chemistry, whereas Green Chemistry is already more confined to chemicals, products or processes themselves and their technical feasibility. Looking at current definition attempts and ongoing discussions within the community, this line of argumentation, provided by Hutzinger almost twenty years ago, is still one of the main distinctions between both concepts.

As early as in 1992, the UNCED emphasised in the Agenda 21 that research for substitution of toxic, persistent or bioaccumulative chemicals should be strengthened (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit 1992). In response to the Johannesburg Plan of Implementation of the World Summit on Sustainable Development (WSSD) in 2002, the Strategic Approach to International Chemicals Management (SAICM) was agreed on in 2006 by the UNEP (United Nations Environment Programme) International Conference on Chemicals Management. SAICM aims "[…] 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 […]" (UN—United Nations 2002) and operates on a global policy level. Despite the early connection between Sustainable Chemistry and sustainable societal development drawn by Hutzinger (1999), the concept has not been an integral part of SAICM. However, in the continuation of these efforts—namely in the Sustainable Development Agenda 2030 with its 17 Sustainable Development Goals (SDGs)—the strong connection between Sustainable Chemistry and global development is clearly visible (Blum et al. 2017). Since Sustainable Chemistry has become an emerging concept in response to various sustainability challenges and is serving as a core concept within the Global Chemical Outlook II (UNEP—United Nations Environment Programme 2019), it is worth taking a closer look at the specific characteristics of the concept.

6.3.3 The Concept of Sustainable Chemistry

Whereas the U.S. EPA and many others still use Sustainable Chemistry as a synonym for Green Chemistry, various attempts have been undertaken to develop a common definition of Sustainable Chemistry (see also above, Hutzinger 1999).

In a collaborative effort, the OECD and the German Environment Agency (UBA) developed five general criteria for Sustainable Chemistry (UBA—German Federal Environment Agency 2009):

- Qualitative Development
- Quantitative Development
- Comprehensive Life Cycle Assessment
- Action Instead of Reaction
- Economic Innovation.

Currently, the OECD uses and presents the following definition originating from an OECD workshop in 1998 (OECD—Organisation for Economic Co-operation and Development 1998) which is in facat more related to Green Chemistry:

> Sustainable chemistry is a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. (http://www.oecd.org/chemicalsafety/risk-management/sustainablechemistry.htm)

The OECD also considers Sustainable Chemistry as a process that stimulates **innovation** in products, processes and also practices for higher performance and value resulting in clear benefits for environment and society.

Kümmerer and Clark (2016) highlighted the **holistic nature** of Sustainable Chemistry encompassing all relevant "[…] aspects of a product related to sustainability, e.g. social and economic aspects related to the use of resources, the shareholders, the stakeholders and the consumers" (Kümmerer and Clark 2016, p. 47). Despite the various efforts in describing, the concept still evades definition—for good reason—as Kümmerer (2017) puts it:

> Chemistry is sustainable if it contributes in a sustainable manner to sustainability. A more precise definition of sustainable chemistry is not possible. […] It is not a new subdiscipline of chemistry, but a guiding principle. (Kümmerer 2017, p. 16421)

In 2017, Blum et al. published a conceptual paper summarising and integrating existing definitions and criteria and developing a shared understanding of Sustainable

Chemistry. They identified a "lack of direction and prioritization of the various activities" (Blum et al. 2017, p. 96) and in response provided a set of guiding principles and objectives:

- Design and Use of Benign Chemicals (referred to as benign by design (Haddad et al. 2015; Kümmerer 2007, 2012; Rieger et al. 2002)
- Development and Use of Alternative Solutions
- Reduction of Impact
- Conservation of Natural Resources
- Promotion of Reuse and Recycling
- Increase of Market Opportunities
- Application of Corporate Social Responsibility (Blum et al. 2017, p. 95).

Their understanding of Sustainable Chemistry is based on the OECD definition as well as on the 12 principles of Green Chemistry and on principles of chemicals management (e.g. operational safe use of chemicals) and is directed towards the SDGs:

> Sustainable chemistry is a holistic approach where the entire life cycle 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. (Blum et al. 2017, p. 99)

The holistic approach and the involvement of different stakeholder groups offer a set of levers for implementation which are not limited to innovative ideas at substance or product level, but encompass new business models, responsible companies, resource recovery, reliable, accessible and transparent data, and demanding and enabling legislation (Blum et al. 2017). Moreover, efficient strategies for communication and co-learning in an interdisciplinary environment among the multiple actors, e.g. voluntary initiatives, NGOs, international organisations, consumers, etc., as well as education and capacity building help to facilitate the successful implementation of Sustainable Chemistry (Barra and González 2018; Blum et al. 2017).

6.4 Unlocking the Potential of Sustainable Chemistry for a More Sustainable Textile Sector

In this chapter, we set out from the understanding of Sustainable Chemistry provided by Blum et al. (2017), but want to add and highlight some key characteristics which not only help to distinguish the concept from Green Chemistry but constitute its enormous capacity for sustainability compared to green chemistry, also in the textile sector.

- Systems thinking approach
- Strong normative roots
- Input prevention

- Stakeholder focus.

After characterising specific sustainability challenges in managing chemical risks within the textile industry, the potential of Sustainable Chemistry in addressing those will be assessed using the aforementioned key characteristics.

The multiple complex, dynamic and highly intertwined sustainability challenges in the textile sector involve such broad and overarching issues like "climate change, chemical society, water shortage, and human rights" (Boström and Micheletti 2016, p. 367), which are all connected to the use of textile chemicals. Indeed, Boström (2015) describes the governance of chemical risks as "one of the key sustainability challenges that the textile sector has to tackle" (Boström 2015, p. 241) due to the "fragmented […] highly insufficient set of regulations and agreements" (Boström 2015, p. 241) both on a global and regional level. Managing and governing risks through legislative, regulatory or corporate efforts mainly raise the question how responsibility and accountability can be distributed effectively and in a democratically justifiable manner. By trying to allocate responsibility within the textile chain, one faces the aforementioned issues: **high uncertainty** and **lack of accessible data** on substances and composition of products or waste streams due to **individual chemical fingerprints** of textiles and processes—and in turn carbon and water footprints—**globalised and intertwined textile supply and demand chain**, **differing legislative and regulatory frameworks,** etc. Hence, risks and responsibilities are diffused, and none of the different actors within the supply chain nor the regulatory authorities seem to be capable of effective chemical risk management. An excellent illustration of the challenges in sound chemicals management is the varying degree of implementation coverage of the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) as described by Persson et al. (2017). It has been shown that in 2017 a staggering number of 128 countries (66% of UN Member States) had not yet put GHS into national legislative practice due to a lack of financial and regulatory capacities and/or willingness (Persson et al. 2017). Among them are countries like India, Bangladesh, Pakistan and Nepal where textile production and the associated use of chemicals plays major role.

Additionally, even if all those challenges would be easily solved, no national government nor existing intergovernmental institution nor industry initiative has "sufficient jurisdictional and/or policy authority to comprehensively regulate the globalized supply and demand chain in clothing and textiles" (Boström and Micheletti 2016, p. 369).

In addition, those challenges are inextricably linked to **societal and cultural systems**. On the supply side, most companies in the textile sector are taking part in a race to the bottom regarding production costs, and hence outsource labour-intensive and hardly automatable textile manufacturing to developing countries or countries in transition (Boström and Micheletti 2016). Less expensive labour costs, lacking environmental regulation and/or respective enforcement of the latter allow for lower production costs and higher profit for companies—at least in the short-term—at the expenses of people's health and the environment outside of Europe (Boström and Micheletti 2016; Busi et al. 2016; Moore and Ausley 2004; UNEP—United

Nations Environment Programme 2017). For example, around 80% of textile products sold nowadays within the EU are imported from non-EU countries, especially from China (KEMI—Swedish Chemicals Agency 2014). Even products labelled as "Made in Europe" are seldom produced within the EU and according to EU labour rights and environmental standards, but instead only the assembly and mixing is carried out within the EU (KEMI—Swedish Chemicals Agency 2014). This raises the question of **environmental justice** and touches upon the social dimension of (global) sustainability:

> The world's poorest people routinely face the highest risk of exposure to toxic and hazardous chemicals, due to their occupations, living conditions, lack of knowledge about safe handling practices, limited access to sources of uncontaminated food and drinking water, and the fact that they often live in countries where regulatory, health, and education systems are weak. (UNDP—United Nations Development Programme 2012, p. 1)

On the demand side, on the other hand, extensive textile production and consumption are linked in the manner of "**fast fashion**" characterised by reduced periods of use through low product quality and low prices that do not reflect the true costs of the product anymore. Fast production cycles become accelerated by consumer's behaviour triggering feedback loops of adverse environmental effects. Large volumes of textiles of low quality, short periods of use, frequent replacement of textile articles by consumers, missing take-back systems and enormous amounts of waste represent considerable sustainability challenges in and of itself and contribute to both increasing volumes and diversity of related chemical substances and material flows (Niinimäki 2011).

Consequently, no single approach, either technological nor managerial, nor any discipline alone could offer satisfactory and sufficient answers to the pressing sustainability questions of the textile industry until now. Another driving force is the growing public awareness about the circumstances and impacts of garment production. The business model of the textile and fashion industry itself is threatened by NGOs releasing information and scandalising current practices, as it happened 2007 with the DETOX Campaign by Greenpeace. Hence, a holistic and innovative approach addressing all dimensions of sustainability is needed.

Although Sustainable Chemistry has been acknowledged by UNEP as an important cornerstone in achieving the Sustainable Development Goals (SDGs), the concept has nevertheless not yet reached all relevant fields like the textile sector (Blum et al. 2017). Since the chemical industry is a key partner for the textile manufacturing sector, almost all sustainability challenges of the textile industry are linked directly or indirectly to chemicals. Despite the abovementioned actions already taken, enhanced communication and integration along the whole supply chain is needed as well as education and cooperation across different sectors.

In the following sections, we will link the concept of Sustainable Chemistry and its key characteristics to the aforementioned sustainability challenges of the textile sector and explain how and why Sustainable Chemistry can act as a beneficial umbrella concept for addressing the highly complex sustainability challenges regarding chemicals in the textile sector.

6.4.1 Systems Thinking Approach

Regarding the highly intertwined sustainability challenges of the textile sector, it is argued that the so-called lock-ins keep us within our current unsustainable system of production and consumption. According to Unruh (2002), lock-in mechanisms, like dominant design, industry standards, routines, policies and social norms, values and behavioural habits reinforce the present situation and hinder transformation. Production and consumption are still mainly seen as separate, even opposite sides of the textile industry, even though they used to be interlinked at different scales (e.g. locally, personally) before industrialisation (Kaiser 2008). Blum et al. (2017) assign Sustainable Chemistry a key role in overcoming these different lock-ins by bringing along innovations at system level. In order to achieve transformation, Sustainable Chemistry reaches beyond disciplinary boundaries, for example in explicitly searching for non-chemical alternatives, and aims at considering all relevant solutions for a sustainability challenge within the chemical sector, but also other sectors where chemicals play an important role, like the textile industry. Moreover, Sustainable Chemistry does nothing less than asking for a new self-understanding of the chemical sector and its relation to society.

> 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. (Blum et al. 2017, p. 95)

While mostly technological fixes are suggested to solve pressing sustainability issues (Ehrenfeld 2004), more scholars nowadays argue that changes in behaviour and practices rooting in changing values and mindsets are promising as well (Boström and Micheletti 2016). Looking at the textile industry and the functions, needs and desires it serves, consumption patterns, fashion business, societal and cultural norms are indeed important (yet largely unaddressed) drivers of current unsustainable practices in the sector; yet they are evading any technological fixes (Fletcher 2009). Sustainable Chemistry is more than a technological fix, but engages in system innovation by changing values and mindsets and recognises the role routines, consumption patterns and societal norms play within a complex and dynamic system. Moreover, while technological fixes and changes in behaviour are seen as short- to mid-term solutions, Sustainable Chemistry offers a long-term perspective not only by substituting hazardous compounds by benign ones (Kümmerer 2012, 2017).

Fletcher (2009) states that recent years have indeed witnessed a growing body of work dealing with sustainability challenges of the textile sector, but that it is all about "optimising parts of the textile production chain, […] improving discrete processes, separate life cycle phases or aspects of the supply chain" (Fletcher 2009, p. 369). Despite their disciplinary justification, rather disparate interventions have until now not been able to address sustainability challenges; sometimes, there is not even clear evidence if the intervention is beneficial or unfavourable concerning overall sustainability. For example, wastewater treatment of dye house effluent seeks to minimise pollution of adjacent water bodies. However, it does neither contribute to finding alternative solutions (e.g. benign chemicals, different processes) to fulfil the same function (e.g. colouring fabric) nor is it always beneficial or sustainable since huge amounts of contaminated sludge are generated and for some pollutants it just does not show any effects. Another example are efficiency improvements in wet processing, sometimes combined with recycling of certain chemical baths that reduce chemicals, water and energy use and often result in substantial time savings. Again, these supposed sustainability interventions seem successful only as long as one looks at the respective process or company. The yields of those efficiency improvements are usually put directly back into the production process resulting in increased productivity—hence, saved chemicals, water, energy and time can be used to produce more with fewer resources in shorter time. Moreover, the potential of (eco)-efficiency strategies is limited to the respective process or product and does not prove suitable for the complex sustainability challenges of the textile sector (Fletcher 2009). Nevertheless, those strategies are often enough first steps towards sustainability and pave the way for more fundamental change (Fletcher 2009). Another example from the area of policies and regulations is the European Commission's Integrated Pollution Prevention and Control (IPPC) regime that lists so-called BATs—"best available techniques"—for textile manufacturing, but lacks perspectives on system and life cycle innovation (Fletcher 2009). While incremental changes in processes or products are usually preferred by companies due to their relatively easy implementation into existing production cycles and the quickly felt benefits, Sustainable Chemistry searches for "long-term sustainable solutions" (Nimkar 2018, p. 16). Due to the inclusion of all life cycle stages, Sustainable Chemistry considers total material flows and seeks to avoid entropy transfers from one life cycle phase to another to prevent rebound effects and second-order problems (Kümmerer 2017). Offering different levers and means for intervention in the different (sub-) systems, it is not limited to technological approaches like benign molecular design, process improvements or enhanced synthesis routes. It does explicitly include levers for changing practices and values like better information and communication, data management, education, consulting and changing institutions (Blum et al. 2017; Boström and Micheletti 2016; Kümmerer 2017). Consequently, a wide range of actors have to be addressed but by that Sustainable Chemistry meets the needs of real-life complex supply and demand chains, which involve numerous stakeholders. Regarding the variety of levers, Westley et al. (2011, p. 762) emphasise that "promising social and technical innovations […] need to be […] connected to broad institutional resources and responses" if they ought to be successful and become common practice. In the case of Sustainable Chemistry, the importance of institutional change comes into play as acknowledgement by UNEP in the Global Chemical Outlook II (UNEP—United Nations Environment Programme 2019), and as the implementation of the International Sustainable Chemistry Collaborative Centre ISC_3 promoting and developing Sustainable Chemistry solutions worldwide (Elschami and Kümmerer 2018).

Ultimately, we need to deal with the problems of the textile sector at their respective levels (e.g. technological improvements, benign molecular design, etc.), and, at the same time, engage even more in systems thinking by reaching beyond boundaries of industries, disciplines and communities to account for drivers of unsustainability emerging outside (Fletcher 2009).

6.4.2 Strong Normative Roots

As shown before, risks and responsibilities are diffused in globalised, intertwined supply and demand chains and differing legislative and regulatory frameworks leaving actors uncapable of effective chemical risk management. This responsibility challenge needs both changing values and mindsets, a strong normative grounding and commitment to sustainability among all actors.

At the core of Sustainable Chemistry is chemistry as an objective natural science. That cannot be changed as chemicals react and behave accordingly to their inherent properties which are encoded in their molecular structure, i.e. the laws of chemistry and physics. However, where, how, when and why chemicals are manufactured and used is its normative basis. That is in the realm of culture, industry, society, politics and economy including Green Chemistry and Sustainable Chemistry. Regarding the textile sector, a short review of its history demonstrates this impressively. While Green Chemistry is rooted in environmental protection, Sustainable Chemistry is inherently connected to sustainability grounding its scientific endeavours on normativity. This normative part of chemistry opens up many opportunities for improvements but also responsibilities including better and in some cases also less use of chemical products in all sectors, including the textile sector.

Traditionally, the development of society within the ecological boundaries is attributed to Sustainable Chemistry rather than to Green Chemistry (Hutzinger 1999). Green Chemistry anchors itself in the normative premise of intentionally beneficial design of processes and chemicals which are not harmful for the environment and human health with one of its core principles—namely benign by design (Kümmerer 2007, 2017; Kümmerer et al. 2018). The principle benign by design has already shown its feasibility by successful redesign of chemicals and even pharmaceuticals where demands are very high concerning drug safety, effects and adverse drug reactions (Rastogi et al. 2015; Rieger et al. 2002; Leder at al. 2015; Haiß et al. 2016). Nevertheless, in accordance with the principles of Green Chemistry chemical warfare agents have been developed which of course cannot be called sustainable (Elschami and Kümmerer 2018). Therefore, strong normative roots and a holistic approach involving all dimensions of sustainability are necessary to achieve truly beneficial solutions for human beings now and in the future and for the environment.

6.4.3 Input Prevention

Another important key characteristic of Sustainable Chemistry is its focus on input prevention of chemicals reducing or even eliminating chemical risks from the beginning onwards (Haddad et al. 2015; Kümmerer et al. 2018). Regarding the textile industry, this principle does not only have great influence on wet processing of textiles, but on the entire supply chain, especially on the chemical burden of post-consumer textiles that nowadays contain up to 90% of the initially introduced chemicals (Nimkar 2018). Consequent input prevention of hazardous chemicals in the first place would make expensive and time-consuming control and risk management approaches at all later stages obsolete and would address global dissipation. Moreover, clear evidence suggests that in terms of economic performance of companies, pollution prevention is better than control approaches towards chemical risks (Alkaya and Demirer 2014; Nishitani et al. 2011; Zeng et al. 2010).

Considering possible benefits for companies, Walton et al. (1998) distinguish three attitudes towards environmental performance among companies—namely resistant, receptive and constructive. A resistant response towards environmental performance is characterised by sole legislative compliance rather than comprehensive implementation of policies (Fransson and Molander 2013). This management strategy often results in short-term end-of-pipe solutions, while the processes creating risks remain unchanged, e.g. wastewater treatment in the textile industry (Fransson and Molander 2013). Resistant adaptation cannot be an option for the textile sector when it comes to chemical use since it is predicted that "[i]f no action is taken, fashion brands will find themselves likely squeezed between falling average per-item prices, deeper discount levels, rising costs, and resource scarcity along the value chain" (Global Fashion Agenda and Boston Consulting Group 2017, p. 20). Moreover, rising pressure from stakeholders such as NGOs and customers will further aggravate the sustainability challenges of the textile industry (Börjeson and Boström 2018). Companies following the second "receptive" management type make incremental changes to their production processes which slightly exceed current policies, as they consider this strategy as more profitable (Fransson and Molander 2013). Companies responding in a so-called constructive way include environmental performance measures clearly exceeding legislation in their production planning right from the beginning (Walton et al. 1998) and aim at gaining advantages from being environmentally friendly at an economic and brand reputation level (Fransson and Molander 2013). The input prevention approach of Sustainable Chemistry represents one tangible way of a constructive response to environmental performance challenges of the textile industry, since it exceeds legislation, and even current MRSLs, and reveals economic advantages by saving money spent on expensive and time-consuming risk management procedures. Furthermore, it opens up possibilities for new business models that focus on the delivery of specific functions and services rather than sole provision of chemical products (Kümmerer 2017).

6.4.4 Stakeholder Focus

As mentioned before, the holistic approach of Sustainable Chemistry calls for engagement with a broad set of actors and stakeholders. This is especially relevant for the textile sector, whose supply chains are highly complex and intertwined. Sustainable Chemistry allocates responsible roles to all actors along the supply chain including "chemical industry, downstream users of substances and materials, manufacturers of products as well as consumers" (Blum et al. 2017, p. 99) and requires a cooperative mindset among them. Of particular importance for the textile sector is the design step where decisions are being made which influence heavily the amount and type of chemicals used for textile production, and subsequently composition of textile waste and possible recycling options. Materials, product requirements, colours and styles are chosen at this point and periods of use get pre-determined, all of which then determine the chemicals management challenges arising at later stages. Hence, designers need to be aware of their influence and about environmentally friendly materials and non-chemical alternatives. In collaboration of a wider stakeholder network including multiple perspectives and different forms of knowledge lies a great opportunity for so-called generative learning, which is about creating rather than adapting (Manring and Moore 2006). Again, Sustainable Chemistry with its distinct focus on all relevant stakeholder groups and its appreciation of interdisciplinary and undogmatic networks offers a highly suitable framework for the textile sector with its numerous professions and actors.

6.5 Examples and Practices of Sustainable Chemistry Within the Textile Sector

In this last part of the chapter, we want to present and discuss different examples and practices within the textile sector that already engage—to a varying degree—in Sustainable Chemistry. The examples and practice represent an own non-exhaustive compilation stemming from the literature (see Table 6.2). By presenting the following examples, we would like to stimulate a discussion within and between the communities of Sustainable Chemistry and textile research and industry. Finally, we would like to draw the readers' attention towards three selected examples and discuss them in depth.

First of all, how can examples and practices of Sustainable Chemistry be defined, if there is still no shared understanding? Since Sustainable Chemistry is "simultaneously both a path and a goal" (Kümmerer 2017, p. 16421), telling examples and practices point in the direction towards more sustainability in chemicals production, use, distribution and disposal and should not be assessed as if they would be a finite solution. Moreover, to avoid buzzwording, green washing and subsequently an arbitrariness of the term, every example has to be verified on a case-to-case basis ensuring that recent insights can be included to account for the uncertainty inherent in highly complex sustainability challenges. Practices of Sustainable Chemistry ideally

Table 6.2 Examples and practices of green and sustainable chemistry

Innovation approach		Example	Benefit	Source
Process optimisation	**Reduction** Energy/heat use	Microwave-enhanced dyeing Sonochemistry	Enhances the rate and selectivity of catalytic reactions	Centi and Perathoner (2009)
		White biotechnology (e.g. Novozyme)	Water and energy saving; eliminates use of harmful chemicals	Chatha et al. (2017), Shahid et al. (2016)
	Water use	**Nanocellulose-enhanced dyeing**	Reduction of water, salt and alkali consumption in cotton dyeing	Kim et al. (2017)
		Waterless dyeing (e.g. supercritical CO_2 dyeing; ColorZen; DyeCoo)	Eliminates the use of water, no effluent discharge	Kim et al. (2017), Nimkar (2018)
Change of feedstock	**Substitution**	Conventional cotton versus organic cotton	No herbicides or pesticides	Dawson (2012)
		PVA instead of starch for cotton sizing	No COD increase in wastewater; PVA is recoverable	Nimkar (2018)
		Non-fluorinated versus fluorinated DWRs	Avoidance of highly persistent PFAS	Schellenberger et al. (2018)
		White biotechnology (e.g. Novozyme)	Eliminates use of harmful chemicals	Chatha et al. (2017), Shahid et al. (2016)
		Clay-based products for oligomer reduction in polyester dyeing	No special treatment or handling after use	Nimkar (2018)
		Earth Colours (Archroma)	Dyes from bio-waste	Nimkar (2018)
	Recycling/Reuse	Regenerated cellulose fibres (e.g. Tencel)	Biodegradable cellulose fibre; closed loop production process for solvents	Dawson (2012)
	Bio-based	Natural dyes	Extracted from renewable sources; biodegradable	Bazzanella et al. (2017)
		Polylactic acid fibres	Produced from renewable carbohydrates by fermentation; biodegradable	Dawson (2012)
New business models		**Chemical leasing**	Minimisation of use of chemicals, reduction of costs and resource consumption	Kümmerer (2017)

(continued)

Table 6.2 (continued)

Innovation approach		Example	Benefit	Source
Alternative solutions		**Self-cleaning textiles**	Reduction of water, energy, detergent consumption	Busi et al. (2016)
Other	**Education, consulting and provision of specific knowledge**	Partnership for sustainable textiles	Trainings on Sustainable Chemical and Environmental Management in the Textile Sector in Asia	https://www.textilbuendnis.com/initiative-sustainable-chemical-and-environmental-management-in-the-textile-sector-in-asia/
	Data management	"Positive Chemicals" List		Nimkar (2018)
		Information flows in networks		Manring and Moore (2006)
	Digitisation	Digital printing—"drop on demand" technology	Eliminates use of harmful chemicals, no effluent load	Nimkar (2018)

address spatial as well as temporal scales, flows, and dynamics of chemicals, materials and products (Kümmerer 2017; Weiser et al. 2017), and hence address drivers of highly complex and currently unsustainable practices. The following examples comply to a varying extent with the definition by Blum et al. (2017) and the aforementioned key characteristics; hence, they should serve as a starting point for critical discussion.

6.5.1 New Business Models—Chemical Leasing

Chemical leasing is a good example for a practice of Sustainable Chemistry engaging in systems thinking and input prevention, as it represents a shift from a sales-oriented to a service-oriented business model. The profit here is not generated by the amount of chemicals sold, but by delivering a function. This function is only partly provided by the chemical itself, but also by communication, provision of specific knowledge about the correct use and application of the chemical, and by taking on full responsibility for the service that is needed by the customer. Hence, the supplier becomes a service provider focusing on the stakeholders within the supply chain and tailoring offers to specific needs of customers. Hereby, the use of chemicals is minimised, costs as well as resource consumption are reduced. This model can also be transferred to the textile sector if long-living clothes of high quality are sold together with specifics services such as free care and repair treatments and/or detailed instructions on how to prolong useful life of products.

6.5.2 Process Optimisation/Reduction—Nanocellulose-Enhanced Dyeing (Kim et al. 2017)

Kim et al. (2017) developed nanofibrillated cellulose fibres decreasing the amount of water, salt and alkali used in cotton dyeing by one order of magnitude, while still providing good dyeing performance. In addition to the reduction in water and chemicals consumption, the fibres are produced from an abundant, biodegradable and renewable material. Moreover, Kim et al. (2017) performed a LCA that revealed significantly lower environmental costs for this textile dyeing method. The authors have been awarded the 1st prize of the Green and Sustainable Chemistry Challenge in 2016 (https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference/about/green-and-sustainable-chemistry-challenge). This example represents the holistic approach, as it is not only concerned with a reduction of resource consumption, but also looks at biodegradability and renewability of the new method and takes the economic perspective into account.

6.5.3 Alternative Solutions—Self-cleaning Textiles Enhanced with Nano-Particles (Busi et al. 2016)

Busi et al. (2016) described the so-called self-cleaning textiles, which have a nanocrystalline TiO_2 photo-catalytic surface coating able to destroy organic material by solar irradiation. The performed LCA showed lower environmental impacts for water, energy and detergent consumption in the production and use phase of the garment (Busi et al. 2016). While highly functionalised textiles or composite materials, e.g. anti-wrinkling or antibacterial treatment with silver nano-particles, may show lower energy or water demand in the maintenance phase, they can have contradicting impacts when looking at the fate of the additional chemicals. In case of silver nano-particles, a valuable resource might be lost entirely due to high material dissipation. Moreover, the silver nano-particles in contact with skin-dwelling bacteria as well as the washed out nano-particles can contribute to the development of resistance in microorganisms within the human body, wastewater treatment plants or the environment (Panáček et al. 2018). Moreover, the reduced energy demand in the use phase can likely be shifted to another life cycle phase, e.g. resource extraction or recycling (Kümmerer 2017). Hence, leaching during home laundry, increased material dissipation (Kümmerer 2016; Kümmerer et al. 2018), and reduced or more difficult recyclability may be associated with the additional chemical load—even for thin layer coatings (Bazzanella et al. 2017). Last, but not least, synthetic nano-particles like TiO2 nano-particles, and their transformation products have been found in the aquatic environment possibly posing ecotoxicological risks (Kümmerer et al. 2011).

As mentioned before, the presented compilation is by no means exhaustive. The last example clearly highlights that "chemical innovations can cause trade-offs or contradicting impacts for different sustainability indicators" (Bazzanella et al. 2017, p. 23) and scales which makes it difficult to assess overall sustainability. Even the use of biomass feedstock remains rather inconclusive in terms of overall sustainability as there can be a potential competition with food supply, undesirable land use changes, and unwanted export of nutrients in soil (Bazzanella et al. 2017). In other words green is not necessarily more sustainable.

6.6 Summary and Conclusion

Finally, the sum of sustainability challenges of the textile sector associated with chemicals can be described as a wicked problem—due to its multi-level, complex and dynamic nature. On the one hand, it has been shown that current management and regulatory instruments hardly seem to be appropriate to govern global chemical risks arising from growing volumes and diversity of chemicals sufficiently, and, on the other hand, technological efforts like effluent treatment have as well proven to be merely end-of-pipe solutions with questionable success. This results in the urgent need for an innovative way of tackling chemical risks in global contexts building on use reduction and input prevention at first and a holistic approach with regard to all dimensions of sustainability, especially including social aspects. Innovative and integrative practices from the field of Green and Sustainable Chemistry applicable to major sustainability challenges of the textile sector need to be assessed on a case-to-case basis. Therefore, we plead for a systematic overview of examples and practices of Green and Sustainable Chemistry in the textile sector to identify areas of success but also gaps, and bundle efforts in tackling sustainability issues regarding chemicals. Moreover, the ongoing development of guiding principles (like the ones Blum et al. 2017 suggested) remains an important tool for mainstreaming and implementing Sustainable Chemistry and also to guide decisions makers in industry, politics and society.

In the light of the previously described potentials of Sustainable Chemistry for the textile sector, we argue that

(1) it is beneficial to join forces in tackling highly complex sustainability challenges,
(2) Sustainable Chemistry should finally come to the fore of stakeholders within the textile industry, and
(3) Sustainable Chemistry can act as an integrating umbrella concept for addressing challenges regarding chemicals in the textile sector.

Acknowledgements This research was made possible within the graduate school "Processes of Sustainability Transformation", which is a cooperation between Leuphana University of Lüneburg and the Robert Bosch Stiftung. We gratefully acknowledge the financial support from the Robert Bosch Stiftung (12.5.F082.0021.0).

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