I. The evolving chemicals economy: status and trends relevant for sustainability

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About Part I

A wealth of economic and scientific information relevant to the sustainability of the chemical industry has been generated since the GCO-I. Part I of the GCO-II presents existing and emerging economic and scientific knowledge and, where possible, trends in regard to a range of topics of relevance for chemicals and waste management. In conjunction with Parts II and III, Part I provides information on progress made towards the implementation of the 2020 goal, focusing on impact indicators. Findings indicate that the international community is not on track to minimize the adverse impacts of chemicals and waste on human health and the environment.

The overarching structure of Part I is as follows: Chapters 1 and 2 provide an overview of the global chemical industry and the production and sales of chemicals. Part I then proceeds by providing knowledge on chemical releases and concentrations, followed by a discussion of the effects of chemicals on human health and the environment, including the cost of inaction and benefits of action related to sound management. As chemical production and sales are heavily affected by, and linked to, global megatrends as well as trends in chemical-intensive industry sectors, these topics are discussed in a dedicated chapter. Special attention is also given to the increasing complexities associated with chemicals in products and global supply chains and to circularity challenges. Throughout Part I, challenges encountered in collecting coherent global data, developing baseline knowledge, identifying trends and documenting knowledge gaps are highlighted.

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1/ The chemical industry

Chapter Highlights

Between 2000 and 2017 the global chemical industry's production capacity almost doubled, from about 1.2 to 2.3 billion tonnes.

If pharmaceuticals are included, global sales totalled US (United States) dollars 5.68 trillion in 2017, making the chemical industry the second largest manufacturing industry in the world.

Sales are projected to almost double from 2017 to 2030.

In emerging economies the sales, production volume and production capacity of the chemical industry have grown and are projected to continue growing rapidly, especially in China.

The chemical industry turns large amounts of resources into chemical products, including oil and natural gas used as primary feedstocks.

The chemical industry is going through a period of mergers, acquisitions and other types of restructuring.

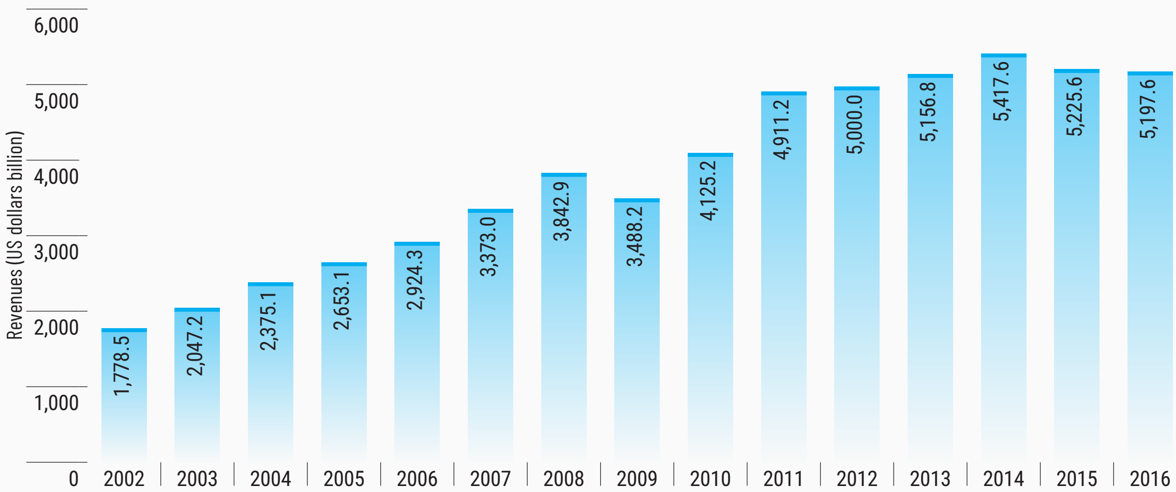
This chapter provides an overview of the global chemical industry. It starts by presenting available data on the status and historic trends in the sales, production volume and production capacity of the chemical industry, followed by an overview of related forecasts. The chapter proceeds by examining the industry's role as a major component of the global system of production and consumption, including its global value chain and its role in global resource flows. The chapter closes by exploring how the chemical industry is restructuring and by briefly examining important trends in research and development.

1.1 The chemical industry: status and historic trends

The chemical industry is one of the world's largest industries

Total chemical industry revenues have a long history of steady growth, at 4-4.5 per cent, although in the past several years there has been some flattening out (Figure 1.1). The growth rate was 4.6 per cent in 2017. Global sales in 2017 are estimated at US dollars 3.47 trillion, excluding pharmaceuticals (European Chemical Industry Council [Cefic] 2018). If pharmaceuticals are included, global sales in 2017 were an estimated US dollars 5.68 trillion (American Chemistry Council [ACC] 2018). This makes the chemical industry the second largest manufacturing industry in the world (International Labour Organization [ILO] 2018).

Figure 1.1 Total chemical industry revenues, 2002-2016 (US dollars billion) (based on ACC 2017)

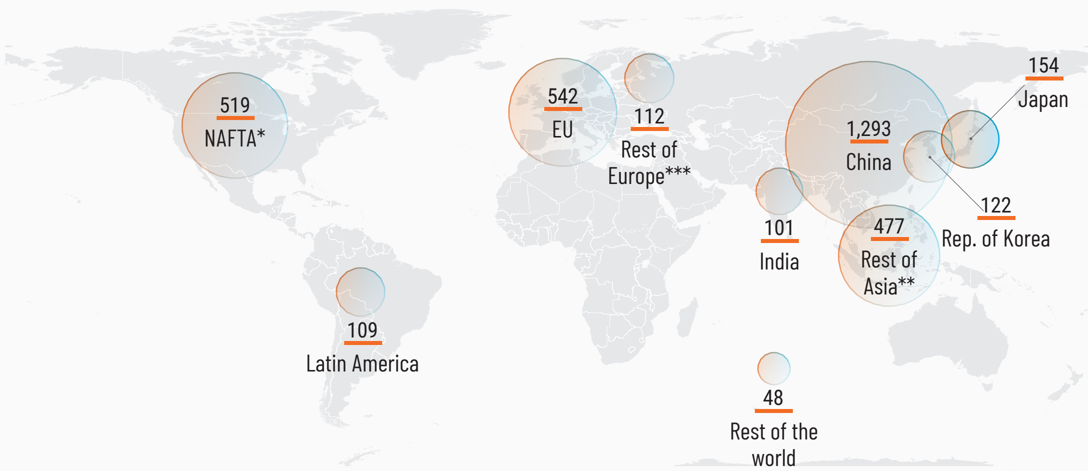


Asia has rapidly increased its market share and China now has the largest chemical industry

Throughout much of the 20th century the chemical industry was based largely in Europe, North America and Japan. Since the 1970s it has expanded internationally, with much new investment occurring in Asia and the Middle East (Budde *et al.* 2017). Faced with the need to increase capacity to meet global demand in the 1990s, growth was driven by investments from multinational companies, based in Organisation for Economic Co-operation and Development (OECD) countries, in production facilities in non-OECD countries. Since 2000 domestic chemical companies, particularly in China and the Middle East, have become increasingly dominant producers. Companies in India are also rapidly expanding their market share.

Today Asia is the largest chemical producing and consuming region (Figure 1.2). China has the world's largest chemical industry, with annual sales of around euros 1,293 billion or about 37 per cent of global sales. Its sales are larger than those of the next nine counties combined.

Figure 1.2 Chemical sales by geographic region, 2017 (EUR billion) (adapted from Cefic 2018, p. 6)



* North American Free Trade Agreement
** Asia excluding China, India, Japan and South Korea
*** Rest of Europe covers Switzerland, Norway, Turkey, Russia and Ukraine

The European Union (EU) ranks second with a market share of about 16 per cent, followed by the United States with about 13 per cent. In 2017 the BRICS countries (Brazil, Russia, India, China and South Africa) accounted for around 44 per cent of all chemical sales (Cefic 2018). As of 2016, four of the top 10 largest chemical companies were based in Asia or the Middle East (Tullo 2017a).

Asia and the Middle East have experienced the strongest growth in production volume and capacity

In terms of production volume, Europe and North America stagnated between 2000 and 2017. During the same period China, the Middle East and India experienced rapid growth at a compound annual growth rate (CAGR) of 11.8, 8.5 and 7.6 per cent, respectively (Cayuela and Hagan 2019) (Figure 1.3).

Figure 1.3 Growth in production volume, 2000-2017 (adapted from Cayuela and Hagan 2019)

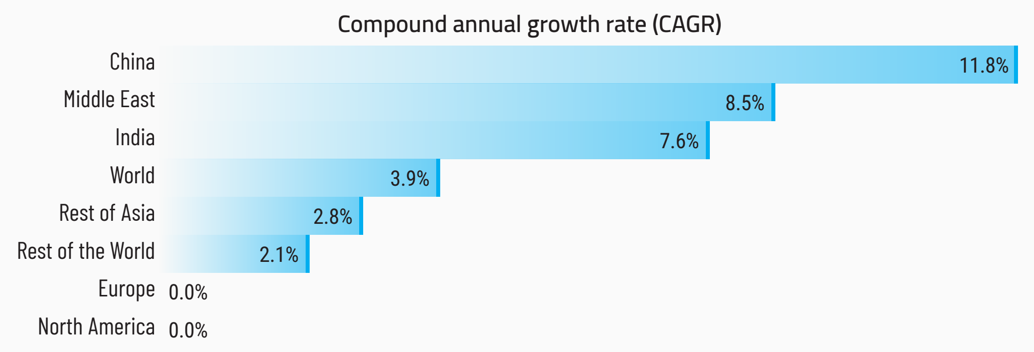
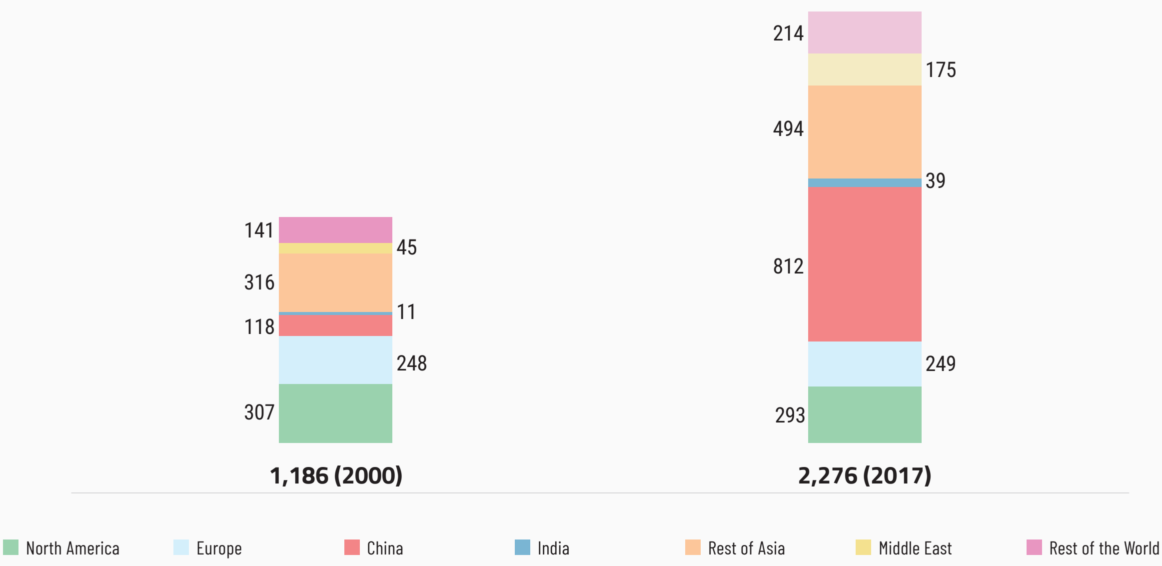


Figure 1.4 Global chemical industry capacity growth in million tonnes, 2000-2017 (adapted from Cayuela and Hagan 2019)



The production capacity of the global chemical industry almost doubled between 2000 and 2017 to reach some 2.3 billion tonnes (Cayuela and Hagan 2019), suggesting continued future increases in the volume of chemicals produced. Growth in production capacity has been particularly rapid in China and India (Figure 1.4).

International trade in chemicals has also been increasing rapidly

As the industry and its markets have grown, so has international trade in chemicals. The value of China's exports of chemicals has increased by 15 per cent since 2013, the year the first *Global Chemicals Outlook* was published (United Nations Comtrade 2018). Chemicals and products containing chemicals are traded in large volumes around the world. Exports (excluding intra-EU exports) reached a global value of around US dollars 748 billion in 2017 (World Trade Organization [WTO] 2018). In terms of export value, the EU is the largest chemicals exporting region (around 20 per cent of global exports), followed by the United States (around 10 per cent) and China (around 7 per cent). As regards import value, the United States (around 10 per cent of global imports) is closely followed by the EU (around 10 per cent) and China (around 9 per cent) (WTO 2018).

1.2 The chemical industry: forecast and outlook

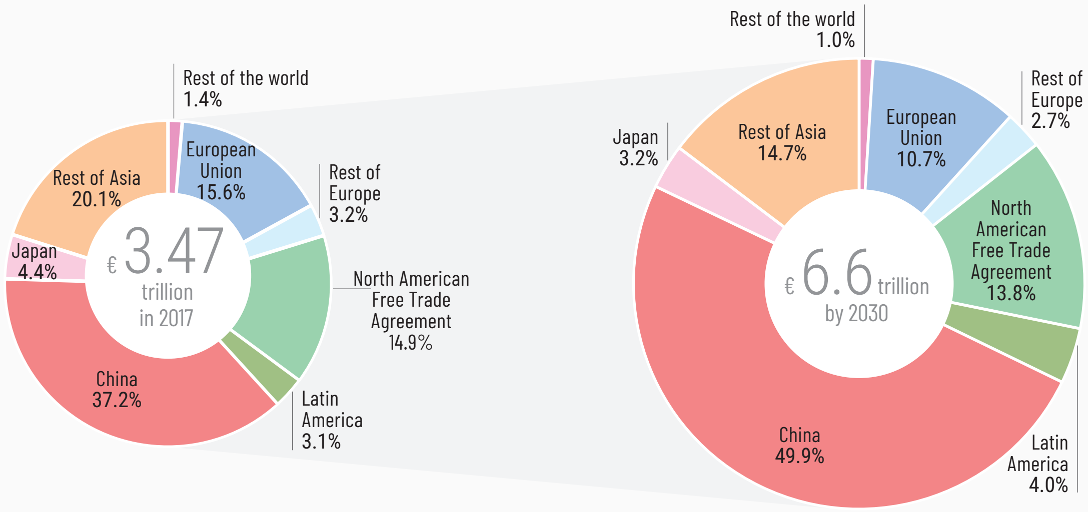
Growth in sales is expected to continue in the medium and long term

Growth in sales is expected to continue, although more slowly than in the past decade. While estimates vary according to the period selected for analysis, some forecasts show world chemical sales almost doubling between 2017 and 2030 to reach euros 6.6 trillion (Cefic 2018). By 2030 China's share of the global market is projected to increase to almost 50 per cent (Cefic 2018) (Figure 1.5). According to the OECD (2019), the value of the global production of chemical products will reach almost US dollars 22 trillion by 2060.

Growth rates are expected to be strongest in Asia, Africa and the Middle East

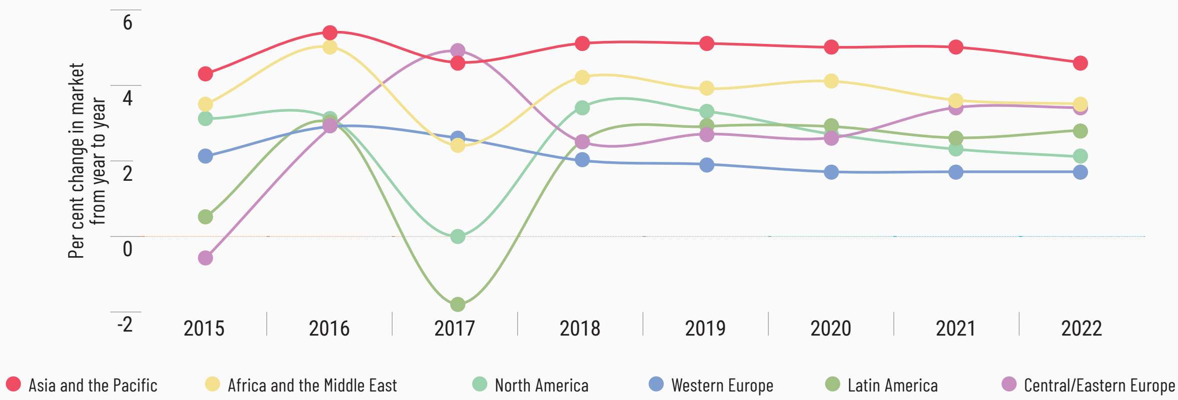
It is expected that future industry growth will be driven mainly by emerging markets, where gains are likely to be 6-10 per cent per year compared with 2-3 per cent in higher-income economies. Growth in the Asia-Pacific region, Africa and the Middle East is projected to be strongest in almost every year until 2022 (ACC 2017) (Figure 1.6).

Figure 1.5 Projected growth in world chemical sales, 2017-2030 (adapted from Cefic 2018, p. 34)



Global chemical sales (excluding pharmaceuticals) are projected to grow from euros 3.47 trillion in 2017 to euros 6.6 trillion by 2030. Asia is expected to account for almost 70 per cent of sales by then.

Figure 1.6 Projection of annual production growth in the chemical industry by region, 2015-2022 (per cent change per year) (based on ACC 2017)



While production of chemicals is projected to grow in each region, annual growth rates are highest in regions with developing countries and emerging economies, particularly in Asia-Pacific, Africa and the Middle East.

1.3 The chemical industry in the global system of production and consumption

Value chain of the chemical industry

The global value chain of the chemical industry and its products extends from the extraction of raw materials to the use and reuse of industrial and consumer products. A simplified representation of this value chain is shown in Figure 1.7. At the core of the chemical industry are huge, highly capitalized installations where millions of tonnes of basic chemicals are produced as feedstocks for the thousands of chemicals that make up the chemical market. However, the industry is

increasingly diversifying into high-technology sectors such as biotechnology, nanotechnology and new materials, which have applications, for example, in health care, consumer goods, manufacturing, communication, transportation and environmental protection (Valencia 2013; Sarathy *et al.* 2017).

Focusing on the first three of the steps in Figure 1.7 and examining, in particular, chemical manufacture, processing or refining in more detail, the global value chain of the chemical industry can be divided into five key segments, as shown in Figure 1.8 (Bamber, Frederick and Gereffi 2016). In a first step feedstocks – such as natural gas and minerals – are processed into high-volume and low-value "bulk" chemicals. These are conventionally produced in high-capacity refineries and milling facilities with high capital investment costs. Intermediate chemicals are generally developed for further use in production or manufacturing processes (e.g. dyes for paint production). Specialty chemicals are higher in value and are designed to fulfil specific functions. Given the relatively lower investment needed, a larger number of smaller companies can operate in this segment. Chemical processing and product manufacturing in downstream facilities is connected to innumerable product manufacturers in sectors such as agriculture, construction and electronics. The various segments may span a number of countries across the world.

The global value chain of the chemical industry is complex and highly integrated globally

The linkages among chemical manufacturers and their suppliers and downstream customers are often complex and heavily integrated. Chemical supply chains can be long. Customers may be global, often located in several countries or on different continents. In addition, a change in market conditions for one high-volume chemical can have important economic implications for many other chemicals, including those co-produced as by-products and others manufactured downstream. For example, production of polyethylene (PE) (the world's most commonly used plastic) generates co-products used to make polystyrene (PS) and polyester. Reduced use of plastic shopping bags and other

Figure 1.7 **Value chain of the chemical industry: from extraction to finished products**

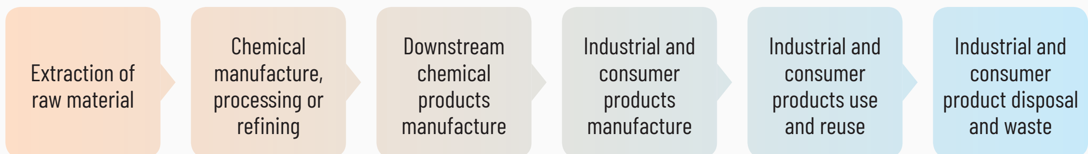
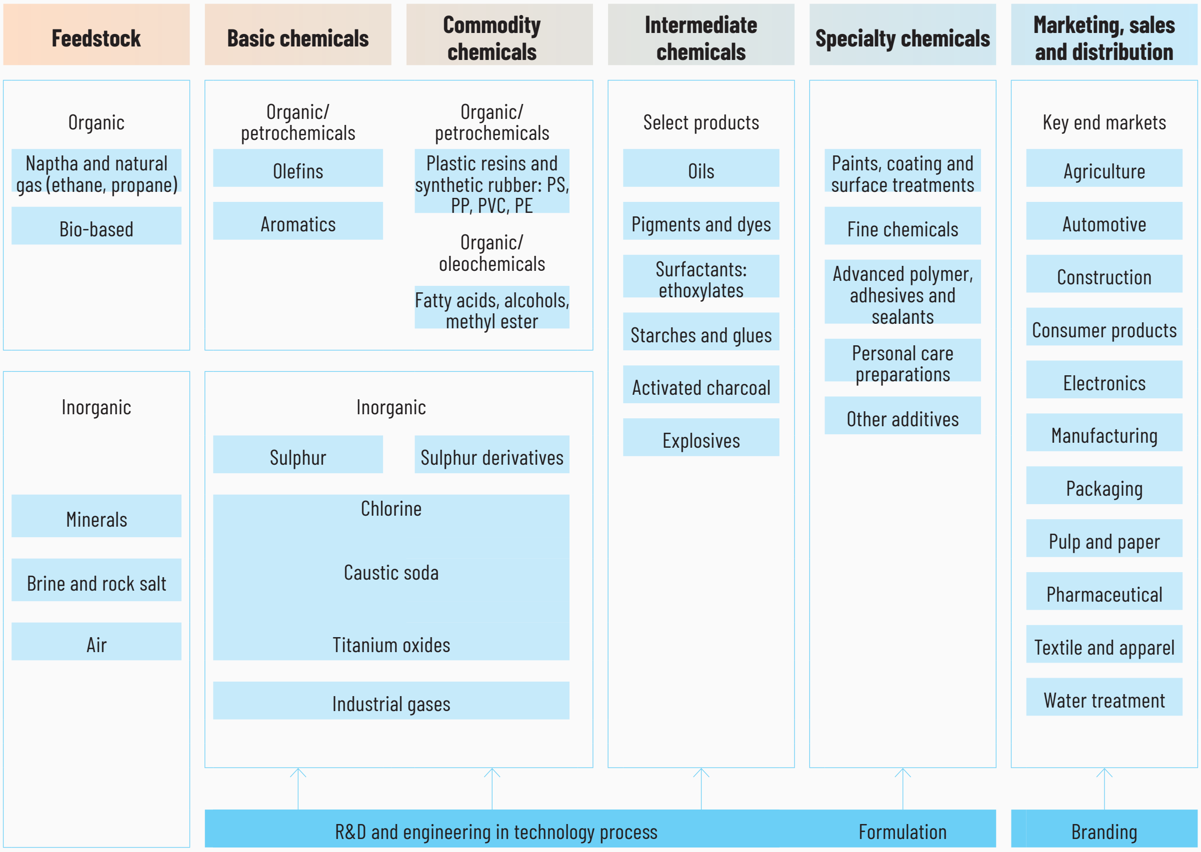


Figure 1.8 Chemical segments in the global value chain (Based on Bamber, Frederick and Gereffi 2016, p. vii)



polyethylene objects affects not only the market for polyethylene itself, but also the availability and price of polystyrene and polyesters.

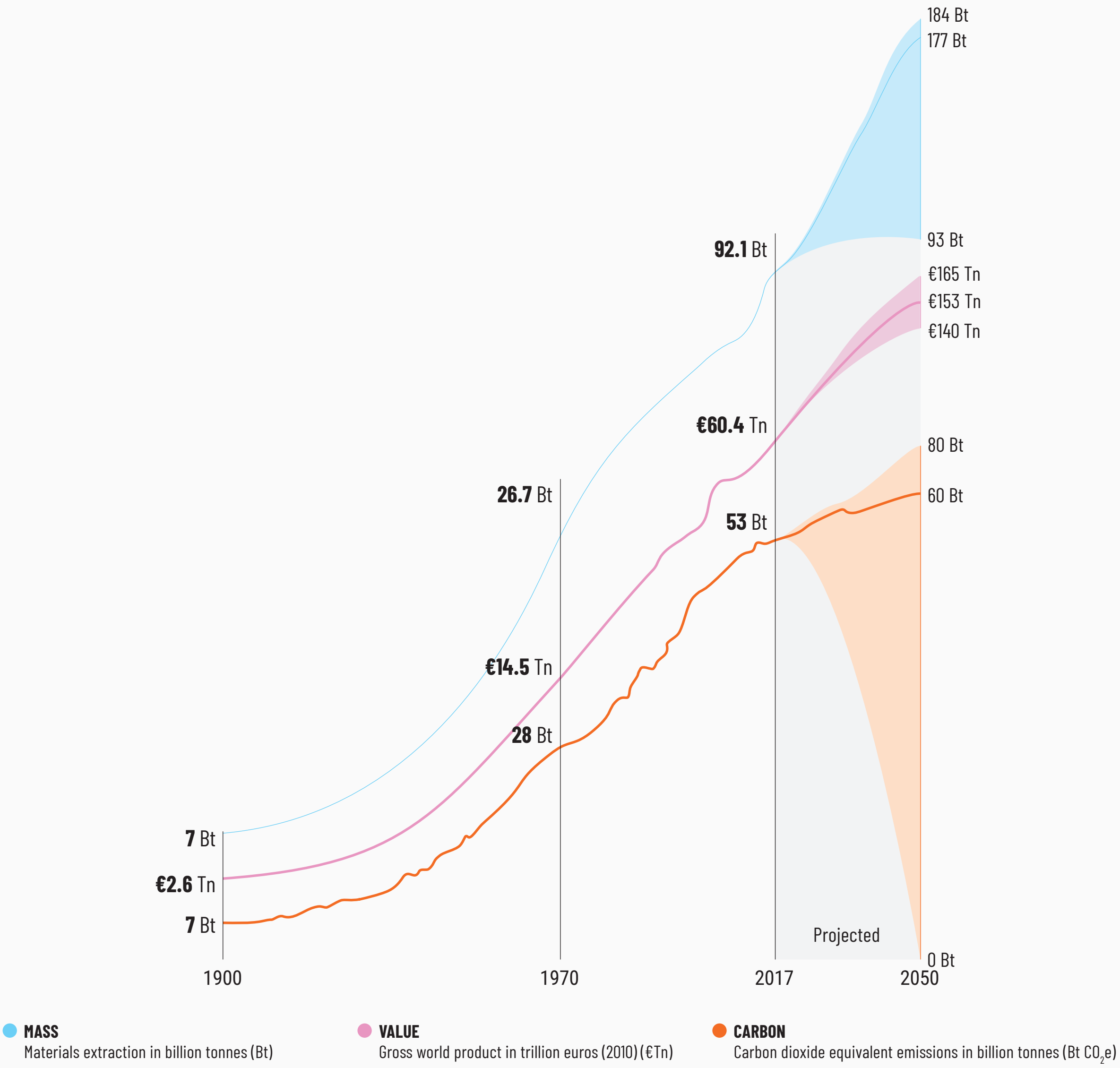
Emerging economies are strengthening their position in higher-value markets

Value chains are governed by global markets that regulate the processing, distribution and formulation of chemicals. The liberalization of these markets, combined with production, logistics and information technology innovations, have decentralized chemical production and decreased costs (Nicita *et al.* 2013). These developments have presented opportunities for low-income countries to participate in the globalized market, e.g. through the production and export of basic chemicals which are then further synthesized and polymerized elsewhere. While the chemical industries in most emerging economies are still focused on producing bulk chemicals, some seek to move up the value chain by strengthening their position in the market for intermediates and specialty products. A study on the role of the Philippines in the global chemical industry found that in 2014 basic and commodity chemicals accounted for more than two-thirds of chemical exports (Bamber, Frederick and Gereffi 2016). However, some firms had started to enter the market for intermediate and specialty chemicals. Emerging countries also play a growing role in manufacturing products for key end markets which are chemical-intensive.

The chemical dimension of global resource flows

Manufactured chemicals are an integral part of the sourced, generated and stored materials flowing through the global economy. According to the International Resources Panel's *Global Resources Outlook* 2019 (Oberle *et al.* 2019), approximately 92 billion tonnes of materials are estimated to have been extracted globally in 2017. The *Outlook* assumes that under a historical trends scenario, this will reach 190 billion tonnes

Figure 1.9 **Trends in materials extraction, financial value creation and greenhouse gas emissions (1900-2050) (adapted from de Wit *et al.* 2019, p. 11)**



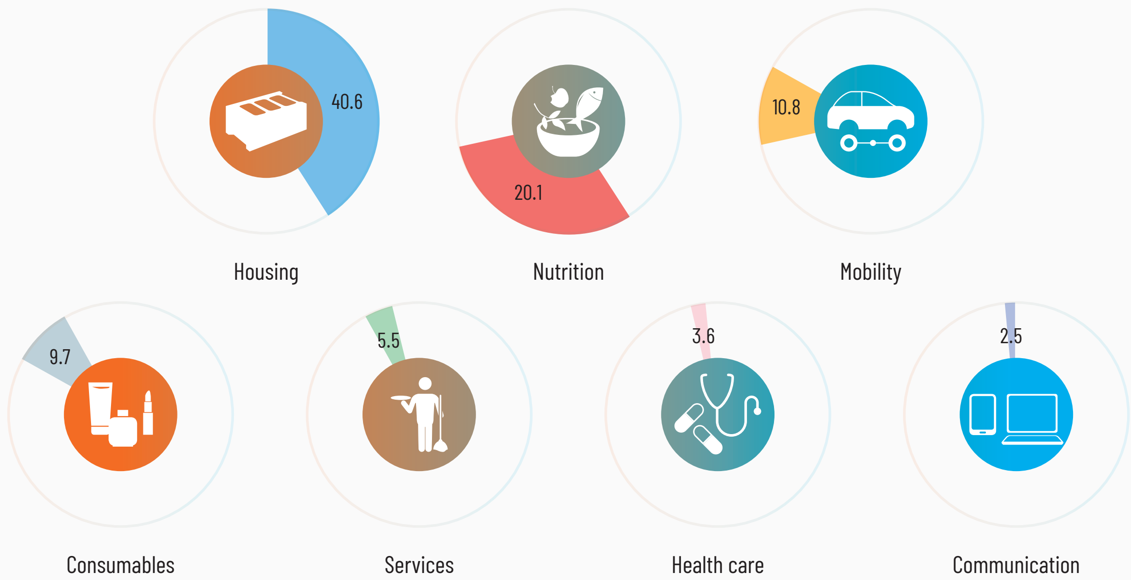
To date, global materials extraction has grown roughly in line with global economic growth and greenhouse gas emissions.

by 2060. The 2019 *Circularity Gap Report* notes that materials use has almost tripled since 1970 (Figure 1.9).

The extraction of resources is driven by societal needs (Figure 1.10). Each of these sectors is chemical-intensive in terms of both production processes and products, ranging from asbestos used in steel beams, to pesticides in agriculture, to heavy metals in batteries, to parabens in cosmetics. To date, the overarching formula has been that as societal needs increase, so does consumption of chemicals.

The chemical industry plays an important role in turning raw materials and feedstocks into valuable products. It therefore performs a key function in the global system of production and consumption and is one of the drivers of resource extraction, together with chemical-intensive sectors. Production of petrochemicals (e.g. styrene), consumer chemicals (e.g. detergents), specialty chemicals (e.g. dyes), basic inorganics (e.g. fertilizers) and polymers (e.g. plastics) relies on the extraction of fuels and minerals (Fantke and Ernstoff 2018). Researchers have mapped the magnitude of the chemical

Figure 1.10 The global material footprint: extracted resources by key societal needs and consumables, 2015 (billion tonnes) (based on de Wit *et al.* 2019, p. 19)



Six key societal needs and consumables represent the largest material footprint globally: housing and infrastructure (ca. 44 per cent), nutrition (ca. 22 per cent), mobility (ca. 12 per cent), consumables (ca. 11 per cent), services (ca. 6 per cent), health care (ca. 4 per cent) and communication (ca. 3 per cent). Each of these sectors is chemical-intensive in terms of both production processes and products, which range from asbestos used in steel beams, to pesticides in agriculture, to heavy metals in batteries, to parabens in cosmetics.

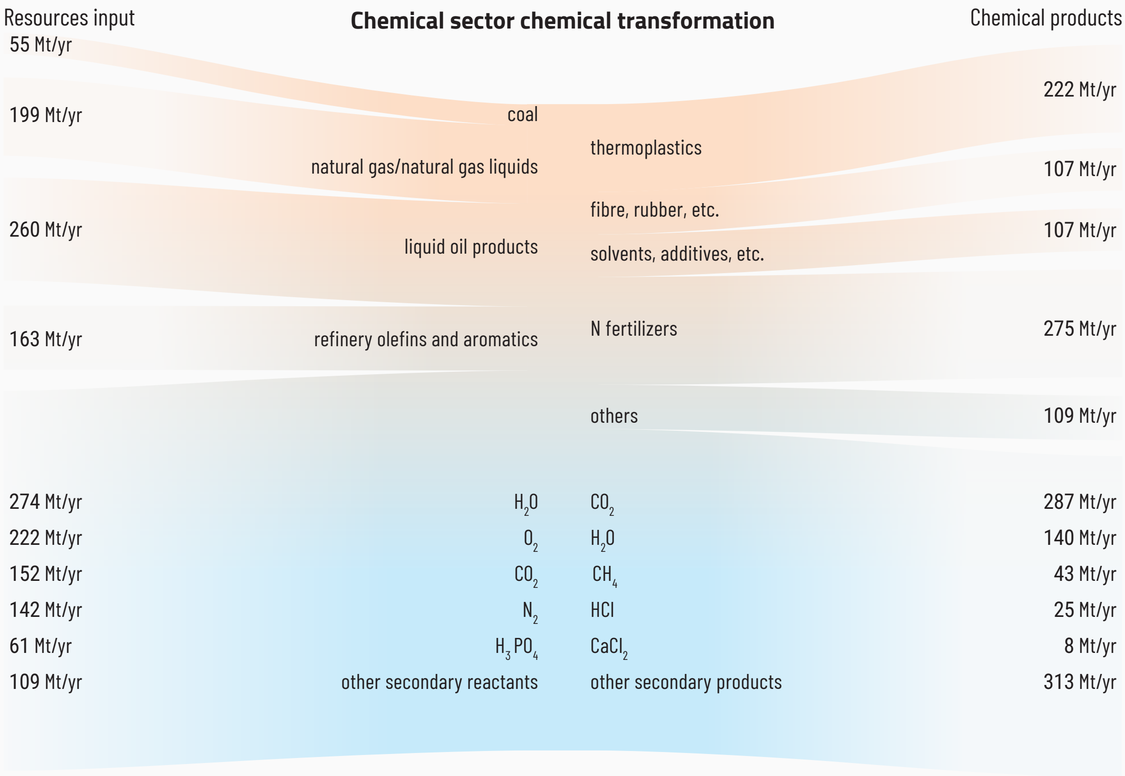
sector's material resources flows (Figure 1.11). In a single year (2015) almost 1,700 million tonnes of feedstocks and secondary reactants were used in this sector to produce 820 million tonnes of chemical products, while also generating almost the same amount of by-products.

The transformation of feedstocks and reactants into chemical products and secondary products also has a qualitative dimension. In the process of chemical production new compounds are created, in some cases with new or increased hazards. Chlorine chemistry, for example, turns basic feedstocks such as salt and water, together with other chemicals, into useful products such as water purification chemicals. At the same time, chlorine and many chlorine derivatives, as well as chemicals used in related production processes (e.g. asbestos or mercury), are hazardous and need to be well-managed.

The global chemical industry consumes a large amount of energy

The chemical industry is the world's largest industrial energy consumer. It is also the third largest industrial emitter of CO_2 (Levi and Cullen 2018). The industry accounts for approximately 10 per cent of global energy demand, or 30 per cent of total industrial energy demand, worldwide. Of the industry's total energy input, 58 per cent is consumed as feedstock. However, this demand is highly concentrated (International Energy Agency [IEA], International Council of Chemical Associations [ICCA] and Society for Chemical Engineering and Biotechnology [DECHEMA] 2013). For example, the manufacture of some 26 basic chemical compounds (including nitric acid, ethylene, propylene and butadiene) within the European chemical industry consumes some 75 per cent of the industry's total energy use and is responsible for more than 90 per cent of its greenhouse gas (GHG) emissions (Boulamanti and Moya 2017).

Figure 1.11 Resource extraction by the chemical sector and related chemicals production, 2013 in millions of tonnes (Mt) (adapted from Levi and Cullen 2018, p. 1725)



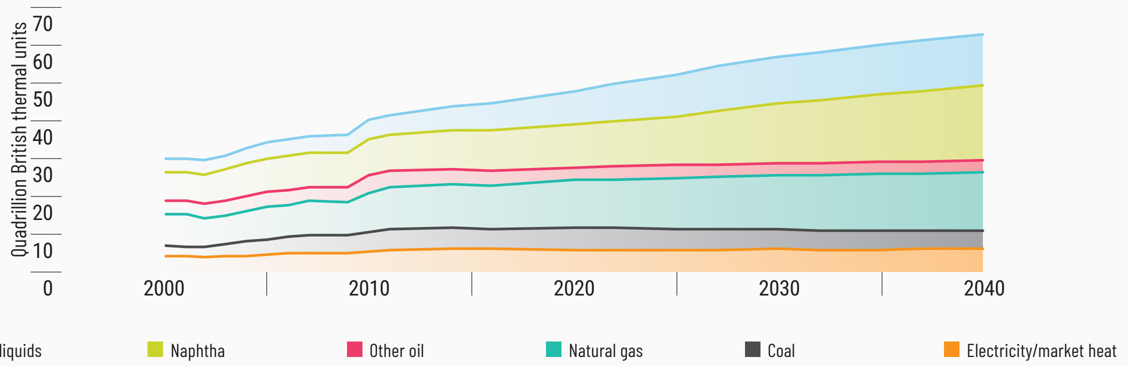
In 2013 around 513 million tonnes (Mt) of fossil fuels and around 163 Mt of olefins and aromatics were used as feedstock by the chemical industry. In addition, it used almost 1,000 Mt of secondary reactants (water, oxygen, carbon dioxide [CO_2], nitrogen and phosphoric acid). These feedstocks were transformed through various stages of upstream and downstream production to produce 820 Mt of chemical products. Around 34 per cent of this output consists of nitrogen fertilizers and around 27 per cent of thermoplastics. The chemical industry also generated 815 Mt of secondary products, including 140 Mt of methane and 287 million tonnes of CO_2.

The chemical industry has made efforts to reduce energy consumption and to invest in energy conservation. Investments have focused on redesigning catalytic processes; improving membranes and separation processes; improving efficiencies in production, storage and transport; better tailoring of heating and cooling; use of lower-carbon fuels; and integrating carbon capture and storage (IEA, ICCA and DECHEMA 2013). Nevertheless, its energy consumption continues to grow (Wernet *et al.* 2011; Darkow and von der Gracht 2013).

Chemical production continues to rely on oil, natural gas and coal

Fossil fuels (oil, gas and coal) are the feedstocks for basic petrochemicals and the source of the large amount of energy needed to manufacture most chemical products (Figure 1.12). Moreover, several of the world's largest chemical producers are owned by fossil fuel producers. The increase in the amount of available, low-cost natural gas has boosted chemical production in several global regions. Shale gas can now be obtained economically using horizontal drilling and hydraulic fracturing ("fracking") technologies. In the United States, which currently produces almost all the natural gas it uses, this technology has encouraged significant new investments in petrochemical capacity (ACC 2013; Center for International Environmental Law n.d.).

Figure 1.12 Feedstocks for chemical production, 2000-2040 (quadrillion British thermal units [BTUs]) (adapted from Exxon Mobil 2018)

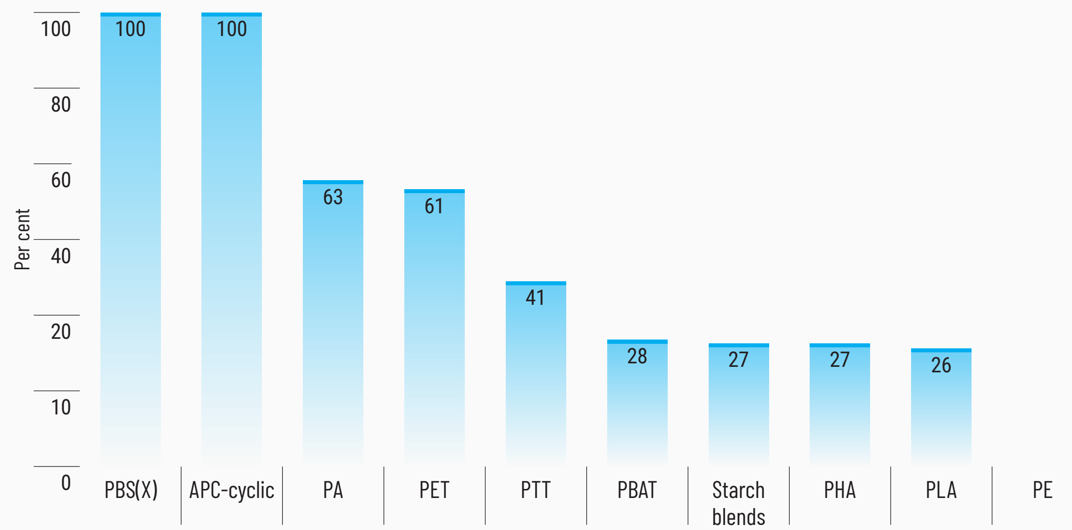


Use of renewable and bio-based feedstocks is increasing

While oil and natural gas will continue to provide the energy and primary feedstocks for the industry, sustainability concerns are driving a growing shift towards the use of bio-based and renewable resources as feedstocks. Some chemicals have long been produced from renewable resources. Examples are the lactic acid esters used as a substitute for chlorinated solvents in cleaning and degreasing agents, and corn used as the basis for a significant share of the ethanol used as motor fuel. Today many high-value polymers and industrial enzymes can be produced from biological feedstocks (Bomtempo *et al.* 2017). The feedstocks used to produce bio-based chemicals have recently expanded from edible sugars to inedible and lignocellulosic biomass. Such a shift could reduce the need for crops as feedstocks in favour of wood pulp. However, significant land use would still be needed for large-scale production. Progress has also been made in the bioprocessing of microbial production of chemicals from renewable feedstocks (Kawaguchi *et al.* 2016).

The next two decades are likely to see significant growth of the global bio-based chemical industry. The market for bio-based chemicals is expected to grow from 2 per cent of the total chemical market to 22 per cent by 2025. While the global polymer market is predicted to exceed US dollars 450 billion by 2025, the share of bio-based chemicals is expected to increase to 10-20 per cent of that market (United States Department of Agriculture 2008).

Figure 1.13 Share of Asian bio-based polymer production capacity in global production, 2016 (per cent) (adapted from Baltus 2017, cover page)



Asia is the largest producer of bio-based polymers

By 2016 global capacity for bio-based polymers production reached 2.4 million tonnes, with more than 45 per cent of the most important bio-based polymers produced in Asia (primarily in China, Japan, Malaysia, the Republic of Korea, Taiwan and Thailand) (Figure 1.13). Global capacity for bio-based polymers production is expected to reach 3.6 million tonnes in 2021, with nearly 52 per cent installed in Asia (Baltus 2017).

1.4 Chemical industry structure and organization

The chemical industry is made up of several hundred highly integrated multinational corporations and thousands of small and medium-sized chemical processing and compounding enterprises. In some industry segments, such as basic chemicals and pharmaceuticals, there are a few very large dominant firms. On the other hand, the specialty chemical segment is highly fragmented, with hundreds of sub-segments and thousands of producers distributed widely around the world. In the last two decades the chemical industry has undergone significant transformations, triggered by the entrance of China and the Middle East into the global chemical industry and increasing competition.

The global chemical industry is represented by national and multinational associations

The ACC and Cefic are the largest chemical industry associations in the United States and Europe, respectively. However, there are international trade associations that represent each step along the chemical industry value chain (Figure 1.14).

The International Council of Chemical Associations (ICCA) is the trade association of the global chemical industry, including both national and regional associations. It represents chemical companies in 69 countries. ICCA members account for more than 90 per cent of global chemical sales. ICCA works with companies and associations around the world by means of its Responsible Care® Leadership Group, through which global chemical manufacturers commit to an ethic of safe chemical management and chemical management performance excellence (ICCA 2015).

Chemical distributors play an important role in the increasingly globalized chemical industry. They have an essential role to play in chemical supply chains by providing access to hard-to-

Figure 1.14 **International trade associations along the chemical industry value chain (adapted from International Chemical Trade Association [ICTA] 2018a)**

reach markets, solving logistical challenges and providing handling services (e.g. repackaging or formulating) while ensuring safety, quality and compliance when working with chemicals. The International Chemical Trade Association (ICTA) represents the interests of over 1,500 chemical distributors worldwide. It promotes the voluntary practices of Responsible Care® and Responsible Distribution, particularly among small and medium-sized enterprises (SMEs) (ICTA 2018b).

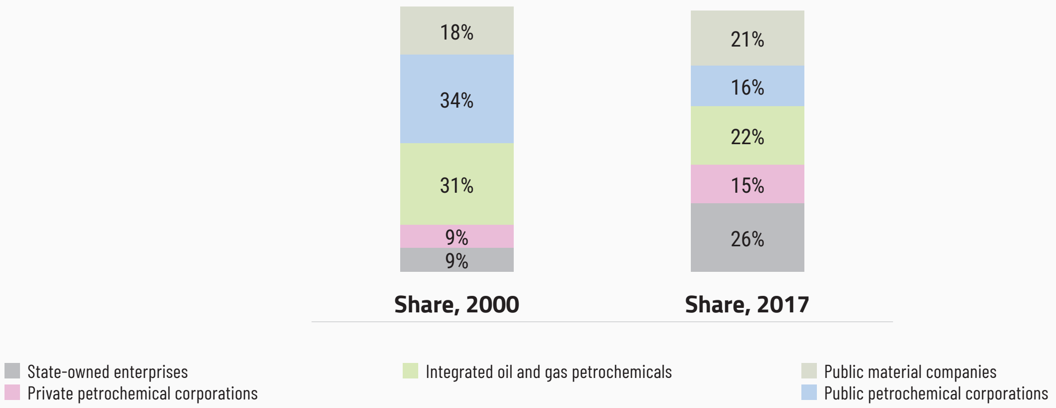
The proportion of state-owned enterprises in the chemical industry is rising

The chemical industry ownership structure is undergoing significant shifts. State-owned enterprises accounted for only 9 per cent of global chemical industry revenues in 2000, compared with 26 per cent in 2017 (Cayuela and Hagan 2019). Public petrochemical corporations (those whose shares are traded) have lost some of their market share (Figure 1.15). Following a period of lower profitability for pure chemical producers, integrated oil and gas petrochemical companies are moving back into chemicals and

Box 1.1 **Women in leadership positions in the chemical industry**

In 2017 *Chemical and Engineering* News undertook a survey to explore gender diversity in chemical companies. While it was noted that the situation is “far from […] equal representation of women and men in leadership roles”, the survey found significant progress in recent years. In particular, the share of women in board of director positions reached a record high at some 19 per cent. Among executive officers, women accounted for 17 per cent, significantly up from around 10 per cent in the years 2010-2012. 2017 was also a record year for women in leadership positions at chemical companies (Tullo 2017b).

Figure 1.15 World chemical industry structure evolution, share of revenue, 2000-2017 (adapted from Cayuela and Hagan 2019)



materials, spurred by lower oil and gas prices, reduced refining margins and a positive growth outlook for chemical demand. New direct crude-oil-to-chemical-product processes have begun to be pursued, challenging the traditional upstream-refining-petrochemical-materials model (Cayuela and Hagan 2019).

A period of corporate restructuring, mergers and acquisitions

Current market instability, increasing competition and greater manufactured product recycling (which reduces demand for virgin materials) are reducing the growth rates of many multinational chemical producers. The industry has responded with a period of restructuring and consolidation during the past decade. To achieve greater focus, companies have sought mergers and acquisitions (M&A) to realize higher efficiencies through vertical integration (e.g. through the production of a basic chemical as well as downstream chemicals) and tighter internal integration. Their aggregate value has reached unprecedented levels, with a handful of very large deals (e.g. Linde-Praxair, Dow-DuPont, Monsanto-Bayer and Syngenta-ChemChina) taking the value of M&A in 2016 to the record level of US dollars 260 billion (Sarathy *et al.* 2017; Deloitte 2018; Gryzwa *et al.* 2018) (Figure 1.16). However, following a string of highly publicized megadeals the number of mergers and acquisitions appears to be returning to historic levels (Deloitte 2018).

Significant M&A activity can be observed in the commodities, fertilizers and pesticides

Figure 1.16 Number and value of corporate acquisitions in the chemical industry, 2008-2017 (US dollars billion) (Gryzwa *et al.* 2018)

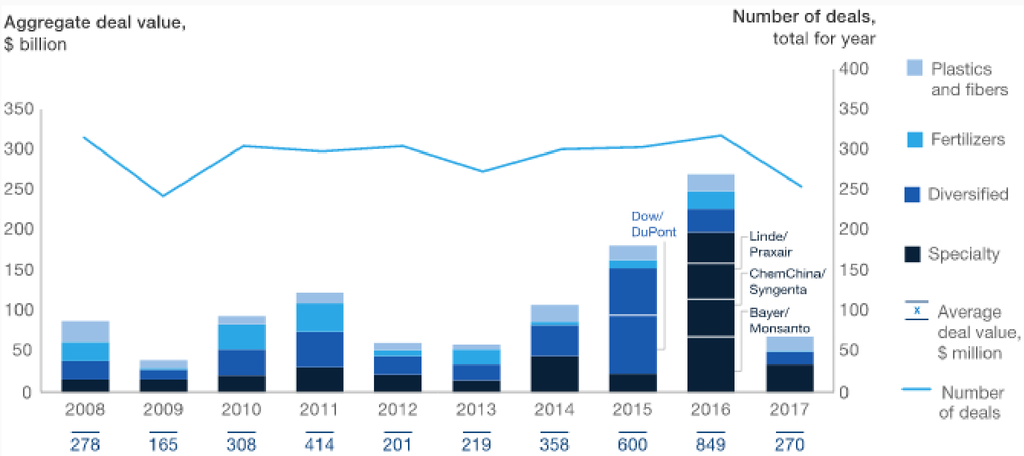
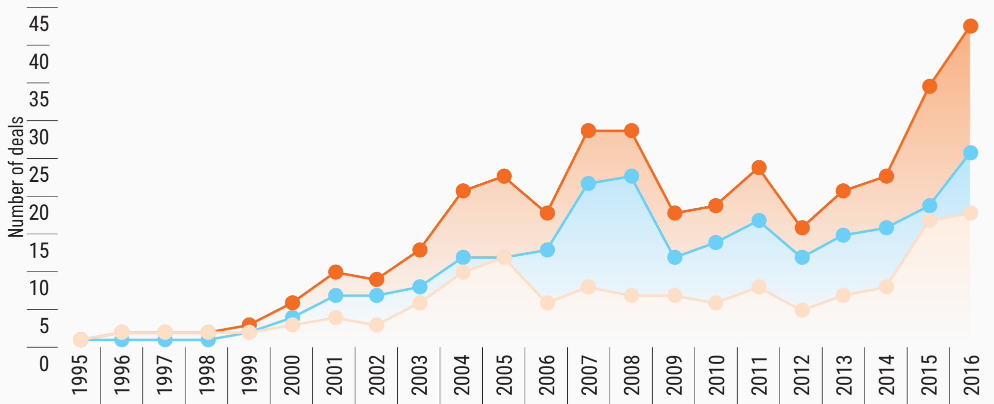


Figure 1.17 Number of completed mergers and acquisitions in the pharmaceutical industry, 1995-2016 (adapted from Gagnon and Volesky 2017, p. 4)



	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Global	0	1	1	1	2	5	9	8	12	20	22	17	28	28	17	18	23	15	20	22	34	42
US	0	1	1	1	1	2	3	2	5	9	11	5	7	6	6	5	7	4	6	7	16	17
Excluding US	0	0	0	0	1	3	6	6	7	11	11	12	21	22	11	13	16	11	14	15	18	25

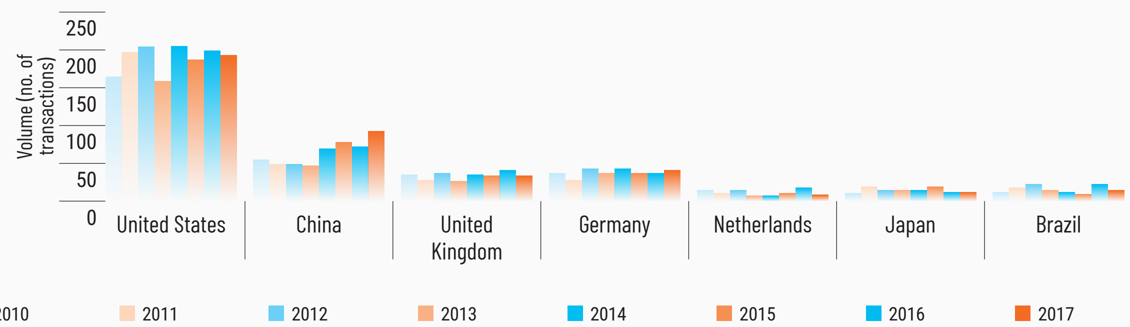
markets (Deloitte 2018). However, mergers and acquisitions have increased most rapidly in the pharmaceutical industry, especially in the United States. Globally, in 1995 there were no deals, in 2014 there were 22 worth US dollars 1.86 billion, in 2015 there were 34 totalling US dollars 33.56 billion, and in 2016 there were 42 worth more than US dollars 44 billion (Gagnon and Volesky 2017) (Figure 1.17).

A small number of countries account for most mergers and acquisitions

Between 2010 and 2017 the United States was by far the largest target market in terms of volume of transactions, followed by China, which experienced significant growth in the number of mergers and acquisitions between 2013 and 2017 (Figure 1.18). State-owned enterprises in emerging markets have played a strong role in M&A in recent years, with significant implications for the industry given their emphasis on low-cost production (Deloitte 2018).

Cost considerations also offer a strong motivation for SMEs to merge with competitors. In China this trend can be observed as a consequence of higher costs associated with increasing regulatory requirements. At the same time, mergers and acquisitions by Chinese companies have decreased in recent years because of capital outflow restrictions. Drivers may be different

Figure 1.18 Global chemical mergers and acquisitions activity by target market, 2010-2017 (adapted from Deloitte 2018, p. 11)



Box 1.2 The benefits of thorough due diligence during mergers and acquisitions

Companies engage in mergers and acquisitions because they offer significant benefits such as improving the company's portfolio, increasing production scale and lowering costs. However, a number of risks may manifest themselves and the company's competitiveness may be damaged, with problems ranging from lower than expected economic performance to the costs of litigation and lawsuits. Various risks are of particular concern in the chemical industry due to potential product liabilities (Deloitte 2016). Companies undertaking mergers and acquisitions in the chemical value chain therefore stand to benefit from thorough due diligence that takes into account environmental and human health factors. A comprehensive due diligence helps to identify potential risks and to internalize potential costs associated with liabilities in the price of the acquisition.

Recent cases illustrate the risk of potential financial liabilities associated with mergers and acquisitions. For example, multinational companies recently experienced heavy losses in stock values in the range of billions of US dollars, or had to pay significant compensation, following allegations of lack of diligence or unsound management practices (Bellon 2018; LaVito 2018). In another case, more than 10 years after the acquisition of a humidifier manufacturer in the Republic of Korea by a British company, authorities fined the company for having sold humidifier sterilizer products linked to local cases of lung disease including some 100 deaths, although the product was launched years prior to the acquisition. Fines were imposed, a former executive received a prison sentence, a multi-million US dollar fund was established, and the company publicly apologized (Niemiec 2016; British Broadcasting Corporation 2017).

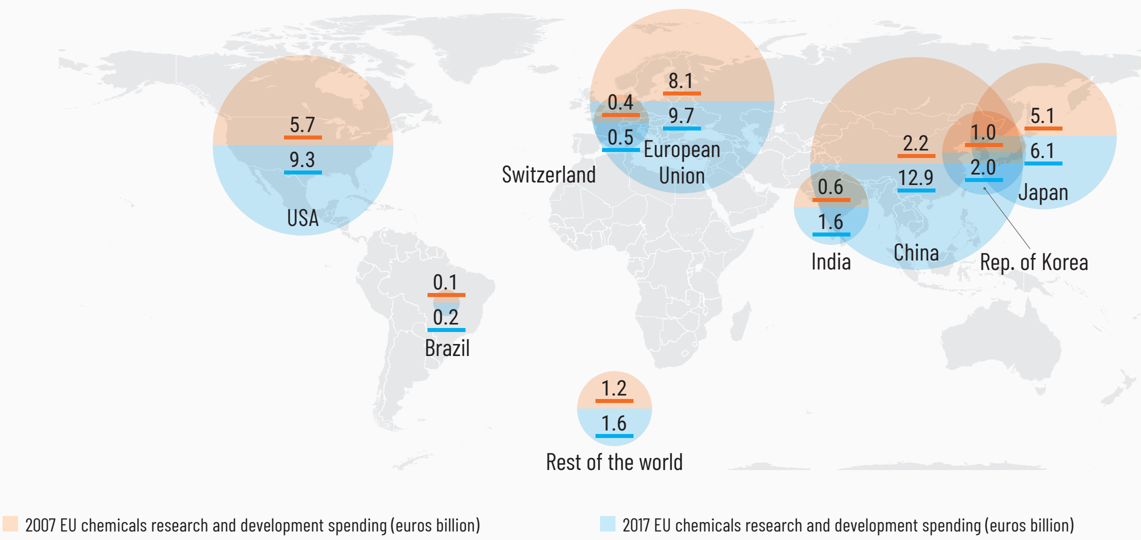
in other countries. For example, portfolio optimization (e.g. a focus on specialty chemicals) has been a key factor in M&A of German companies (Deloitte 2018). As companies acquire assets, particularly when these assets are located in other countries with different regulations, due diligence plays an important role in maximizing opportunities and minimizing the risks of liabilities (Box 1.2).

1.5 Research and development trends in the chemical industry

The industry is investing in R&D, especially in China

The chemical industry continues to invest in potentially high-value areas of research and development (R&D), including nanotechnology,

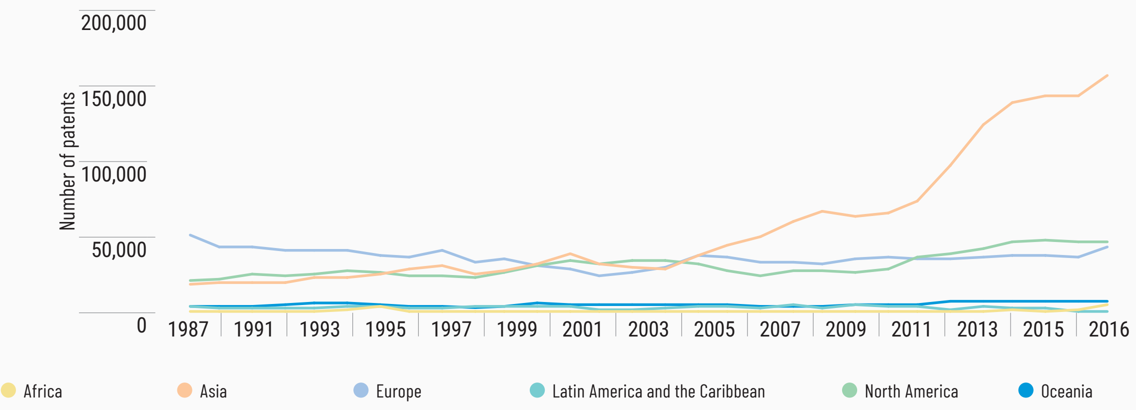
Figure 1.19 Corporate research and development spending globally, 2007 and 2017 (EUR billion) (adapted from Cefic 2018, p. 66)



high-density resins, conductive polymers, organometallics, hydrogels, conversion technologies and biochemistry. In 2017 the global industry spent euros 39.4 billion on R&D. R&D spending by China's chemical industry has exceeded that of all other countries. Between 2007 and 2017 the European industry's spending on R&D grew by 4.6 per cent (Figure 1.19) and that by the industry in the United States by 2.6 per cent, while the Chinese industry's R&D spending grew by 18.8 per cent. During this period R&D spending by the Indian chemical industry grew by 7.8 per cent and that by the industry in Brazil by 4 per cent (Cefic 2018).

The significant growth of spending on R&D in Asia is consistent with the number of patents filed. Data available from the World Intellectual Property Organization (WIPO) show a rapid increase in the number of chemistry-related patents in Asia between 2003 and 2016 compared with other regions (WIPO 2018) (Figure 1.20).

Figure 1.20 Number of chemistry-related patents granted by region, 1987-2016 (based on WIPO 2018)



2/ Trends in production and sales of specific chemicals

Chapter Highlights

The chemical industry spans several market segments, of which basic organic and inorganic chemicals represent the largest share by volume and continue to grow.

Production of some phased-out legacy chemicals of concern has declined significantly.

Production of fertilizers and pesticides, pharmaceuticals, perfluorinated chemicals, flame retardants, nanomaterials, and other groups of chemicals is increasing in many regions.

The market for most heavy metals (including lead and mercury) is stable or increasing, despite regulatory action taken in many countries and at the international level.

Production of plastics, including primary microplastics, is increasing rapidly.

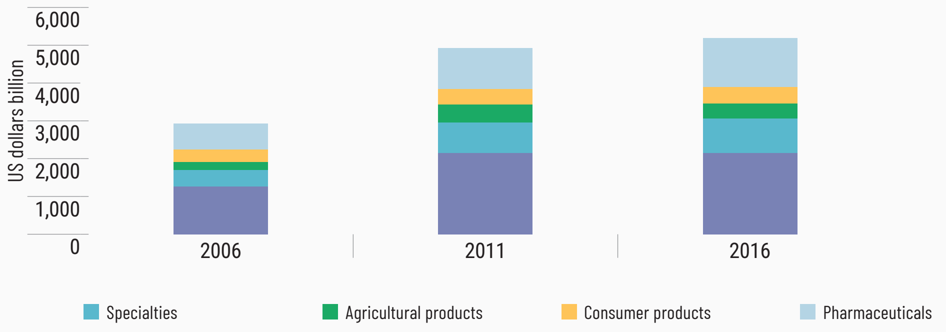
The previous chapter presented an overview of the chemical industry. This chapter focuses on trends in production and sales of specific chemicals or groups of chemicals, many of which are of concern because of their impacts on human health and the environment. Groups of chemicals can be classified in a number of ways. This chapter is structured around basic chemicals, agricultural chemicals, pharmaceuticals, specialty chemicals, metals, manufactured fibres, and plastics. Since the first *Global Chemicals Outlook* was published in 2013 the scale of production of some chemicals has remained steady while that of others has changed appreciably, along with the rates of growth and regional profiles of their markets.

2.1 Market segments in the chemical industry value chain

The chemical industry spans several market segments

The chemical industry can be divided into five market segments: basic chemicals, specialty chemicals, agricultural chemicals, pharmaceuticals, and consumer products. Basic organic and inorganic chemicals (also called “commodity chemicals”) are produced in large quantities. They are the foundation feedstock for a wide range of downstream chemicals. Basic organic chemicals include methanol; olefins such as ethylene and propylene; and aromatics such as xylenes, benzene and toluene. Inorganic chemicals include acids and bases; salts; industrial gases; and elements such as the halogens. These chemicals are the feedstocks and intermediaries used to make thousands of specialty chemicals such as solvents; coatings; surfactants and electronic chemicals; agricultural

Figure 2.1 Global chemical shipments by segment in 2006, 2011 and 2016 (US dollars billion) (adapted from ACC 2017a, p. 31)



chemicals, including pesticides and fertilizers; and the wide array of consumer products sold around the world.

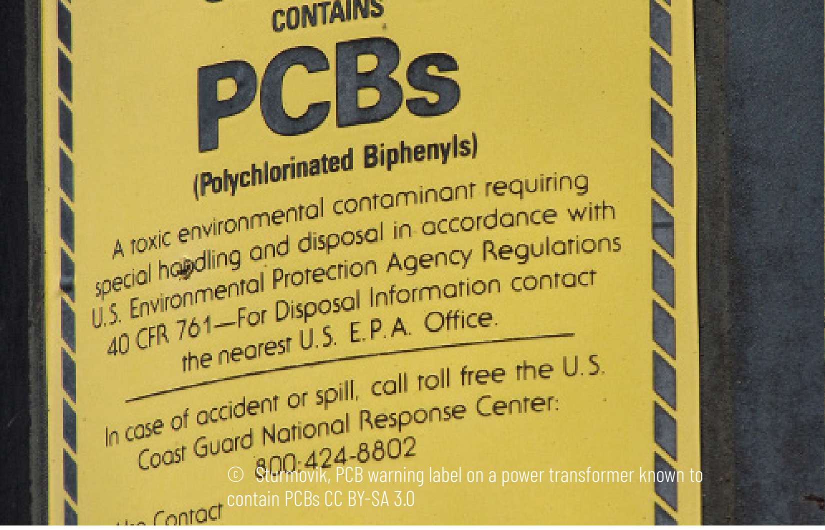
Recent growth varies by market segment

The ACC provides information on trends in the value of global chemical shipments by market segment. In both 2016 and 2017 pharmaceuticals accounted for 25 per cent of the value of global chemical shipments, while basic petrochemicals and intermediates accounted for about 17 per cent (Table 2.1). Plastic resins made up roughly 13 per cent, and agricultural and consumer products about 8 per cent. The smallest categories were adhesives and sealants and manufactured rubber (1 per cent each) (ACC 2018).

There was a rapid increase in global chemical shipments between 2006 and 2011, followed by slower growth between 2011 and 2016

Table 2.1 Total global chemical shipments, 2016 and 2017 (US dollars billion) (ACC 2018)

	2016	2017
Total chemicals	5,198	5,681
Pharmaceuticals	1,304	1,431
Chemicals, excluding pharmaceuticals	3,893	4,250
Basic chemicals	2,150	2,394
Agricultural chemicals	421	425
Specialty chemicals	897	967
Consumer products	425	465
Basic chemicals		
Inorganic chemicals	386	422
Bulk petrochemicals & intermediates	846	943
Plastic resins	651	744
Synthetic rubber	50	52
Manufactured fibres	216	232
Specialty chemicals		
Adhesives and sealants	69	76
Coatings	197	214
Other specialties	631	677



© Sturmovik, PCB warning label on a power transformer known to contain PCBs CC BY-SA 3.0

© Cjp24, Power transformer originally filled with PCB decontaminated and refilled with mineral oil CC BY-SA 4.0

(Figure 2.1). In the decade 2006-2011 shipments of basic chemicals and pharmaceuticals increased more rapidly than those of chemicals in other segments.

Production of legacy chemicals – the examples of PCBs and DDT

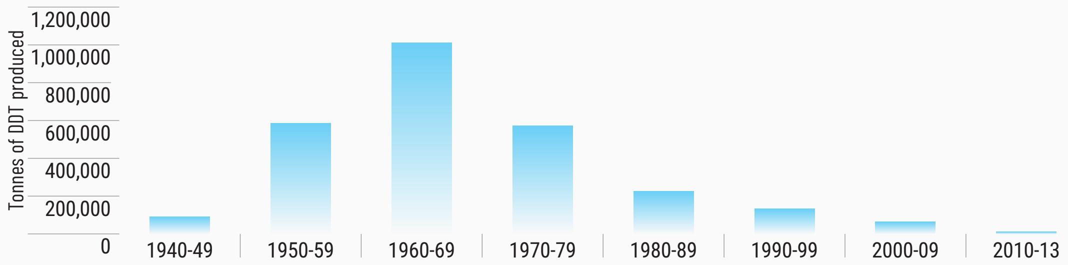
Due, among other reasons, to international action taken, the production and use of some hazardous chemicals has been successfully reduced or phased out. However, ensuring environmentally sound waste management of these chemicals still poses significant challenges. Polychlorinated biphenyls (PCBs), production of which is prohibited for Parties to the Stockholm Convention, are classified by the International Agency for Research on Cancer as Class 1 carcinogenic to humans. A total of around 1 to 1.5 million tonnes of technical grade PCBs have been produced (Table 2.2). Production stated in 1929/1930 and was progressively phased out during the second half of the century. However, one country US dollars was reported to still be producing PCBs as of 2016 (United Nations Environment Programme [UNEP] 2015; UNEP 2016a).

In the case of dichlorodiphenyltrichloroethane (DDT), another one of the original 12 persistent organic pollutants (POPs) covered by the Stockholm Convention, production and use

Table 2.2 Overview of estimated total production of PCBs (UNEP 2016a, p. 11)

Country	Start of production	End of production	Quantity (1,000 tonnes)	
	Earliest estimate	Latest estimate	Lowest estimate	Highest estimate
Korea (DPR)	1960s	>2006	25	30
Soviet Union/Russia	1938	1993	180	180
Spain	1930	1986	25	29
Czechoslovakia	1959	1984	21	21
West Germany	1930	1983	59	300
Italy	1958	1983	24	31
France	1930	1984	102	135
Poland	1966	1977	2	2
United States	1929	1977	476	648
China	1960	1983	7	10
Japan	1952	1972	59	59
UK	1951	1977	66	67
Total			**1,046**	**1,512**

Figure 2.2 Production of DDT by decade since 1940 (adapted from UNEP 2015, p. 44)



has been significantly reduced. DDT production increased rapidly from the 1940s and reached its peak in the 1960s, with total production exceeding 1 million tonnes annually (Figure 2.2). Thereafter, production quickly and steadily decreased. During the first decade of the new millennium only three countries continued producing DDT. As of 2017, India was the only known remaining producer (UNEP 2015; UNEP 2016a). Both these examples demonstrate the important role of multilateral treaties in stimulating reductions in the production and use of chemicals of concern as well as promoting research and development of alternatives (see also Part II, Ch. 3 and Part III, Ch. 5).

2.2 Basic chemicals

The basic chemicals market continues to expand

Basic organic and inorganic chemicals represent the largest share of global chemical production and consumption by volume (roughly two-thirds of the industry total). The manufacture of basic chemicals is characterized by high capital costs, large-scale production and high energy consumption. Production of basic chemicals is considered a mature industry: the fundamental products, processes and production technologies have changed little during the past 50 years.

The global inorganic chemicals market is highly concentrated. There are a few very large multi-product producers. Nitrogen compounds make up the largest share of the market. However, soda ash and caustic soda sales are growing rapidly as demand for glass and paper products increases. Rising demand for food and cosmetic products is also driving the inorganic chemicals market. The global inorganic chemicals market totalled US dollars 277 billion in 2017. It is estimated that this market will reach US dollars 362 billion by 2022, increasing at a CAGR of 5.5 per cent (BCC Research 2018).

The global organic chemicals market is largely composed of petrochemicals (chemicals derived from fossil fuels). More than 90 per cent of all organic chemistry products are derived from seven petrochemicals: benzene, toluene and xylene (aromatics); ethylene, propylene and butadiene (olefins); and methanol. (ACC 2017b). Globally, shipments of petrochemicals and their derivatives (e.g. organic intermediates, plastic resins and synthetic fibres) account for the largest share of shipments of basic chemicals. The highest global production capacity for petrochemicals includes ethylene, propylene

Table 2.3 Global production capacity for petrochemicals, 2016 (Smith, Glauser and Eramo 2017)

Chemical	Percentage of global market
Ethylene	27.9%
Propylene	20.3%
Methanol	19.6%
Xylenes	12.6%
Benzene	10.6%
Toluene	6.6%
Butadiene	2.5%

Table 2.4 Evolution of global production capacity for primary petrochemical building blocks (kg per capita) (Cayuela and Hagan 2019)

	World population (billion)	High-value chemicals						Average high-value chemicals
		Olefins			Aromatics			
		Ethylene	Propylene	Butadiene	Benzene	Toukene	Xylenes	
1990	5.3	11.9	7.1	1.5	5.8	3.1	4.1	33.5
2000	6.1	16.0	10.8	1.5	7.1	3.7	6.2	45.4
2010	6.9	21.1	15.0	1.8	8.3	4.9	8.7	59.9
2017	7.4	23.0	18.2	2.0	8.5	5.4	10.2	67.3
Estimated growth by 2030 (business as usual scenario)	8.5	26.2	19.4	2.2	8.7	7.1	16.4	79.9
CAGR	1.2%	2.0%	2.5%	1.0%	1.0%	2.1%	3.5%	2.2%

and methanol, followed by xylenes, benzene and toluene (Smith, Glauser and Eramo 2017) (Table 2.3).

The petrochemical industry has been robust since the start of the century, buoyed by high demand in the emerging economies and low-cost gas feedstocks. The global market for petrochemicals is expected to grow at a CAGR of around 8.8 per cent to reach US dollars 975 billion by 2025. Factors influencing this growth include increasing demand for propylene products, favourable regulatory policies in emerging economies, and increasing use of coal and shale gas as major feedstocks for petrochemicals production (Cision 2017). The global production capacity for primary petrochemical building blocks has been growing faster than the world population (Table 2.4), pointing to increased future per capita chemicals consumption. For example, the production capacity for xylenes, which was 4.1 kg per capita in 1990, is projected to reach 16.4 kg per capita by 2030 (Cayuela and Hagan 2019).

2.3 Agricultural chemicals

Markets are growing to keep pace with demand for food and fibre

The global market for agricultural chemicals is driven by continuing world population growth and rising living standards, which require an increasing and diverse food supply. The global market for agricultural chemicals was US dollars 215.18 billion in 2016 and is projected to reach US dollars 308.92 billion by 2025 (ACC 2017b).

2.3.1 Fertilizers

The market for agricultural chemicals is dominated by fertilizers

Fertilizers make up the largest share of agricultural chemicals by volume. The Food and Agriculture Organization of the United Nations (FAO) has estimated that global consumption of the three fertilizer nutrients nitrogen (N), phosphorous (expressed as phosphate (P_2O_5)) and potassium (expressed as potash (K_2O)) reached 186.67 million tonnes in 2016, an increase of 1.6 per cent compared with 2015. The FAO further forecast that demand for N, P_2O_5 and K_2O will grow by 1.5, 2.2 and 2.4 per cent annually until 2020. Global capacity for producing fertilizers, intermediates and raw materials was also expected to increase during this period (FAO 2017). The International Fertilizer Association (IFA) has estimated that between 2018 and 2022 the industry will invest close to US dollars 98 billion in more than 60 new fertilizer production units, adding 78 million tonnes of production capacity (IFA 2018). The largest share of fertilizer consumption occurs in Asia, where the fertilizer market has been growing most rapidly (Mateo-Sagasta, Zadeh and Turral 2017).

2.3.2 Pesticides

Continued growth in the pesticide/crop protection industry

Pesticides include herbicides, insecticides, termiticides, nematicides, rodenticides and fungicides. These products are largely used for crop protection in agriculture. While biocides (including bactericides, preservatives and disinfectants) are included in this economic segment, they are largely used in manufacturing, medical facilities, commercial facilities, schools and residences. In 1960 the global crop protection industry was worth less than US dollars 10 billion and around 100 active ingredients were available to farmers. Today the industry is valued at over US dollars 50 billion and there are around 600 active ingredients. Herbicides account for approximately 80 per cent of all pesticide use (Phillips McDougal 2018).

Asia has been the largest producer of pesticides in the past decade, with the largest manufacturing capacity in China. Pesticide production in Europe and the United States has remained fairly stable, while growth in Latin America has been increasing steadily (Table 2.5).

While pesticide production has grown steadily in volume, the value of global trade has grown even more rapidly, particularly since 2002 (Mateo-Sagasta, Zadeh and Turral 2017) (Figure 2.3)

Over the past decades the insecticide market has shifted away from organochlorinated compounds to organophosphorus compounds and biopesticides (including microbials [bacteria, algae, protozoa viruses and fungi], pheromones and semiochemicals, macrobials/invertebrates such as insects and nematodes, and plant extracts/ botanicals). Table 2.6 shows the transition in pesticide sales in the United States between 1968 and 2016, noting changes due to government and international agreement regulations, product innovation and market pressures (Phillips McDougal 2018).

Around 300 biopesticide active substances and organisms are currently available, including products derived from fermentation, microbes and pheromones, and predatory insects (Phillips McDougal 2018). As the growth of low-pesticide organic and sustainable or agroecological agriculture increases globally, the market for conventional pesticides used in agriculture is expected to decline. Although the rate of new product approvals has fallen in recent years, investment remains high, with major companies investing 7-10 per cent of their sales annually (Phillips McDougal 2018). Major constraints on the development of new pesticides include high R&D costs and the extensive testing necessary to apply for government registrations (Elsevier 2017; European Federation of Pharmaceutical Industries and Associations [EFPIA] 2018; Phillips McDougal 2018; Transparency Market Research n.d.).

Table 2.5 Global manufacture of pesticide active ingredients by region, 2008-2016 (thousand kg) (Oliver 2018)

	2008	2010	2012	2014	2016
Asia	822,485	1,066,678	1,236,767	1,204,490	1,265,285
China	417,477	454,239	678,545	760,416	887,564
India	104,557	124,018	133,754	161,912	195,983
Latin America	410,366	419,694	475,955	549,150	645,412
North American Free Trade Agreement	410,751	502,257	523,957	576,254	547,625
United States	406,102	477,830	492,070	498,155	498,149
Europe	382,352	434,846	464,858	513,745	515,490
Total global	**1,979,402**	**2,342,879**	**2,577,086**	**2,665,617**	**2,837,770**

Figure 2.3 **Value of global pesticide trade, 1970-2016 (US dollars billion) (adapted and updated based on Mateo-Sagasta, Zadeh and Turral 2017, p. 10)**

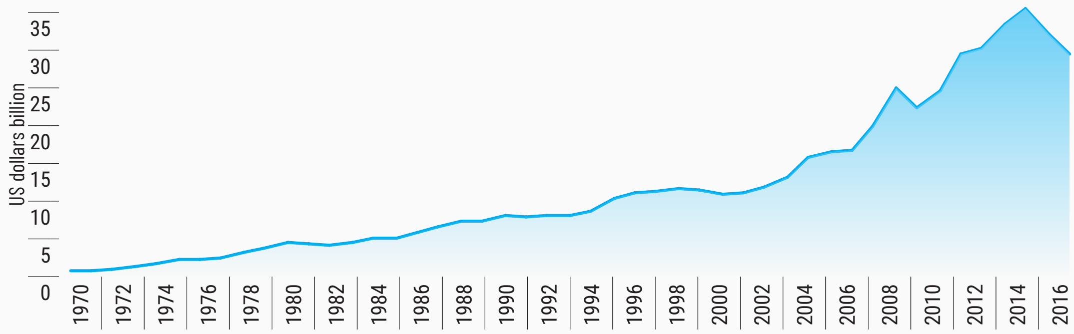
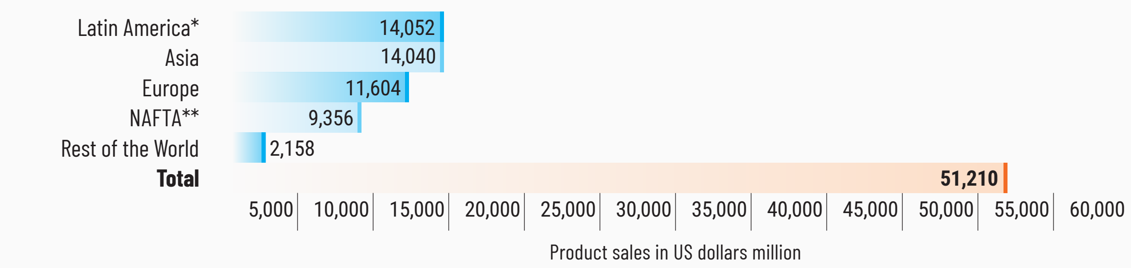


Table 2.6 **Top 10 products used on major crops in the United States by volume, 1968 and 2016 (Phillips McDougal 2018, p. 4)**

Top 10 products in 1968	Top 10 products in 2016
Atrazine	Glyphosate
Toxaphene - *banned*	Metolachlor
DDT - *banned**	Pyraclostrobin
2,4-D	Mesotrione
Methyl parathion - *banned*	Thiamethoxam
Aldrin - *banned*	Acetochlor
Trifluralin	Azoxystrobin
Propachlor	Atrazine
Dinoseb - *banned*	Abamectin
Chloramben - *banned*	Clothianidin

*DDT is banned globally as an agricultural and household pesticide, but is allowed for vector control in some countries when locally safe, effective and affordable alternatives are not available.

Figure 2.4 **Global and regional sales of crop protection products in 2015 (US dollars million) (based on Informa 2017, p. 40)**



* Excluding Mexico

** NAFTA - North American Free Trade Agreement

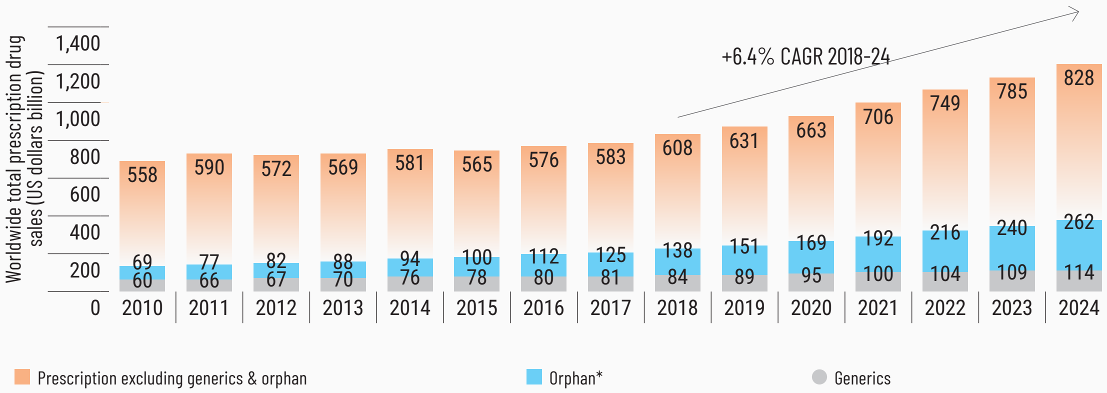
Historically the largest pesticide markets have been in North America and Europe; however, markets for crop protection products are currently growing faster in Asia and South America than in those regions (Informa 2017) (Figure 2.4). Between 2013 and 2014 the value of markets in South America increased by 13 per cent, while the value of those in Africa and the Middle East, Europe and the Asia-Pacific grew at lower rates and the value of markets in North America (Canada, the United States and Mexico) fell by more than 4 per cent. Important regional factors influencing these trends include a strong agricultural sector in South America, increasing food demand worldwide, and declining crop prices in Europe, North America and Asia (CropLife International 2015).

2.4 Pharmaceuticals

The production and sales of pharmaceuticals are growing rapidly

The global pharmaceutical market will reach nearly US dollars 1,485 billion by 2021, up from US dollars 1,105 billion in 2016 (International Federation of Pharmaceutical Manufacturers and Associations [IFPMA] 2017), equivalent to an annual growth rate exceeding 6 per cent. Global prescription drug sales are projected to grow quickly, at 6.4 per cent CAGR in 2010-2024 (Figure 2.5). Assuming a similar growth rate thereafter would see global sales almost double by 2030.

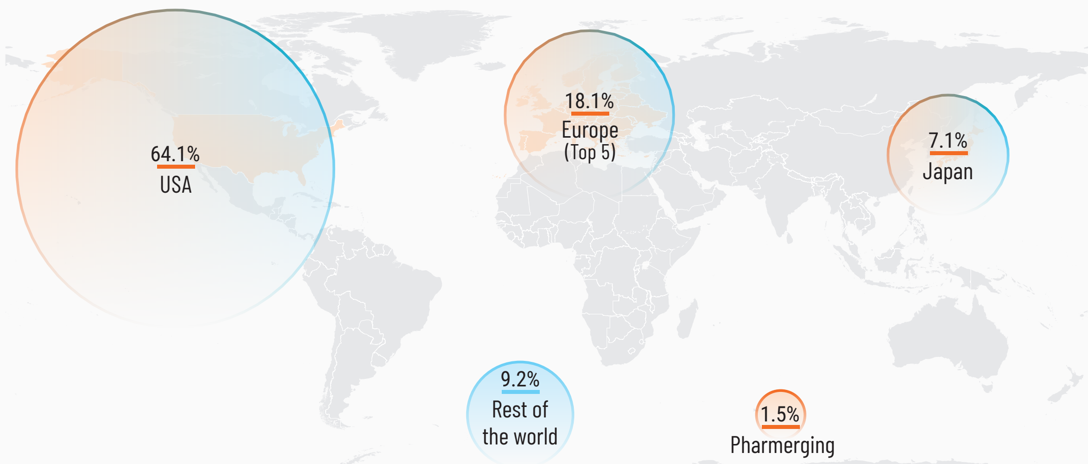
Figure 2.5 **Worldwide total prescription drug sales (US dollars billion) and growth rate (per cent), 2010-2024 (adapted from EvaluatePharma 2018, p. 8)**



* An orphan drug is a pharmaceutical agent developed to treat medical conditions which, because they are so rare, would not be profitable to produce without government assistance.

Emerging markets in Asia, Latin America, Russia, the Middle East and Africa are expected to stimulate new growth during the next decade owing to increasing demand (Gautam and Pan 2016). The term 'Pharmerging' markets has been introduced to refer to 21 countries ranked by IQVIA (formerly Quintiles and IMS Health, Inc.) as high-growth pharmaceutical markets, namely Algeria, Argentina, Bangladesh, Brazil, Colombia, Chile, China, Egypt, India, Indonesia, Kazakhstan, Mexico, Nigeria, Pakistan, the Philippines, Poland, Russia, Saudi Arabia, South Africa, Turkey and Viet Nam (EFPIA 2018). Another factor driving the growth in pharmaceuticals production and sales is increasing demand from an ageing population in developed countries (IFPMA 2017). Despite

Figure 2.6 **Geographical breakdown (by main markets) of sales of new medicines launched in the period 2012-2017 (adapted from EFPIA 2018, p. 4)**



The figure shows the share of sales of new medicines covering all new active ingredients marketed for the first time on the world market during the period 2012-2017, with Europe (Top 5) comprising Germany, France, Italy, Spain and the United Kingdom. While this figure suggests that innovation markets are still concentrated in the US and Europe, pharmaceutical markets in emerging economies, including the pharmerging countries, are projected to experience significant growth.

significant growth in the emerging economies, the pharmaceutical sector is still dominated by markets in North America and Europe, particularly in sales of medicines marketed for the first time on the world market in recent years (Figure 2.6). Most consumption occurs in the higher-income countries where most of the top 10 drug companies are located, although drug manufacture often occurs in emerging economies. The United States dominates the global market, in terms of both consumption and development, and is projected to hold around 41 per cent of the global market share in 2020 (IFPMA 2017). Between 2010 and 2016 total expenditure on pharmaceuticals in that country grew from approximately US dollars 316 billion to US dollars 450 billion. This represents about 64.7 per cent of global sales of new medications launched between 2010 and 2015 (McGovern 2018).

The pharmaceutical industry is highly innovative and competitive. It is heavily dependent on research and is subject to strong government regulation in higher-income countries. The industry has been shifting away from the development of primary care and small-molecule medicines, while progressively transitioning towards specialty medications and biologics targeted at high unmet patient needs (United States Food and Drug Administration 2018).

2.5 Specialty chemicals

2.5.1 Per- and polyfluorinated chemicals

The variety of per- and polyfluorinated chemicals is large and increasing

Per- and polyfluoroalkyl substances (PFASs) are used in firefighting foams and as coatings for textiles, paper, non-stick cookware and other products. Long-chain compounds (eight carbons), such as perfluorooctane sulphonate (PFOS) and perfluorooctanoic acid (PFOA), are used as inputs in the production of a range of fluoropolymers (OECD 2013). The OECD has identified some 4,700 PFASs-related compounds (OECD 2018a.). World

Table 2.7 Geographic distribution of fluoropolymer consumption in 2015 in tonnes (per cent share) (Zhang *et al.* 2016)

	PTFE	All fluoropolymers
United States	15	22
Western Europe	18	16
Japan	5	5
China	44	38
Rest of the world	17	19

consumption of all fluoropolymers in 2015 was 297,000 tonnes, with polytetrafluoroethylene (PTFE) accounting for more than half of all consumption. China was both the largest producer and largest consumer of PTFE in 2015 (Zhang *et al.* 2016) (Table 2.7). Overall, production of fluoropolymers is shifting from the United States, Europe and Japan to China, as it is an important producer of fluorspar, from which fluorine is derived (Zhang *et al.* 2016) (Table 2.7).

Production and use of PFOS and PFOA have been restricted in the EU (Janshekar *et al.* 2015) and in Canada since 2009 and 2016, respectively (Government of Canada 2019a; Government of Canada 2019b), and voluntarily phased out by manufacturers in the United States due to concerns about health and environmental effects. PFOS is currently listed as restricted under the Stockholm Convention, while PFOA has been proposed for listing (Secretariat of the Stockholm Convention 2008). Consequently, these chemicals are being replaced by shorter-chain (e.g. six- or four-carbon) perfluorinated compounds. However, these shorter-chain compounds are also highly persistent in the environment and present some of the same health and environmental concerns as their longer-chain counterparts (Brendel *et al.* 2018).

2.5.2 Flame retardants

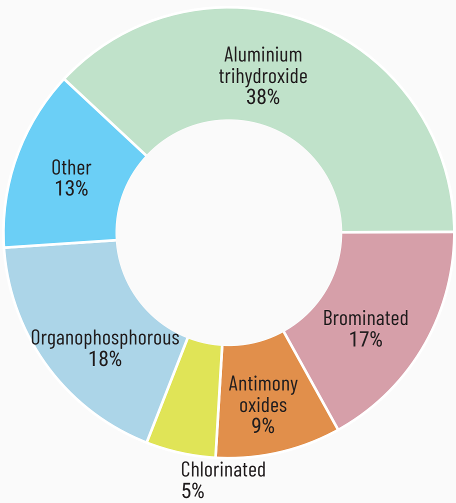
Production and use of certain flame retardants is increasing, but shifting due to regulatory action

Flame retardants are used to deter or extinguish flame propagation in many plastics, resins, textiles, elastomers, coatings, adhesives and sealants. There are around 80 types of brominated flame retardants with widely varying chemical properties. There are five brominated flame retardants that, historically, are the most widely used and about which there is considerable knowledge: pentabromodiphenyl ether, octabromodiphenyl ether, decabromodiphenyl ether, tetrabromobisphenol A and hexabromocyclododecane.

In 2017 worldwide consumption of flame retardants amounted to more than 2.25 million tonnes per year. Aluminium hydroxide is the largest selling flame retardant (38 per cent of the market). Halogenated flame retardant systems comprising brominated and chlorinated products, which are commonly used together with the synergist antimony trioxide, make up another 31 per cent. Organophosphorus and other flame retardants (e.g. inorganic phosphorus compounds, nitrogen- and zinc-based flame retardants) make up the remaining 31 per cent (IHS Markit 2017) (Figure 2.7).

Global consumption of flame retardants has been forecast to grow at an average annual rate in the lower 3 per cent range between 2016 and 2021. Government regulations and policies targeting some or (in some cases) all chemical flame retardants have slowed growth of consumption

Figure 2.7 **Global flame retardants market by chemistry, 2017 (adapted from IHS Markit 2017)**



(IHS Markit 2017; United States Environmental Protection Agency [US EPA] 2017a). The use of hexabromocyclododecane (HBCD), once one of the largest-volume products, is restricted under the Stockholm Convention and is no longer allowed in Japan and the EU. Because of such pressures there is an ongoing shift from most brominated compounds to organophosphorus, aluminium trihydroxidephosphorus compounds, or brominated co-polymers of styrene and 1,3 butadiene in insulating foams. China is the largest market for flame retardants; however, since restrictions have been placed on HBCD the market is shifting towards phosphorous compounds (IHS Markit 2017).

2.5.3 Nanomaterials

The nanomaterials market is expanding rapidly

Nanomaterials are materials with at least one dimension measuring between 1 to 100 nanometres. They can be made from various combinations of gold, copper, carbon, silver, iron, platinum and other elements, as well as clays and cellulose (Rothfeder 2017). According to one set of estimates, the global nanotechnology market could grow from US dollars 39.2 billion in 2016 to US dollars 90.5 billion by 2021 (a five-year CAGR of 18.2 per cent). This would include well-established commercial applications such as nanoparticle-based sunscreen products and nano-catalyst thin films for catalytic converters, as well as new technologies such as thin film solar cells, nanolithographic tools and nanoscale electronic memories. Nanoparticles and nanoscale thin films dominate the nanomaterials market (BCC Research 2017).

The largest end-use markets for nanotechnology in 2015 were environmental applications (38.8 per cent of the total market), electronics (22.4 per cent) and consumer applications (21.1 per cent) (BCC Research 2017). Nano silver, due to its antibacterial and antimicrobial properties, is among the most popular nanomaterials used in the manufacture of consumer products, with most uses in electronics, information technology, health care, textiles and personal care products. Titanium dioxide and silicon dioxide nanoparticles are also widely used (Inshakova and Inshakov 2017).

However, a range of scenarios and estimates exist regarding the future of the global nanomaterials market. Factors affecting its development include concerns about impacts on human health and the environment during product production, use and disposal, as well as evolving government regulations (US EPA 2017b; European Chemicals Agency [ECHA] 2018; OECD 2018b).

2.6 Metals

2.6.1 Lead

Global lead production has remained stable

Global lead production and use remained roughly constant between 2013 and 2017, although over half comes from secondary production as recycled lead (International Lead and Zinc Study Group [ILZSG] 2018). Mine production fell somewhat during this period, primarily due to declining mine production in China (Guberman 2017) (Table 2.8).

China is the largest producer of lead from mines, accounting for 52 per cent of global production in 2017. It is also the top producer of refined lead, estimated to have produced about 43 per cent of total global refined lead in 2015; the United States was second, accounting for an estimated 10 per cent (United States Geological Survey [USGS] 2018a). China was also the top lead consumer and the top producer of lead-acid batteries in 2015 (Guberman 2017).

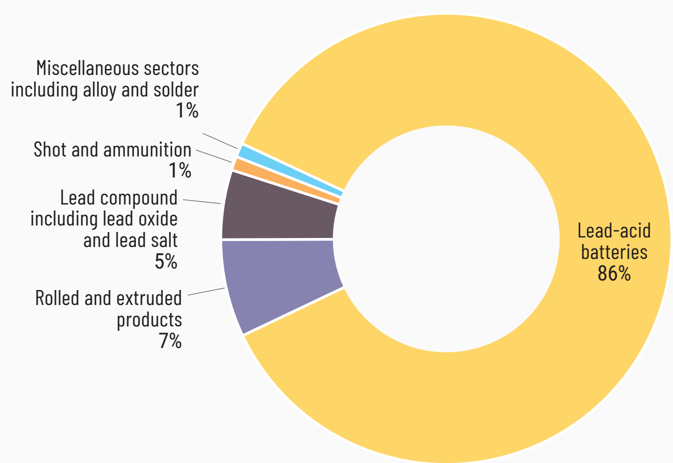
Table 2.8 Global refined lead production and usage (thousand tonnes), 2013-2018 (ILZSG 2018)

	2013	2014	2015	2016	2017
Mine lead production	5,089	4,946	4,850	4,679	4,703
Total lead production	11,225	11,023	10,959	11,158	11,445

The market for lead-acid batteries is projected to grow significantly in some regions

Globally, in 2018 about 86 per cent of lead was used in lead-acid batteries. Most of this lead came from battery recycling (ILZSG 2019) (Figure 2.8). Spent lead-acid batteries from vehicles are one of the world's most recycled consumer products. In the United States and Europe nearly 100 per cent of these batteries are recovered for recycling (International Lead Association 2018). In China the growing production of lead-acid batteries for use in automobiles, electronic bicycles and other applications is the key driver of the global market (Guberman 2017). The market for lead-acid batteries in Africa (where lead-acid battery recycling and the presence of these batteries as

Figure 2.8 Global lead consumption by product, 2018 (adapted from ILZSG 2019)



hazardous waste present risks to health and the environment) is expected to grow significantly, potentially increasing from around US dollars 709 million in 2014 to more than US dollars 1,000 million in 2021 (Transparency Market Research 2016).

Lead use in other applications is declining following regulatory action taken in many countries. For example, 71 countries have legally binding controls to limit the production, import and sale of lead paints (UNEP 2018). In addition, lead-free options are used increasingly for wire and cable jacketing; tin is replacing lead for solder in drinking water systems; and electronic products are increasingly manufactured without lead.

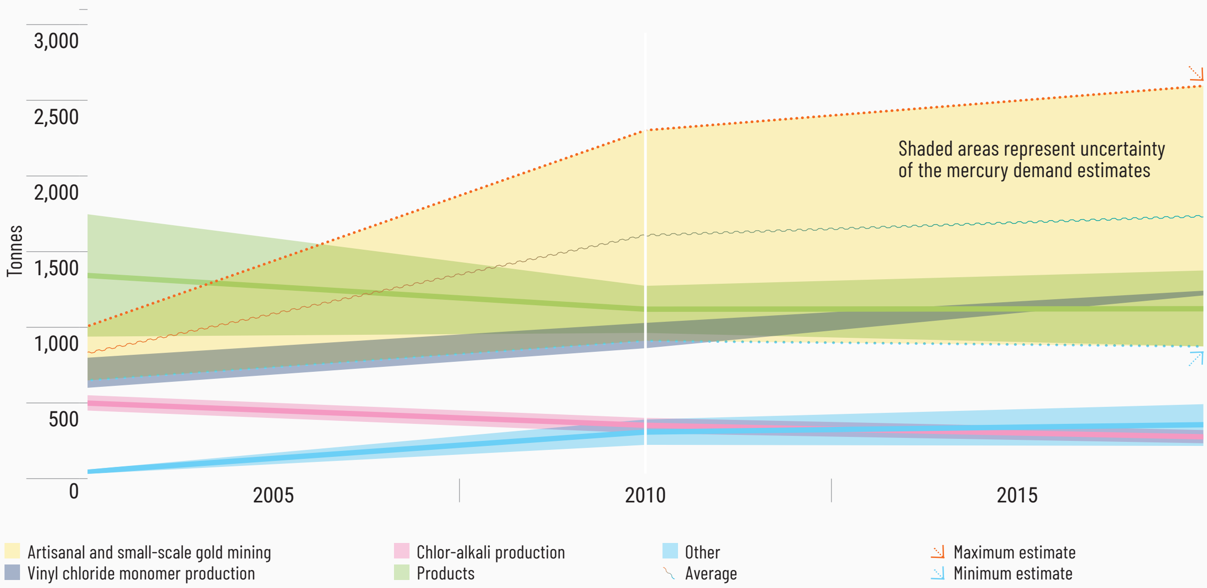
2.6.2 Mercury

Driven by continued growth in major applications, global mercury mining has increased rapidly

Mercury is used in a variety of applications, including (in order of magnitude as of 2015) artisanal and small-scale gold mining (ASGM), vinyl chloride monomer (VCM) production, measuring and control devices, chlor-alkali production, dental amalgams and batteries. ASGM and VCM production are responsible for over 60 per cent of global mercury demand. Between 2005 and 2015 worldwide mercury use increased overall. While consumption for some applications (including chlor-alkali production, batteries and electrical/electronic devices) has decreased, other applications have increased significantly, particularly VCM production and ASGM (Figure 2.9). By 2015 global mercury demand was in the range of 4,500 to 4,900 tonnes, over half of which in East and Southeast Asia (UNEP 2017).

The global mercury market is highly dynamic. One of the major changes in mercury supply since the 2013 *Global Chemicals Outlook* is the reduced supply of residual mercury from the chlor-alkali industry due to restrictions imposed by export bans. The former EU and United States trading hubs have given way to those in emerging economies. Recent shifts in mercury

Figure 2.9 Global mercury demand by sector, including uncertainties, 2005-2015 (tonnes) (adapted from UNEP 2017, p. 63)



Products refers to batteries, dental applications, measuring and control devices, lamps, electrical and electronic devices.

Other refers to paints, laboratory, pharmaceutical, cultural/traditional uses, etc.

Table 2.9 Global mercury supply, 2015 (tonnes) (UNEP 2017, p. 21)

Mercury source	Min. mercury supply (tonnes)	Max. mercury supply (tonnes)
Primary (mined) mercury	1,630	2,150
By-product mercury	440	775
Chlor-alkali residual mercury	370	450
Mercury recycling	1,040	1,410
Total supply	**3,480**	**4,785**

trade have also been accompanied by an increase in undocumented or illegal trade (UNEP 2017).

In 2015 global supply from various sources totalled between 3,480 and 4,785 tonnes (Table 2.9). As demand for mercury for ASGM and VCM production has increased, this demand has been met through increased primary mercury mining, including opening of new mercury mining sites in Mexico and Indonesia, most of which are informal (UNEP 2017). The only other countries mining mercury are China and the Kyrgyz Republic. China is by far the largest producer of mercury. In 2015 global primary mercury production, both formal and informal, was estimated to be in the range of 1,630-2,150 tonnes (UNEP 2017). In addition, a number of countries produce mercury as a by-product during the mining of non-ferrous ores and the extraction of oil and natural gas. The entry into force of the Minamata Convention on Mercury is expected to affect global mercury production and use significantly (see Part II, Ch. 1-3).

2.6.3 Cadmium

Production of cadmium is stable as demand shifts across applications

The largest use of cadmium is in nickel-cadmium (NiCd) batteries. Other end uses include pigments, polyvinyl chloride (PVC) stabilizers, anti-corrosive coatings, non-ferrous alloys and photovoltaic devices. Global cadmium production has remained approximately constant since 2012, somewhat above 20,000 tonnes per year excluding production in the United States, which is not reported (Table 2.10). However, the geographic distribution of production has changed significantly. Most of the world's primary production (e.g. mining) takes place in the Asia-Pacific region (59 per cent), followed by Europe and Central Eurasia with 22 per cent production, North America with 15 per cent and South America with 4 per cent. Secondary production (e.g. recycling of NiCd batteries) currently takes

© Zoï Environment Network, Primary mercury mine in Khaidarkan, Kyrgyzstan

Table 2.10 Cadmium: refinery production by country, 2012-2016 (tonnes) (Tolcin 2018, p. 16.8)

Country	2012	2013	2014	2015	2016
Argentina	37	28	30[e]	30[e]	30[e]
Australia	380	380	350	380	400
Brazil	200	200	200	200	200
Bulgaria	360	411	382	344	340[e]
Canada	1,290	1,310	1,190	1,160	2,310
China	7,270	7,500	8,200	8,200[e]	8,200[e]
Germany	400	400	400	400	400
India	396	285	107	200[e]	21
Japan	1,860	1,830	1,830	1,960	1,990
Kazakhstan	1,170	1,320	1,630	1,460	1,500[e]
Korea, Republic of	3,900	3,900	4,090	3,600	3,600
Mexico	1,480	1,450	1,410	1,280	1,190
Netherlands	560	610	640	640	630
Norway	310[e]	310	310	310	310[e]
Peru	684	695	769	757	820
Poland	370	460	628	383	400[e]
Russia	1,500[r]	1,200	1,200	1,200	1,300
United States	W	W	W	W	W
Uzbekistan	300	300	300	300	300
Total	**22,500**	**22,600**	**23,700**	**22,800**	**23,900**

e = estimated, p = preliminary, w = withheld to avoid disclosing proprietary data; not included in total

place in facilities in Asia, Europe and the United States (Tolcin 2018).

In the future it is likely that some factors will reduce cadmium demand while others will increase it. The amount of cadmium used in NiCd batteries is decreasing. However, use of cadmium telluride (CdTe), a principal component of lightweight, low-cost thin-film photovoltaic (PV) solar panels, will likely soar in years to come as more thin-film PV panels are produced globally (Fthenakis n.d.). Regulations, especially in the EU, are reducing or eliminating cadmium use in many applications (USGS 2016). Lithium-ion batteries have significantly replaced NiCd batteries in some low-cost electronic products. This trend is expected to continue as lithium-ion efficiency increases and manufacturing costs fall. Nevertheless, NiCd batteries continue to be used in industrial applications such as electric vehicles and hybrid power systems that generate electricity in remote locations. Regardless of cadmium demand, zinc smelting processes and NiCd battery retirement will continue to produce by-products containing cadmium, which may need to be managed as demand for cadmium continues to decline (Tolcin 2018).

2.6.4 Rare earth minerals

China dominates the market for rare earth minerals

Seventeen elements found within the Earth's crust are considered rare earth elements. The largest global use of these elements globally is in production of high-performance lightweight neodymium ion boron (NdFeB) and samarium cobalt (SmCo) permanent magnets, which are used in the growing markets for wind turbines and electric vehicles. Other end products include polishing powders, vehicle emissions control catalysts, rechargeable batteries, glass additives and phosphors (Wietlisbach and Gao 2016; Pavel *et al.* 2017).

China has been the dominant supplier and user of rare earths during the last 20 years (Table 2.11). In 2015 it produced 84 per cent and consumed 65 per cent of available global rare earths. China's influence on world production has fallen slightly since 2012 as a result of increased production in Australia and the United States. World consumption of rare earths peaked at 138,000 tonnes in 2007; it was estimated to be 121,000 tonnes in 2015. Global consumption is expected to increase by 2.4 per cent annually through 2020 (Dutta *et al.* 2016; Wietlisbach and Gao 2016).

2.7 Asbestos

Regulatory action has successfully reduced the demand for asbestos, but production continues

Increasing regulation at the national level has slowed the consumption and production of asbestos. In 1980 only three countries had asbestos bans, but the number has grown to 70 today (Kazan-Allen 2018). Estimated worldwide consumption of asbestos minerals fell from approximately 2 million tonnes in 2010 to nearly 1.4 million tonnes in 2016; asbestos cement products are expected to continue to be the leading global market for asbestos (USGS 2018a).

Notwithstanding, production of asbestos continues. As of 2016, the leading producers were Russia China, Kazakhstan and Brazil (Figure 2.10). Brazil accounted for roughly 10 per cent of global production and consumption in 2017; however, in that year the Brazilian Supreme Federal Court enacted a ban on the extraction, commercialization and use of asbestos (Kazan-Allen 2017). Pending further legal action, the only remaining commercial producers will be China, Kazakhstan, Russia and potentially Zimbabwe, where two former asbestos mines could possibly reopen (Guberman 2017).

2.8 Plastics

Plastics production is growing exponentially

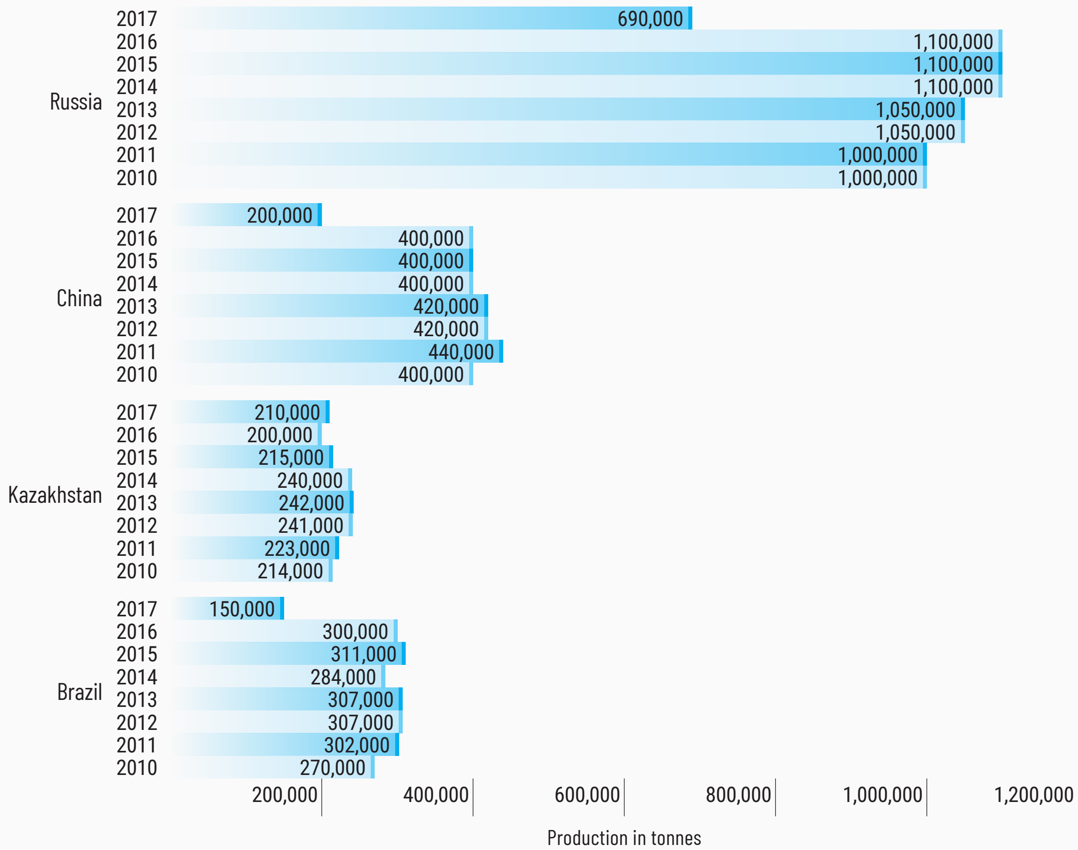
Plastics are polymers derived from fossil material (coal, natural gas, crude oil) and/or organic resources (cellulose, salt) and renewable compounds (grains, corn, potatoes, palm, sugar beet). During the manufacture and compounding of plastics other chemicals are used, including initiators, catalysts, solvents and a wide range of additives.

Global plastics production has increased exponentially since the 1950s (UNEP 2016b; Boucher 2017; Pravettoni 2018). While 1.5 million tonnes were produced in 1950 (Boucher 2017), in 2017 global production reached almost 350 million tonnes (Plastics Europe 2018). If

Table 2.11 World production of rare earth mineral concentrates (thousand tonnes) and total estimated increase (per cent), 1990-2015 (Wietlisbach and Gao 2016)

Year	Australia	China	US	Other	Total
1990	6.1	16.5	22.7	14.7	60.0
2000	0.0	73.0	5.0	7.0	85.0
2010	0.0	120.0	1.0	3.4	124.0
2015	10.0	105.0	4.2	6.7	125.9
Total estimated % increase 1990-2015	**63.9%**	**536.4%**	**-81.5%**	**-54.4%**	**109.8%**

Figure 2.10 **Asbestos mine production in the largest producer countries, 2010-2017 (tonnes) (based on USGS 2018b)**



current production and use trends continue unabated, annual global production is estimated to increase to about 2,000 million tonnes per year by 2050 (Pravettoni 2018) (Figure 2.11). Global production of plastic resins and fibres increased from 2 million tonnes in 1950 to 380 million tonnes in 2015, a CAGR of 8.4 per cent. About 7.8 billion tonnes of plastic resins and fibres were manufactured between 1950 and 2015. Half of this amount was produced in the past 13 years (Geyer, Jambeck and Law 2017).

Figure 2.11 **Global and regional plastics production, 1950-2050 (million tonnes) (adapted from Pravettoni 2018)**

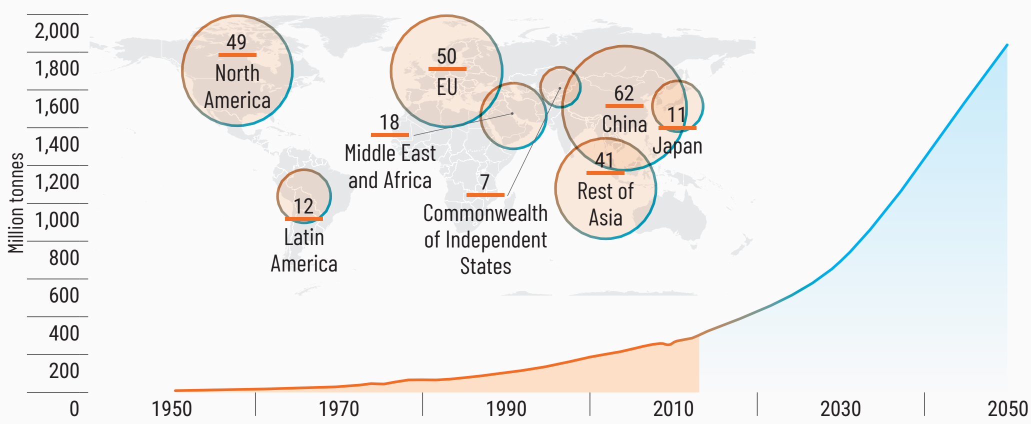
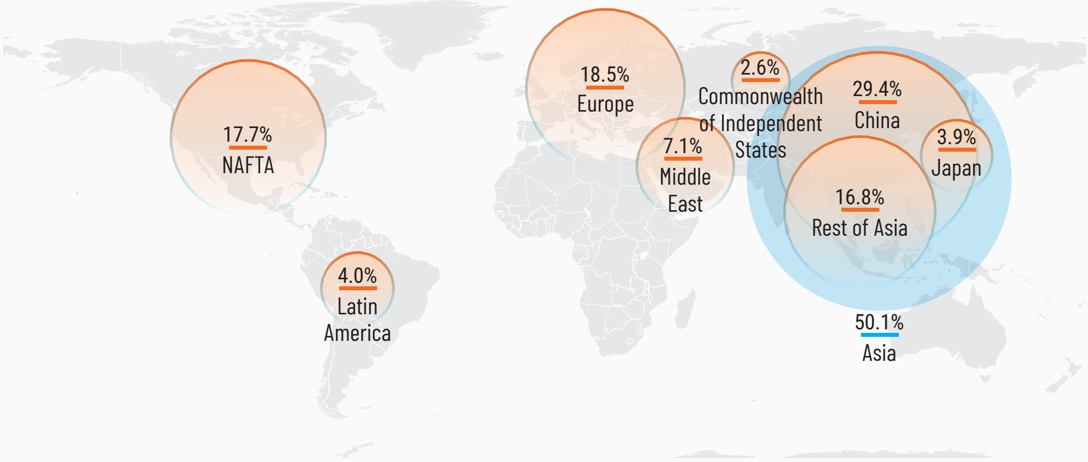


Figure 2.12 **Distribution of global plastics production, 2017 (per cent) (adapted from Plastics Europe 2018, p. 19)**



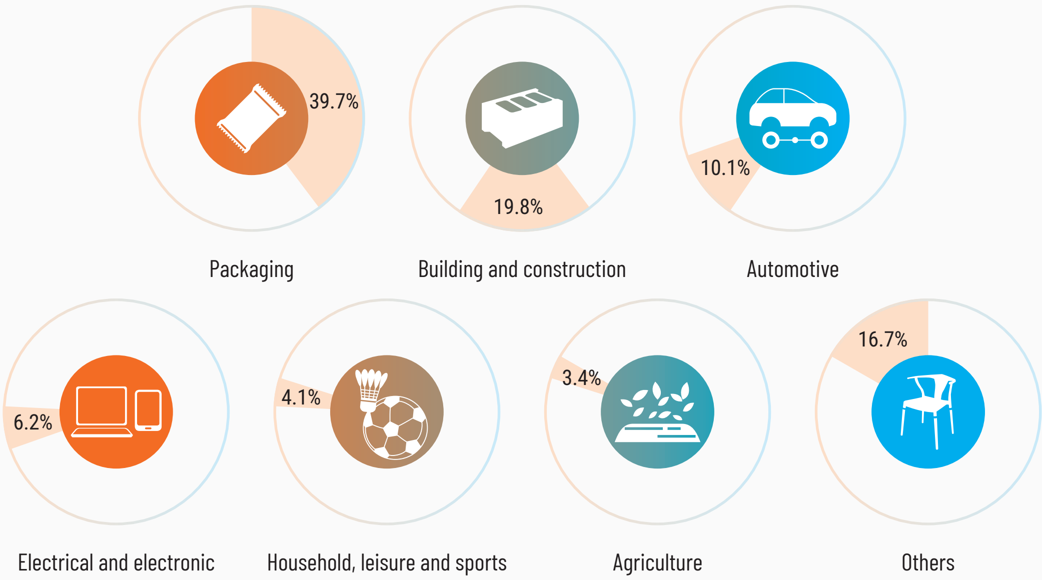
Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and polypropylene fibres. Polyethylene terephthalate, polyamide and polyacrylic fibres are not included.

About half the world production of plastics occurs in Asia (Figure 2.12). Europe and North America (including Mexico) account for some 19 and 18 per cent, respectively (Plastics Europe 2018). China accounts for 28 per cent of global polymer resin and 68 per cent of global polymer fibre production (Geyer, Jambeck and Law 2017).

Many types of plastic are produced. Thermosets such as polyesters, epoxies and polyurethanes make up a significant share of the plastics market, but the largest share of the market is dominated by four main classes of thermoplastics: polyethylene (PE) (73 million tonnes in 2010), polyethylene terephthalate (PET) (53 million tonnes), polypropylene (PP) (50 million tonnes) and polyvinyl chloride (PVC) (35 million tonnes) (UNEP 2016b).

Plastics are used in a variety of downstream sectors (Figure 2.13). Durable products, ranging from construction materials to medical devices, make up nearly half the global plastics market, but packaging is the largest single application for plastics. Growth in the plastic packaging market has been stimulated by a global shift from

Figure 2.13 Uses of plastic: main downstream sectors, 2017 (per cent) (adapted from Plastics Europe 2018, p. 24)



Others refers to medical equipment, plastic furniture and furniture equipment, technical parts used for mechanical engineering or machine-building, etc.

reusable to single-use containers, particularly in the prepared food, beverage and pharmaceuticals markets. Asia is the fastest growing region for plastic packaging currently and will be in the future, with the most rapid national growth taking place in China and India (Zion Research 2016).

There are strong vertical linkages between the oil and gas industry and plastic resin producers. At the feedstock level, plastic production is shifting from naphtha to low-cost natural gas. This means that ethylene, which had been conventionally produced with propylene as a co-product, can now be produced alone and firms reliant on propylene need to produce it separately. China, already the world's leading propylene producer, is building new production facilities to turn both oil and methanol (from coal) into propylene (Plotkin 2015).

Primary microplastics are used in a variety of products and processes

Global plastics production also includes microplastics, very small plastic particles intentionally added to products or used in manufacturing processes to carry out a range of specific functions (Galloway 2015) (Box 2.1). Primary microplastics include capsules used to blast clean surfaces, plastic powders used in moulding, pellets used in plastic manufacturing process, microfibres in textiles, and plastic nanoparticles used in a variety of industrial processes (Gibb *et al.* 2017). Microplastics are also used in personal care and cosmetic products and, more recently, 3-D printing (UNEP 2016b).

Production of bioplastics is growing, but remains a marginal share of the market

Bioplastics currently represent about 1 per cent of the about 335 million tonnes of plastic produced annually. However, global bioplastics production capacity is set to increase from around 2.11 million tonnes in 2018 to approximately 2.62 million tonnes in 2023 (Figure 2.14). Innovative biopolymers such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs) are the main drivers of this growth. Packaging is the largest field of application for bioplastics, at almost 65 per cent of the total bioplastics market (1.2 million tonnes) in 2018 (European Bioplastics and nova-Institute 2018).

Box 2.1 Microplastics

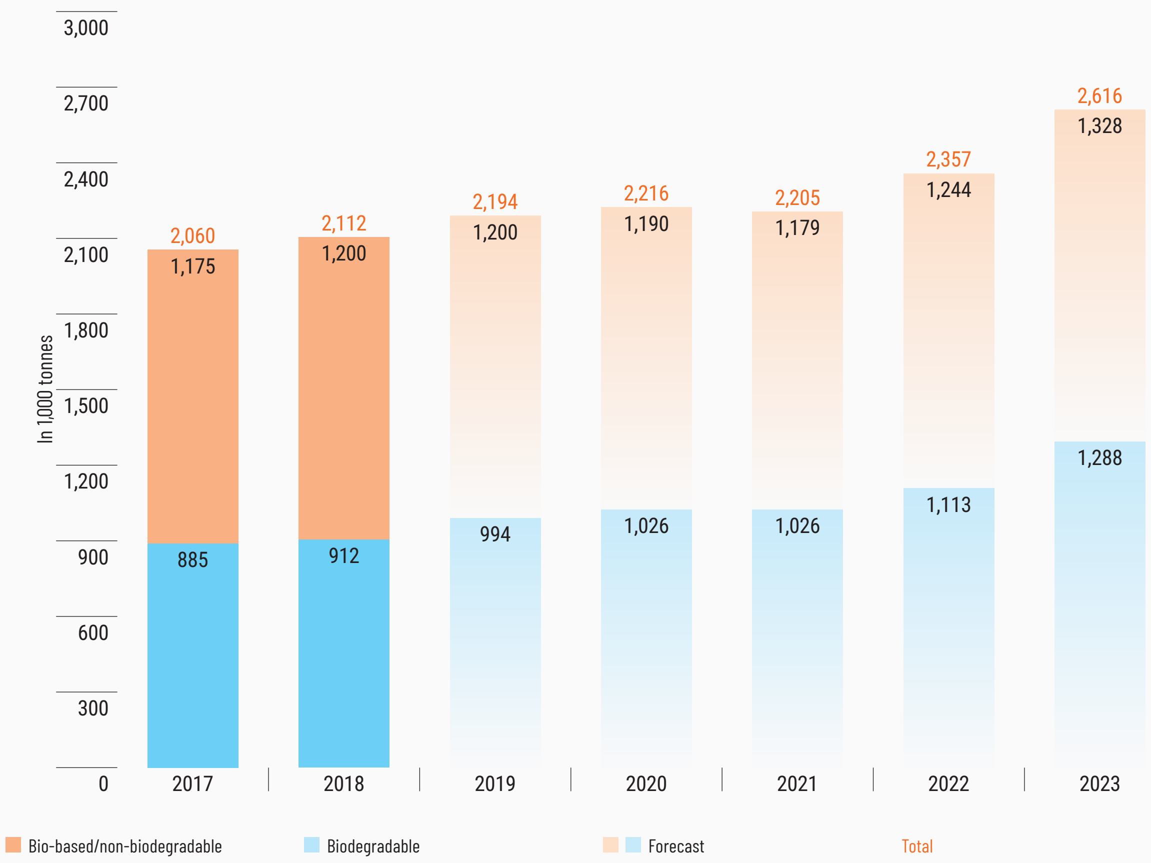
Microplastics are extremely small pieces of plastic. They are commonly considered to be micrometre-sized particles less than 5 millimetres (mm) in length (United States National Oceanic and Atmospheric Administration [US NOAA] 2018; Joint Group of Experts on Scientific Aspects of Marine Environmental Protection n.d.). This definition is used in some regulatory instruments (e.g. France, Ministry of Environment Energy and the Sea 2017).

There are two types of microplastics (Essel *et al.* 2015):

- *Primary microplastics* are directly manufactured as microscopic particles that are used in certain products and other applications.
- *Secondary microplastics* are fragments of macroscopic plastic materials which arise, for example, through the fragmentation of plastic bottles or the abrasion of tyres and textiles.

Microbeads are a type of primary microplastics that are intentionally added to cosmetics and personal care products (e.g. scrubs and toothpastes). Exfoliating agents, for example, may contain more than 10 per cent microbeads (Brande-Lavridsen n.d.).

Figure 2.14 Global bioplastics production capacity, 2017-2023 (thousand tonnes) (adapted from European Bioplastics and nova-Institute 2018, cover page)



3/ Megatrends and chemical-intensive industry sectors: risks and opportunities

Chapter Highlights

Megatrends such as global economic shifts, urbanization and climate change have significant and diverse implications for chemicals and waste.

Megatrends affect the patterns of chemical production and consumption and may enhance exposure and related impacts; they also influence the direction and pace of innovation.

Driven by megatrends, many chemical-intensive industry sectors are growing, fuelling demand for chemicals.

Growth in chemical-intensive downstream industry sectors may create risks, depending on which technologies and chemicals of concern are used.

Downstream industry sector growth also creates opportunities for innovation towards improved production processes and safer products.

The evolution of the chemical industry is heavily influenced by (and needs to be understood within the context of) megatrends such as population growth, urbanization, globalization, digitalization and climate change. The implications of these megatrends for the sound management of chemicals and waste are discussed in the first section of this chapter. The chapter then turns to trends in chemical-intensive industry sectors, which create both risks and opportunities. While megatrends and industry sector trends are often global in nature, they may play out with important differences across regions.

3.1 Megatrends

3.1.1 The chemicals and waste dimension of megatrends

Megatrends and their implications for chemicals and waste

The future of the chemical industry is being shaped by many internal and external factors. All these factors exist in the context of large, long-term transitions or megatrends. Megatrends, which affect the economy and societies globally, can be defined as “large-scale, high impact and often interdependent social, economic, political, environmental or technological changes” (EEA 2015). To identify the megatrends influencing global development and innovation, particularly in relation to the chemical industry, 11 studies were assessed and synthesized for six key megatrends, shown in Table 3.1. These megatrends and their implications for chemicals and waste are examined in greater detail below. Other megatrends referred to in the literature

Table 3.1 **Matrix analysis of megatrend studies**

	Dugarova and Gülasan 2017	UN General Assembly 2017	National Intelligence Council 2017	KPMG 2014	EEA 2015	Ernst & Young 2016	Frost and Sullivan 2014	OECD 2016	Deloitte and VCI 2017	Valencia 2013	Global Manufacturing Industry Group 2010
Economic shifts	-	o	o	o	o	-	o	o	o	o	-
Technological change	o	o	o	o	o	-	-	-	o	-	o
Resource use, scarcity and competition	-	-	-	o	o	o	-	o	(o)	o	o
Demographic changes	o	-	-	o	o	-	-	o	o	o	-
Urbanization	-	-	-	o	o	o	o	-	-	o	o
Climate change, pollution	o	o	o	o	o	-	-	o	o	o	o

include health, disease and well-being; the labour market; interconnectivity; consumption patterns; and poverty and inequality.

The megatrends discussed below (and others not treated here in depth) have implications for the sound management of chemicals and waste. They affect patterns of production and consumption in the chemical industry and downstream sectors. They also influence the direction and pace of innovation with respect to new chemicals and chemical applications (Valencia 2013; Whitesides 2015). Rapidly accelerating innovation may exacerbate current trends and create yet new challenges for chemicals management. However, these challenges may also provide new solutions, both to address legacies and to develop greener and more sustainable chemistry (Valencia 2013; Whitesides 2015).

3.1.2 Demographic changes

Demographic changes include growth in the total world population, greater life expectancy, and ageing populations in most countries. In 2017 the global population was nearly 7.6 billion. It is expected to reach 8.6 billion in 2030 and almost 10 billion in 2050. Africa is projected to have the fastest growing population during the next decades, with millions of new consumers. By

Table 3.2 World population prospects, (millions) (UN DESA 2017, p. 1)

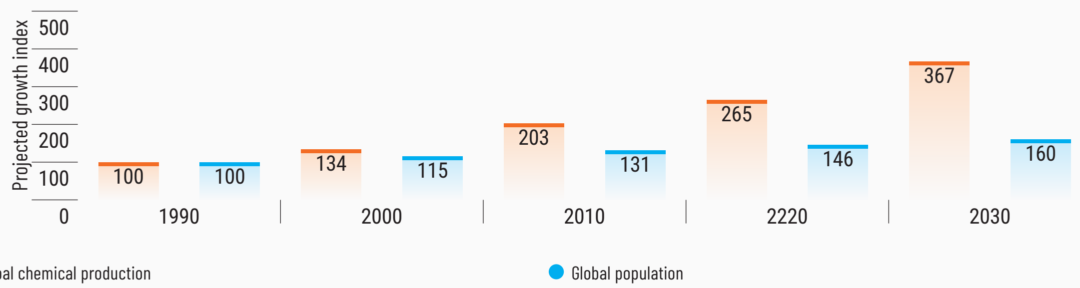
Region	Population in millions			
	2017	2030	2050	2100
World	7,550	8,551	9,772	11,184
Africa	1,256	1,704	2,528	4,468
Asia	4,504	4,947	5,257	4,780
Europe	742	739	716	653
Latin America and the Caribbean	646	718	780	712
Northern America	361	395	435	499
Oceania	41	48	57	72

2050 over one-quarter of the global population will live on the African continent (OECD 2016; United Nations Department of Economic and Social Affairs [UN DESA] 2017) (Table 3.2).

A growing population will drive demand for chemicals and chemical-intensive products. Under a business as usual (BAU) scenario, the rate of growth of chemical production is projected to exceed that of population growth at least until 2030 (Figure 3.1). This means per capita consumption of chemicals is increasing steadily, further amplifying the effect of population growth on demand for chemicals. These developments highlight the need to achieve sustainable consumption and production, as called for by Sustainable Development Goal 12 of the 2030 Agenda for Sustainable Development. They also reinforce the need to decouple material use from economic growth, enhance resource and eco-efficiency, advance sustainable materials management, and prioritize source reduction, reuse and recycling, as called for by the waste hierarchy.

A rapidly increasing population in Africa and Asia, along with the growing global middle class, are likely to lead to changing consumption patterns – from necessity-based to choice-based spending – which will increase demand for chemicals and cause resource scarcity, land use conflicts, and pressure on social and health care systems (Kharas 2017). At the same time, a relatively young and well-educated work force could lead to an increase in the number of scientists, researchers and innovators addressing present and future challenges (OECD 2016). An ageing population in developed countries will likely correspond to

Figure 3.1 Growth of basic chemical production capacity vs. population growth, 1990-2030 (based on UN DESA 2018 and Cayuela and Hagan 2019)



The growth rates of chemical production capacity are derived from the past and projected growth rates for basic petrochemical building blocks (ethylene, propylene, butadiene, benzene, toluene and xylenes).

a shift in these countries from being economic powerhouses to being more socially and health care-oriented societies (UN DESA 2015), which is likely to increase demand for pharmaceuticals.

3.1.3 Global economic shifts

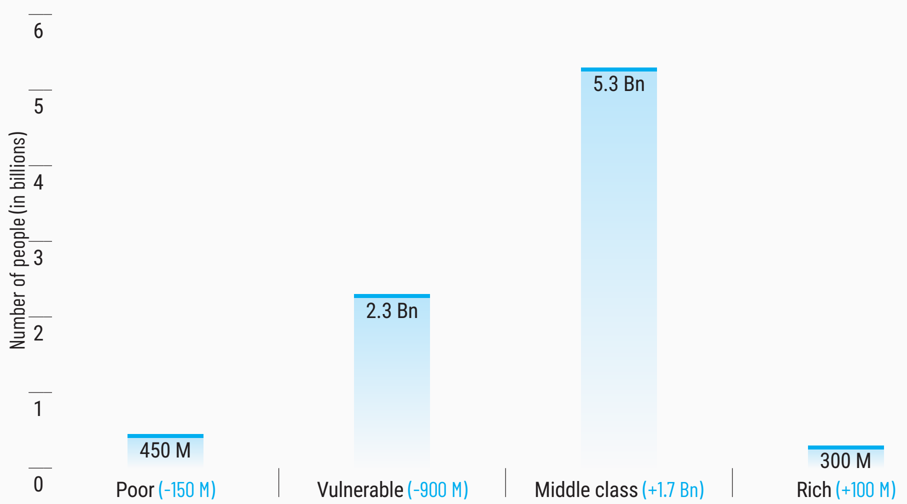
Profound economic shifts are taking place owing to dynamic global economic growth, especially in some emerging economies. While long-term projections come with uncertainties, the global economy could more than double by 2050. In 2050 six of the seven largest economies in the world are projected to be current emerging economies, led by China and India. At the same time, the EU is expected to lose a significant market share. Despite these dynamics, most of the largest developed countries are projected to continue to have higher per capita incomes than the emerging economies, although the gap will be closing (PricewaterhouseCoopers [PwC] 2017). Meanwhile, multinational corporations have grown to vast size: among the 100 largest economic entities worldwide, 31 are countries and 69 are corporations (Green 2016).

Economic growth is also driving the expansion of the global middle class, which accounts for the majority of demand in the global economy. The middle class accounts for approximately two-thirds of global household consumption and is growing more rapidly than other segments. It is estimated that by 2030 around 5.3 billion people will belong to the middle class, significantly more than to the other segments combined (Figure 3.2). Trends in the chemical industry reflect larger changes and increasing consumer purchasing power (Schulz, Rings and Forrest 2012). As explained in Part I, Ch. 1, chemical production and consumption have shifted to Asia.

3.1.4 Technological change

R&D efforts and expenditure, as well as the rate at which new technologies are adopted, have increased significantly in the past decades (DeGusta 2012; Arbesman 2016; United Nations Educational, Scientific and Cultural Organization Institute for Statistics [UIS] n.d.). A surge in innovation can be seen in the increasing number of patents, which has doubled since 2002 and surpassed 3 million in 2016 (WIPO 2017). North America is the largest investor in science, technology and innovation (OECD 2016) and many European countries rank among the world leaders in R&D expenditure (UIS n.d.).

Figure 3.2 Middle class dominance in 2030 (in billions) (adapted from Kharas and Hamel 2018)



Note: Figures in parentheses indicate the increase/decrease in the number of people in each category by 2030 compared to 2018.

A related development is a shift in innovation capacities, including for chemistry innovation. The number of substances registered with the Chemical Abstracts Service has grown exponentially. It took 50 years to see the listing of 100 million substances, yet in the following two years another 30 million chemicals were registered. Since 1965 an average of one new substance has been registered every 2.5 minutes; by 2016 this rate increased to one new substance every 1.4 seconds. This increase in the number of new substances is likely to lead to greater complexity in chemical management.

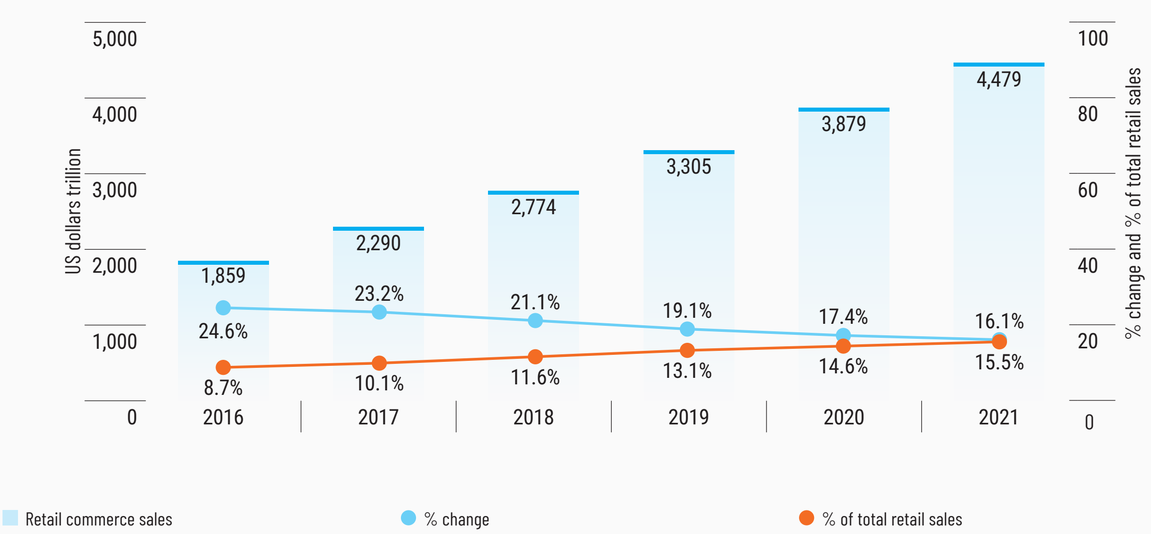
Digitalization is predicted to lead to profound changes in the chemical industry (Deloitte and German Chemical Industry Association [VCI] 2017; Klei *et al.* 2017). Data utilization will become increasingly important for value creation through further automation of manufacturing processes – allowing the use of advanced decision-making methods, realizing efficiency gains, and improving products and services for increased customer utility. This may offer opportunities for chemicals and waste management in, for example, the digitalization of agriculture, which includes the use of soil analysis sensors, drones and automated, data-driven steering systems to allow targeted application of fertilizers and pesticides (European Innovation Partnership for Agricultural Productivity and Sustainability 2017; Geisler 2018; OECD 2018).

The nature of the production and sales of goods and products is also undergoing fundamental changes. New business models, such as additive manufacturing (or 3-D printing; see Part IV, Ch. 4) and e-commerce are driving the decentralization of production and sales. Direct sales of chemical products via the internet are circumventing traditional distributors, many of which have management systems in place. Retail e-commerce sales may hit US dollars 4,479 trillion and surpass 16 per cent of total retail sales by 2021 (Figure 3.3). Cross-border e-commerce is growing by 25 per cent annually (DHL 2016).

3.1.5 Resource use, scarcity and competition

The increasing demand and competition for finite and increasingly scarce resources, including water, land, food and minerals, presents major challenges for the global community. For example, in the Asia-Pacific region rapid economic growth, intensified industrialization, urbanization and the changing lifestyles of a growing middle class have led to a sharp increase in natural resource use and consequently emissions of GHGs and other pollutants (Singhsachakul 2014).

Figure 3.3 The growth of e-commerce, 2016-2021 (adapted from McNair 2017)



The complexity of this megatrend and its relevance for chemicals and waste can be illustrated by the interplay of growing food demand and water scarcity. Overall food production needs to increase by about 60 per cent between 2005/07 and 2050, while global water demand is projected to increase by 55 per cent (OECD 2016; FAO 2017). In most regions of the world over 70 per cent of freshwater is used for agriculture, and water withdrawals are projected to increase (Khokhar 2017). Depending on the practices used, growth in food demand is likely to increase the use of pesticides and fertilizers, which, in turn, may further aggravate water scarcity by polluting freshwater. Some regions are particularly affected. For example, agriculture accounts for around 23 per cent of exports from the Latin America and Caribbean region (Bárcena *et al.* 2015) and consumes double or triple the water volumes of countries in other regions (Cadena *et al.* 2017). Agriculture is the main economic sector in the Mashriq sub-region of West Asia, where water is a scarce resource. Discharges from marine desalination in the region are associated with chemical releases, including heavy metals (Alshahri 2017).

An innovative chemical industry has the potential to provide solutions to address challenges related to resource use and scarcity. It can be an engine for generating safe new materials and extending the life of existing ones as one way to reduce unessential production and consumption and the consequent demand for particularly scarce resources, thus making a contribution to waste prevention (Barra and Leonard 2018). There are also opportunities for the industry to substitute raw materials with renewable feedstocks, increasing the reuse and recycling of end user products, and to promote energy recovery and carbon utilization, which requires phasing out and substituting hazardous chemicals in manufacturing and in products (Accenture 2017; ECHA 2018).

3.1.6 Urbanization

Urbanization is taking place on a historically unprecedented scale. In 2008 for the first time, more people lived in cities than in rural areas. By 2050 an additional 2.5 billion people will move to cities, where 66 per cent of the global population will live. While 28 cities had more than 10 million inhabitants in 2014, by 2030 the number will increase to 41 (UN DESA 2014a) (Figure 3.4). With already relatively high rates of urbanization in North America (where 82 per cent of the population lives in cities), Latin America and the Caribbean (81 per cent) and Europe (74 per cent), the related dynamics are less discernible in these regions. On the other hand, the Asia-Pacific region (50 per cent) and

Africa (43 per cent) are still much more rural and increased urbanization has a much higher impact there: about 90 per cent of people who will be moving to cities by 2050 are (and will be) living in Asia-Pacific and Africa (UN DESA 2018).

The rate and scale of urbanization will likely lead to the need to develop accompanying infrastructure, including housing and transportation (UN DESA 2014b). This strong growth demands massive resources for construction purposes, as well as for maintenance and use by inhabitants, all of which will increase the use of chemicals. By 2050 China needs to create housing for 292 million new urban inhabitants, while in India 404 million people are expected to move to cities (UN DESA 2014a, p. 56). Urbanization also leads to changing needs in regard to employment and mobility, food and a healthy environment. Material consumption in the world's cities is expected to increase from 40 billion to 90 billion tonnes by 2050 (Swilling *et al.* 2018). Depending on the substances used in construction (e.g. for insulation), significant risks may emerge from a chemicals and waste perspective. New business opportunities for safer materials in the building sector may also emerge, however, for example following the regulation of asbestos in many countries.

3.1.7 Climate change and pollution

Global emissions of CO_2 and other GHGs continue to increase rapidly. In order of magnitude, fossil

Figure 3.4 Growth of the urban population by city size, 1990-2030 (adapted from UN DESA 2014a, p. 10)

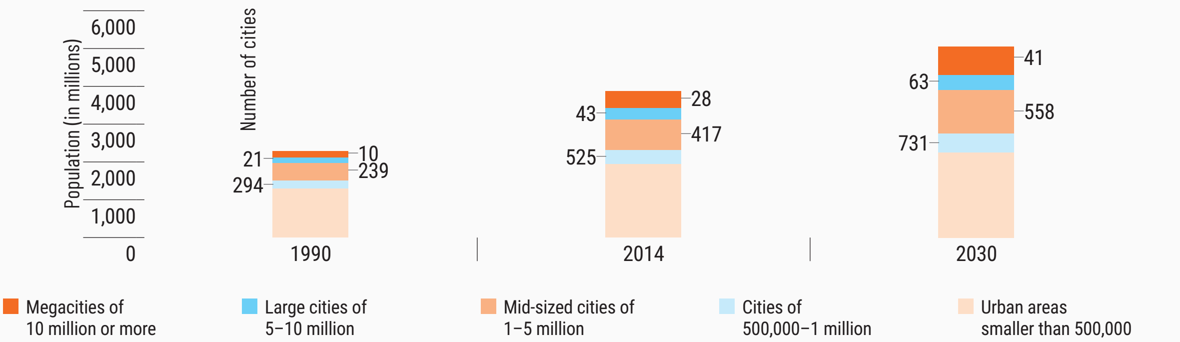
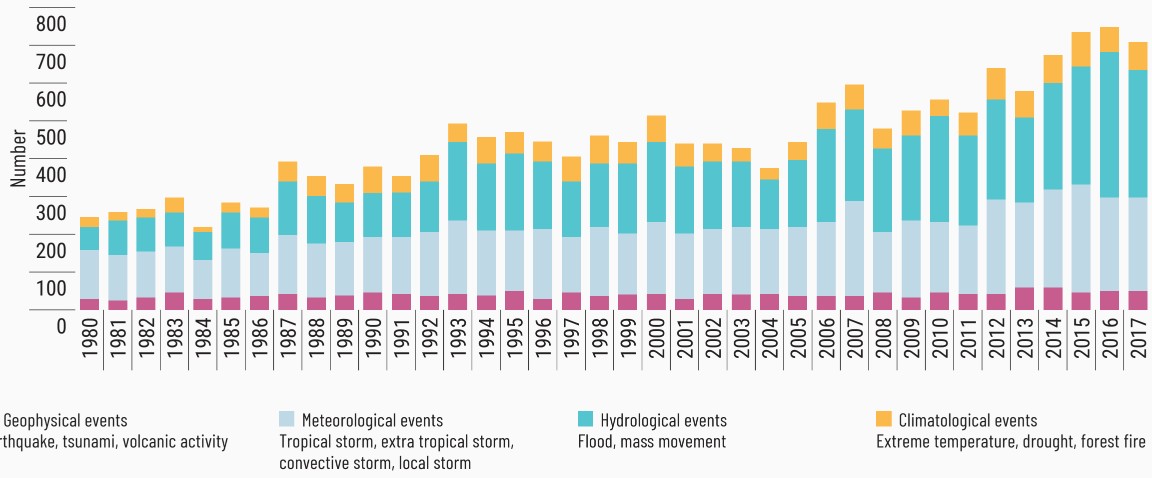


Figure 3.5 Trends in the number of loss-relevant natural events, 1980-2016 (adapted from Munich Re 2017)



fuel combustion and agriculture are among the largest sources of CO_2 emissions (OECD 2016). The chemical industry is a significant source of pollution and contributor to GHG emissions (see Part I, Ch. 5). Global warming also leads to the remobilization of pollutants such as POPs due to melting glaciers and thawing permafrost (Grannas *et al.* 2013). Moreover, climate change may affect pesticide use (i.e. in the form of higher amounts, doses and frequencies, and different varieties or types of products applied) (Delcour, Spanoghe and Uyttendaele 2015). Chemical accidents are frequently caused by natural disasters and weather-related events (see Part I, Ch. 5), adding another dimension to the increase in the frequency of climate-related loss events (Hoeppe 2016) (Figure 3.5). Three out of five of the countries most affected by the impacts of weather-related loss events between 1996 and 2015 are in Latin America and the Caribbean.

The chemical industry can also help reduce pollution, not only through improving resource efficiency in the chemicals sector but also by supporting innovations leading to materials and products which can reduce emissions of CO_2 and other pollutants in many other sectors or, for example, by providing innovations for carbon capture and storage. Biotechnology can make a positive contribution to the reduction of the negative health and environmental impacts of the petroleum and petrochemicals industries through the development of bio-based batteries for e-mobility, as well as through research on artificial photosynthesis processes and microorganisms for biofuel production.

3.2 Chemical-intensive industry sectors

3.2.1 The chemicals and waste dimension of industry sectors

Chemicals are used across industry sectors

The chemical industry is an important backbone of various downstream industry sectors such as electronics, agriculture, pharmaceuticals, construction, textiles, transportation and energy. It supplies raw materials, feedstocks and speciality chemicals to each of these sectors. Table 3.3 provides an overview of the primary commodity chemical groups used in chemical-intensive downstream sectors (or "end markets").

Megatrends and industry sector trends create risks and opportunities

Many chemical-intensive industry sectors are expected to grow, responding to the dynamics of global megatrends. In turn, growth in chemical-intensive industry sectors and markets continues to drive growth in the markets for chemicals used in these sectors. This includes construction,

Table 3.3 Major end markets for four primary commodity chemical groups (adapted from Bamber, Frederick and Gereffi 2016, p. 18)

	Petrochemicals: Polyethylene, polyprolylene, polyvinyl chloride, polystyrene	**Industrial gases:** Oxygen, nitrogen, argon, hydrogen, acelyne, CO_2	**Inorganic chemicals:** Caustic soda, hydrochloric acid, liquid chlorine, sulphuric acid, chlorine, sodium hypochlorite, ferric chloride, titanium dioxide	**Oleochemicals:** Fatty acids, fatty alcohol, methyl esters, glycerine
Agriculture		o	o	
Automotive	o			
Construction	o	o		o
Personal care & detergents		o	o	o
Electronics	o	o	o	
Food & Beverage		o	o	o
Manufacturing		o	o	
Packaging	o			o
Pulp & paper		o	o	o
Pharmaceutical				o
Textiles & apparel	o			o
Water and waste treatment		o	o	

Table 3.4 End markets for chemicals (adjusted based on Global Manufacturing Industry group, 2011, p. 18)

End market size and chemical revenue from end market			**Megatrends likely to have the most significant impact**							
	Chemical revenue (US dollars billion)	End market size (US dollars billion)	Resource scarcity	Green/ sustainability	New pattern of consumption	Demographic change	Conver-gence of technologies	Urbanization	Human health	Patterns of mobility
Construction	695	8,016	o	o		o	o	o		
Electronics	371	2,458	o		o		o	o		o
Household	159	800		o	o	o	o	o	o	
Agriculture	142	1,772	o	o	o	o			o	
Paper and packaging	130	702			o		o			
Automotive	128	1,932	o	o			o	o		o
Health care	113	1,368			o	o	o		o	
Energy	113	3 833	o	o			o			
Transportation	61	1,023	o	o				o		o
Nutrition	29	4,022	o		o	o	o		o	
Personal care	20	225		o	o	o			o	
Machinery	15	457						o		
Apparel and textiles	11	1,097				o	o	o		
Mining and metals	4	1,333	o	o					o	

electronics, agriculture, pharmaceuticals, energy, transportation and textiles (discussed in this chapter), as well as other sectors such as mining and cosmetics. These chemical-intensive downstream sectors vary considerably in terms of the size of the respective industry, as well as the types and volumes of chemicals used. An overview of the size of the end markets and the chemical revenue in each end market is presented in Table 3.4, which also indicates megatrends that are likely to have the most significant impacts on the respective sectors. Construction is the largest end market and is also the sector generating the largest chemical revenue.

Industry sector growth creates opportunities for innovation, such as replacing chemicals of concern with safer chemicals or non-chemical alternatives. However, growth may also increase risks when old technologies that are dependent on chemicals of concern are used even when adequate risk management measures are not in place. In some cases, conflicting objectives may play a role, such as use of better insulation to save heating energy leading to higher emissions of facade coatings (biocides) to the environment, which then need to be reduced (Burkhardt *et al.* 2011).

3.2.2 Construction

The global construction sector is expected to grow by 3.5 per cent annually, with its chemicals market projected to grow by 6.2 per cent annually between 2018 and 2023 (Mordor Intelligence 2018). This growth will primarily be driven by the rapidly urbanizing Asian and African regions (UN DESA 2014a). It is estimated that the United States, China, India, Indonesia, the United Kingdom, Mexico, Canada and Nigeria will account for 70 per cent of global construction growth by 2030, with India the fastest growing market (Global Construction Perspectives and Oxford Economics 2015). The global market for construction chemicals (comprising concrete admixtures, protective coatings, asphalt modifiers, adhesives and sealants) is expected to grow by 9 per cent per year and increase to more than US dollars 50 billion by the end of 2024 (Global Market Insights 2017).

Some of the chemicals used in construction cause severe harm to workers on construction sites. These chemicals can also affect the health of future building occupants and office workers as a result of indoor air pollution. In developing countries asbestos use for construction remains a serious hazard. The World Health Organization (WHO) has estimated that 125 million people in the world are exposed to asbestos in the workplace and that 107,000 die each year due to diseases caused by occupational exposure to asbestos (WHO 2014). PVC materials are a major source of indoor chemical residues of substances such as DEHP, which have, for example, been linked to asthma (Jaakkola and Knight 2008; Kanchongkittiphon *et al.* 2015). Plastic is a widely

used construction material: about 21 per cent of the 47 million tonnes of plastic used in Europe goes into the construction sector (Plastics Europe 2012). Labour- or technology-intensive sorting is needed in order to obtain a high quality recyclate from construction waste (Hahladakis *et al.* 2018). There are also concerns about lead exposure during the demolition, retrofit or renovation of older buildings, both in occupational and residential (do-it-yourself) settings (US EPA 2011).

There are many opportunities to use safer chemicals in construction, particularly for siding and roofing materials, structural members, insulation and coatings. There are also opportunities to use safer chemicals in information technologies, particularly those that integrate sustainability criteria into material selection decision-making (Agarwal, Chandrasekaran and Sridhar 2016). The global green building materials market is expected to grow from 2016 to 2022 at a CAGR of 11.9 per cent (Prasad and Sinha 2016). Stronger incorporation of recyclability criteria in choosing construction materials provides additional opportunities (Zimmann *et al.* 2016).

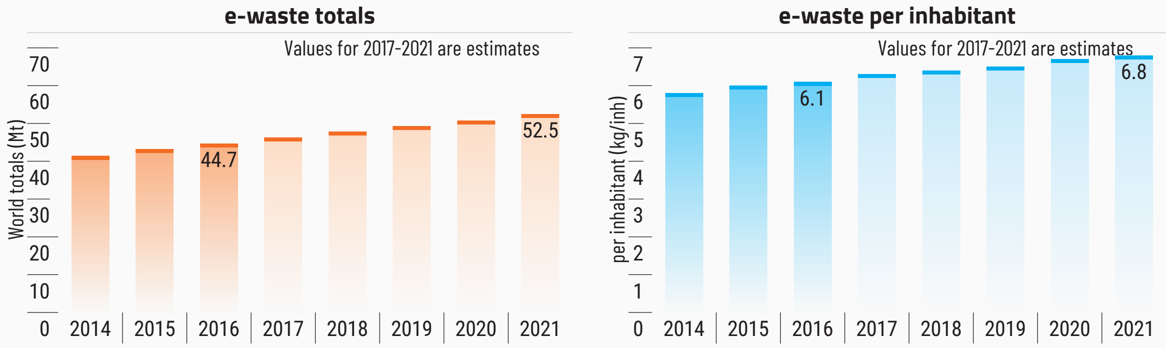
3.2.3 Electronics

The consumer electronics market continues to grow rapidly. The top producing regions are Asia (73 per cent), the Americas (12 per cent) and Europe (14 per cent). The top three countries in terms of output and market share are China (51 per cent), the United States (10 per cent) and Japan (7 per cent) (ZVEI 2017). More than half of global electrical and electronic product production takes place in China. Investment in electronics manufacturing in India is increasing at a CAGR of 27 per cent and could reach US dollars 104 billion by 2020. For almost all electrical and electronic products, chemicals are essential. It has been estimated that the global electronic chemicals and materials market will grow to US dollars 30.5 billion by 2020, compared with US dollars 22 billion in 2014 (McWilliams 2016).

Electronic and electrical products contain a number of hazardous substances including lead, mercury and other metals, flame retardants and certain phthalates (Nimpuno and Scruggs 2011). There are risks of exposure to harmful chemicals during production and end-of-life recycling, when e-waste is informally scrapped to obtain valuable material (Perkins *et al.* 2014). In 2016, 44.6 million tonnes of electronic waste were generated (Figure 3.6), of which 80 per cent was handled illegally (Baldé *et al.* 2017). Workers in the supply chains of developing countries are particularly at risk of exposure to these chemicals due to the unregulated nature of the electronic waste (e-waste) recycling sector (Lundgren 2012). While informal e-waste operations are among the world's most hazardous occupations (Pure Earth and Green Cross Switzerland 2016), exposure to toxic substances is common even in formalized e-waste recycling in developed countries (Julander *et al.* 2014).

Opportunities exist for the safer design of products for longevity and ease of recycling, as

Figure 3.6 **Global e-waste generated by volume and per inhabitant, 2014-2021 (adapted from Baldé *et al.* 2017, p. 5)**



well as for using "products as service" to make the sector more sustainable. The value of the raw materials in all e-waste is estimated to be around US dollars 55 billion (Baldé *et al.* 2017). The Apple GiveBack programme, Dell's laptop line that uses post-industrial recycled carbon-filled polycarbonate, and Samsung's cadmium-free high-definition televisions are examples of electronic companies' initiatives aimed at greater sustainability (Stanislaus 2017).

3.2.4 Agriculture and food production

Agriculture and food production are chemical-intensive. Output will increase considerably in the coming decades due to the growing global population and changing, more resource-intensive diets (UN DESA 2017). The FAO estimates that overall food production needs to increase by about 60 per cent between 2005/07 and 2050 (FAO 2017). This demand, and increasing pressure on farmland, will lead to significant growth of the agrochemicals market, which had a value of US dollars 215.18 billion in 2016 and is projected to reach US dollars 308.92 billion by 2025 (Grand View Research 2017). However, the increasing trend of organic agriculture and agroecology in many countries may affect this forecast growth. The Asia-Pacific region accounts for the largest share of the global agrochemicals market, with China and India as major consumers. Latin America is expected to have the highest growth rate, with Brazil and Argentina being significant markets (Reuters 2018).

While agrochemicals have helped to significantly increase food production, the use of pesticides and fertilizers has nevertheless caused widespread adverse impacts on soils, ecosystems and human health (Carvalho 2017). Exposure to some pesticides has adverse effects on humans, including reproductive disorders and cancers as well as acute poisonings, and pose threats to biodiversity (Kim, Ko and Lee 2013; Hallmann *et al.* 2017; Rim 2017). Pesticide use varies significantly across countries (FAO 2018) (Figure 3.7). Moreover, excessive use of nitrate-based fertilizers may lead to ground and surface water contamination (Liu *et al.* 2014). Agriculture remains the largest economic sector in terms of contribution to gross domestic product (GDP) and employment in Africa (African Development Bank [ADB], OECD and United Nations Development Programme [UNDP] 2017), which presents challenges regarding exposure to certain agrochemicals and the management of stockpiles of obsolete chemicals.

Biological alternatives to synthetic or chemical fertilizers and pesticides are in increasing demand. The global biological crop protection market is forecast to grow at a CAGR of 11.33 per cent during 2016-2021 (Business Wire 2016). This shift in the consumer market offers opportunities for

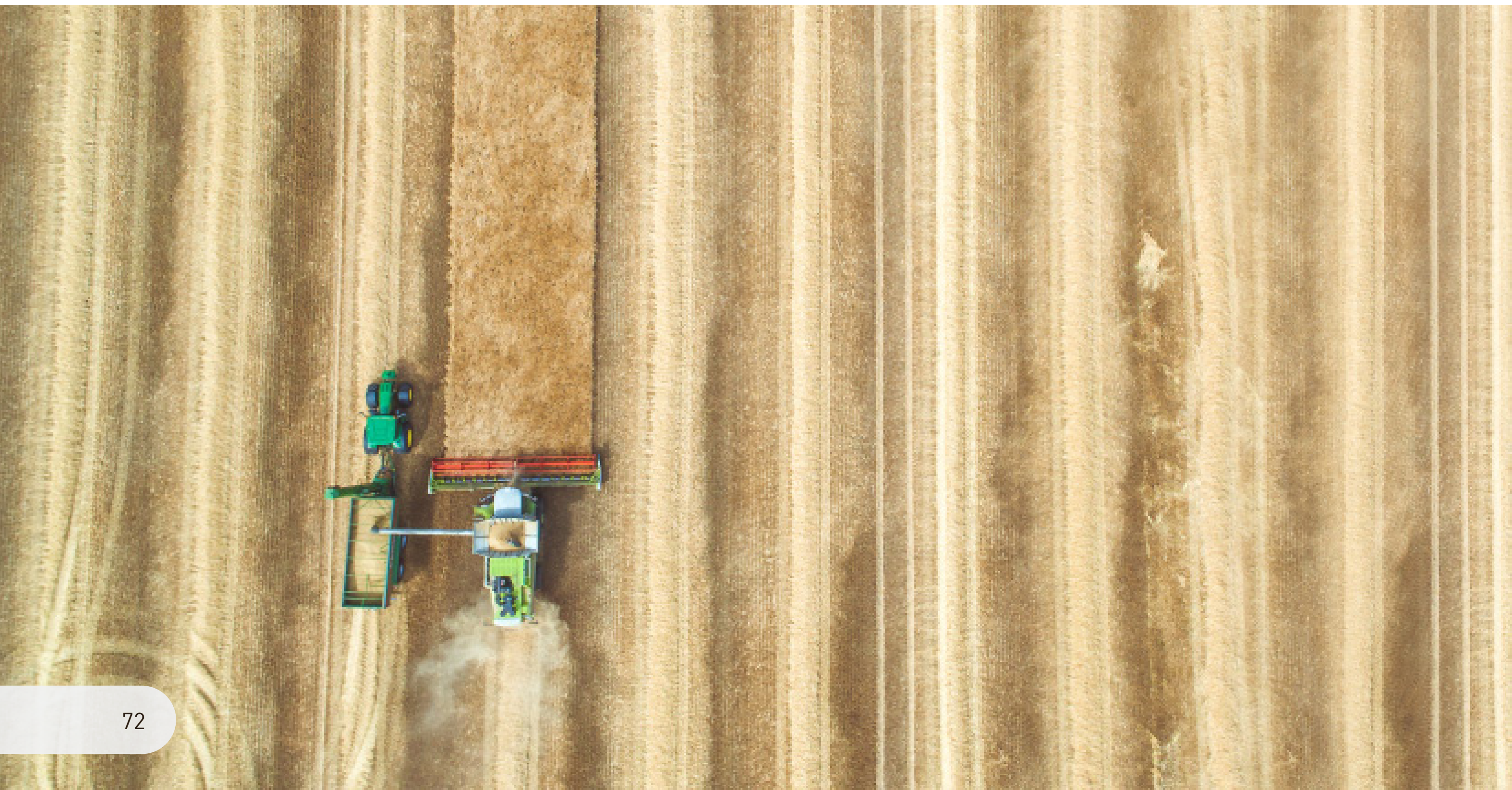
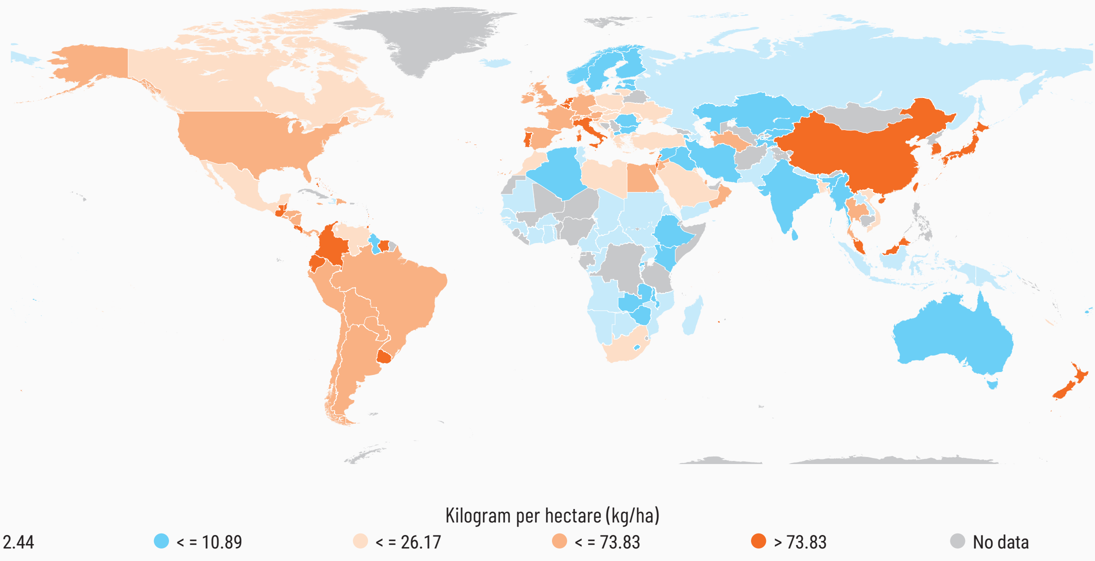


Figure 3.7 Use of pesticides per area of cropland, kg/ha, sum 2006-2016 (adapted from FAO 2018)



new chemical nutrients and plant protection biologicals. In 2016 the global organic food market was worth US dollars 110.25 billion and it is projected to grow to US dollars 262.85 billion by 2022 (Produce Marketing Association Research 2017). However, in these areas it is important to assess the alternatives' hazard properties and potential adverse impacts, including on other ecosystem services, in order to avoid regrettable substitution. Significant opportunities also exist to scale up Integrated Pest Management (IPM) and agroecological approaches, including the development and use of non-chemical alternatives and other good agricultural practices.

3.2.5 Pharmaceuticals

Global spending on medicine is projected to reach nearly US dollars 1.5 trillion by 2021, about US dollars 370 billion higher than in 2016. The total volume of medicines consumed globally will increase by about 3 per cent per year through 2021. In 2016 North America accounted for 49 per cent and Europe for 21.5 per cent of world pharmaceutical sales (QuintilesIMS 2016). North America is also among the regions with the greatest number of pharmaceuticals detected in its water sources (Owens 2015). Pharmaceuticals research, development and production capacities are growing quickly in emerging economies such as Brazil, China and India. "The number of new medicines reaching patients will be historically large, with 2,240 drugs in the late-stage pipeline and an expected 45 new active substances (NAS) per year forecast to be launched on average through 2021" (QuintilesIMS 2016).

From a chemicals and waste management perspective, environmental and health concerns in this sector are primarily related to releases of pharmaceuticals to the environment, where they can lead to detrimental effects, especially on aquatic life, or contribute to antimicrobial resistance (Owens 2015; see also Part I, Ch. 5, 7; Part II, Ch. 4). Sources of releases of pharmaceuticals to the environment include direct emissions from drug manufacturing, patient and animal excretion, and disposal of unused or expired medicines (Larsson 2014; Some of Us 2015; Changing Markets Foundation and Ecostorm 2016; Nordea 2016; Access to Medicine Foundation 2018; Health Care without Harm Europe 2018). Workers engaged in the manufacture of pharmaceuticals may be at risk due to occupational exposure to harmful chemicals; nearby communities and ecosystems may also be at risk because of pharmaceutical discharges (Gathuru *et al.* 2015; Nordea 2016; Changing Markets Foundation and Nordea 2018). Given the critical role of pharmaceuticals in human and veterinary health, addressing chemicals and waste issues in this area requires careful balancing and consideration of potential trade-offs.

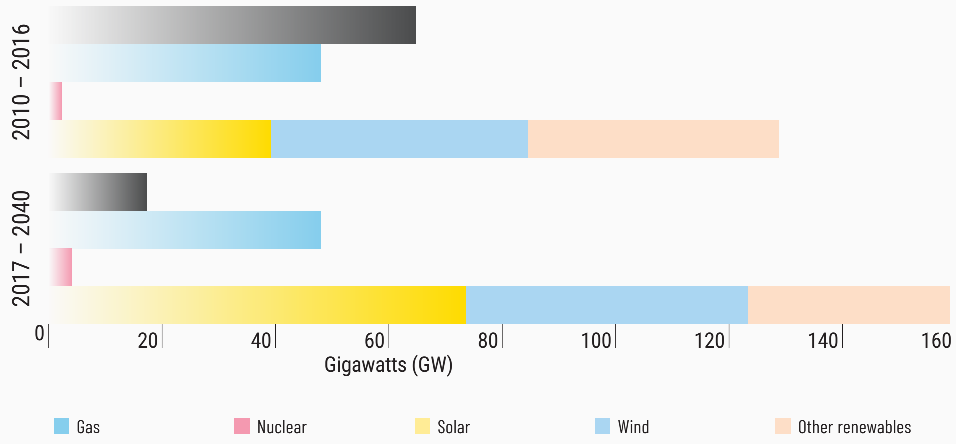
The pharmaceutical industry has been described as moving towards the development of more efficient, less polluting processes, the use of less hazardous reagents, and the development of improved catalysts American Chemical Society (2015). Companies such as Pfizer and Merck have developed new biocatalytic processes for their drugs Lyrica and Januvia, respectively, that decrease the use of solvents as well as the organic chemical waste produced (Sharma 2015). Founded on the principles of product stewardship and a life cycle perspective, the ECO-Pharmaco-Stewardship (EPS) initiative has been developed to identify the potential environmental risks of pharmaceutical ingredients; improve manufacturing effluents management; and use extended environmental risk assessments (EFPIA 2016). Substitution of viscosity and binding agents in pharmaceuticals with alternatives that have lower environmental impacts (e.g. the use of starch-based polymers) is another promising area for innovation (Kadajji and Betageri 2011). Governments could take action, for example, through regulations and fiscal incentives to promote green and sustainable pharmacy.

3.2.6 Energy

Global energy demand is projected to increase nearly one-third by 2040 despite a slowdown in demand growth due to energy efficiency regulations (IEA 2017). India and China – currently the world's largest consumers – are expected to account for the largest share of the increase in primary energy demand. Overall, developing countries in Asia will account for two-thirds of global energy growth, with the remainder coming mainly from the Middle East, Africa and Latin America (IEA 2017). Key trends in the global energy system include the rapid advance of renewable energy (IEA 2017) (Figure 3.8) and increasing electrification of energy. It is estimated that one-third of the world's new wind power and solar photovoltaic technology will be installed in China. Among industrial activities, the chemical sector is expected to see the highest growth in energy demand at around 45 per cent between 2015 and 2040.

Hazardous chemicals used in renewable energy solutions may pose threats to human health and the environment and create future legacies. For example, carcinogenic chemicals such as cadmium and lead are used in the manufacture of solar panels (Aman *et al.* 2015). With many first-generation solar panels nearing their end of life, the challenge of adequate disposal comes to the forefront. A similar spectre is being raised about the future management of energy storage provisions. As regards wind power, it has been estimated that by 2040 more than 400,000 tonnes of composite material per year from blades will have to be disposed (Ramirez-Tejeda, Turcotte and Pike 2016). Currently there are

Figure 3.8 **Global average annual net capacity additions by type of energy (gigawatts), 2010-2016 and 2017-2040 (adapted from IEA 2017)**



no established recycling solutions for the large amounts of blades that have reached the end of their life (Liu and Barlow 2017).

Chemicals will play a central role in incorporating resource efficiency and climate friendliness in energy generation, storage, distribution and use. Chemistry is essential to the development of innovative battery technologies, wind turbines and solar panels, among others, for example by providing resins for blades and coating materials used in wind turbines or sealants for PV panels (ICCA 2017). Chemistry innovations can help decrease the costs of renewable energy solutions and increase their durability (e.g. through novel polymers used in wind turbines) (Scott 2017). The global market for energy efficiency technology is expected to grow from US dollars 995 billion in 2017 to US dollars 1,781 billion by 2025. It is estimated

Box 3.1 **Lead-acid batteries: avoiding future legacies**

In 2018, around 86 per cent of all lead was used in the production of lead-acid batteries, whose primary use is in conventional vehicles (ILZSG 2019). The growing market for automobiles in low- and middle-income countries is expected to lead to an increasing number of lead-acid batteries. The total annual generation of used lead-acid batteries (ULABs) in Africa is estimated to amount to more than 1.2 million tonnes (Tür, Manhart and Schleicher 2016).

When conducted informally or without proper pollution and occupational health and safety controls, recycling of ULABs can be highly polluting. Globally, 1.9 million people are at risk from severe damage to their health from lead exposure due to unsound lead-acid battery recycling (Daniell *et al.* 2015; Pure Earth and Green Cross 2016). The often informal operations in many low- and middle-income countries pose severe health risks, especially to children (Haefliger *et al.* 2009; García and Marín 2016) while implying a high burden of disease predominantly in Southeast Asian countries but also in China (van der Kuijp, Huang and Cherry 2013), Africa and Latin America. A 90-country study estimated that from 10,599 to 29,241 informal lead-acid battery processing sites were putting the health of as many as 16.8 million people at risk in 2013 alone (Ericson *et al.* 2016).

As an alternative to lead-acid batteries, lithium-ion batteries are also expected to pose a quickly growing environmental and health challenge in coming decades with their own specific recyclability challenges (Lv *et al.* 2018), particularly the very diverse mix of compounds that are not easily separated (Gaines 2014). Innovation needs to be encouraged not only in order to develop cheaper batteries with higher capacities, but also to design them to be more sustainable throughout their life cycle with a special focus on end-of-life and recyclability (Larcher and Tarascon 2015).

that the global market for environmentally friendly technology for the generation, storage and distribution of energy will nearly double in the same period (Berger *et al.* 2018). Extended producer responsibility systems for batteries would minimize the risk that batteries will end up in informal recycling operations or dump sites.

3.2.7 Transportation

Although the global transportation sector has experienced relatively low growth rates in recent years, it is likely to continue growing (KPMG 2017). Passenger transport is projected to more than double by 2050. Low growth rates are projected in OECD countries, with most of the increase expected in Asia (OECD and International Transport Forum [ITF] 2017; PwC 2018). Urbanization, population growth and a growing middle class (particularly in emerging economies) are expected to lead to continuous growth in car sales at around 2 per cent per year (Hannon *et al.* 2016; Pucher and Buehler 2017). The World Bank (2018) has estimated that there will be twice as many vehicles on the roads by 2050 than the 1 billion in 2015. Non-urban transport (particularly aviation) is expected to grow strongly, while construction of rail networks is also projected to grow. Freight transport may triple by 2050 (OECD and ITF 2017).

Air pollution, particularly that due to road traffic via particulate matter and sulphur emitted by diesel motors, is a significant health and environmental concern (UNEP 2017). Growth in the transport sector also presents challenges from a chemicals management perspective. Lithium-ion batteries containing heavy metals and other toxins are expected to pile up after their use in electric vehicles (Stanway 2017). Lead-acid batteries used in combustion engines also present a risk, particularly during recycling (Daniell *et al.* 2015) (Box 3.1).

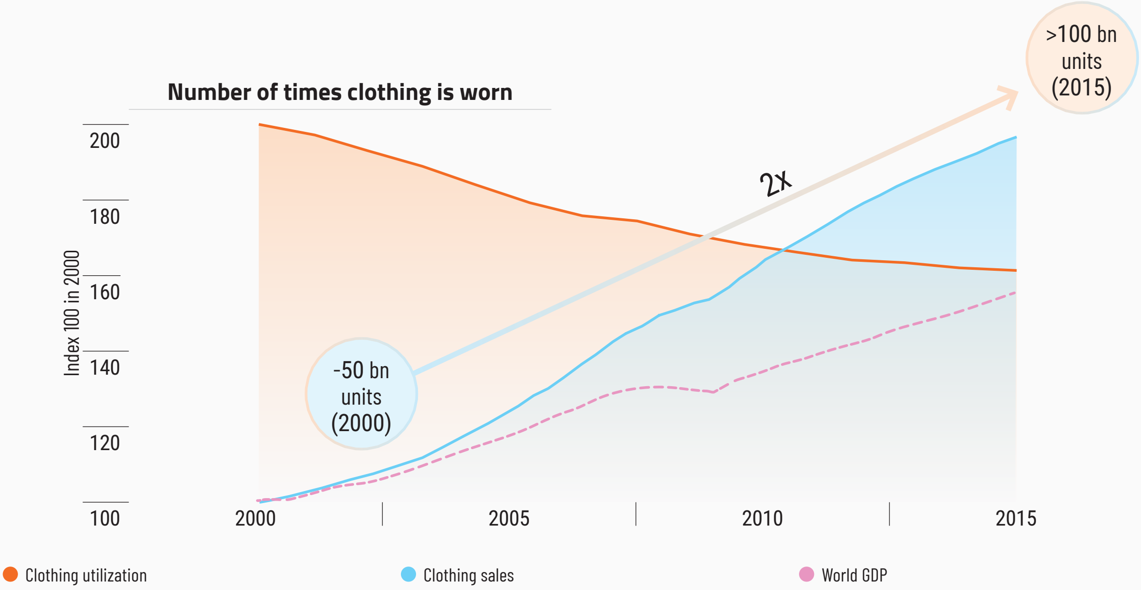
The shift from internal combustion to electric motors will have mixed implications: an increase in volume is expected for battery materials and polymers, while demand for lubricants, catalysts, fuel additives and automotive fluids is expected to decrease (Kumpf, Eliaz and Aldred 2018). Green and sustainable chemistry opportunities exist for lighter weight materials and high-performance polymers in vehicle construction (BASF 2013). Opportunities for more sustainable materials and technologies also exist in the paving industry. Some have already found their way onto the market, such as recycled asphalt pavement or warm mix asphalt technology (Huang *et al.* 2017).

3.2.8 Textiles

The global textiles sector has doubled in production over the last 15 years (Ellen MacArthur Foundation 2017) and the annual retail value of apparel and footwear is expected to increase by 30 per cent between 2017 and 2030 (Eder-Hansen *et al.* 2017). A key driver is a phenomenon known as “fast fashion”, characterized by quick turn-arounds of new styles, a larger number of collections offered per year, and lower prices coupled with a lower cloth utilization rate (Ellen MacArthur Foundation 2017) (Figure 3.9). The Asia-Pacific textile chemicals industry is expected to experience the fastest growth while China is likely to remain the world’s largest manufacturer of textiles and apparel, although many garment makers are exploring new manufacturing facilities in other Asian countries. Bangladesh, Viet Nam and India have large textile industries. Ethiopia is projected to become a fast-growing manufacturing hub in Africa (Berg, Hedrich and Russo 2015). Several other African countries are expected to expand their garment and textile industry as part of national industrialization strategies (ADB, OECD and UNDP 2017).

A growing textile industry leads to an increase in the chemicals used in textile processing, the market value of which is estimated to be US dollars 31.8 billion by the end of 2026 (Transparency Market Research 2018). For example, increased demand for weather-resistant textiles may, depending on the chemicals and technologies used, increase the use of PFASs. When washed, some garments release plastic microfibres, 0.5 million tonnes of which leak into oceans each year. Less than 1 per cent of the material used to produce clothing is recycled into new clothing, representing a loss of over US dollars 100 billion worth of materials each year (Ellen MacArthur Foundation 2017). The World Bank has estimated that 20 per cent

Figure 3.9 **Growth of clothing sales and comparison with declining clothing utilization (adapted from Ellen MacArthur Foundation 2017, p. 18)**



Refers to the average number of times a garment is worn before it ceases to be used.

of industrial wastewater pollution worldwide originates from the textile industry (Kant 2012). 73 per cent of clothing ends up in landfills or is incinerated at the end of their life. Hazardous chemicals can leach out as textiles degrade in landfills, while incineration can lead to harmful emissions. It has been estimated that eliminating the negative health impacts emanating from poor chemicals management in the textile industry would yield an economic benefit of around US dollars 8 billion per year (Eder-Hansen *et al.* 2017).

Regulatory restrictions, increasing consumer concern, civil society campaigns (e.g. DETOX, Greenpeace) and industry-driven initiatives such as Zero Discharge of Harmful Chemicals (ZDHC 2018) drive innovation in the industry. Leading brands have introduced sustainable collections without harmful chemicals, and with low water and carbon footprints (Ellen MacArthur Foundation 2017). Sustainable textile fibres such as hemp, sisal and jute are becoming popular. The ecofibre market is estimated to grow, with a CAGR of more than 10 per cent by 2022 (Technavio 2018). Other opportunities for innovation include safer textile chemistries and advanced technologies for chemical recovery from wastewater (Sustainable Business 2013).

4/ Global supply chains, chemicals in products, and circularity

Chapter Highlights

Chemicals fulfil various performance functions in materials and products; they are also widely used in auxiliary processes, manufacturing, waste treatment and other areas.

Modern-day products contain a large number of chemicals at varying concentrations; unintentional contaminants are present in a range of products.

Hazardous chemicals in secondary raw materials create specific challenges for recycling and for a circular economy.

Complex chemical and product supply chains span the globe; adverse effects may occur at various stages in the life cycle, including manufacturing, consumption, reuse and disposal.

Understanding and managing chemicals in global supply chains is critical to advance sustainable consumption and production; a holistic life cycle perspective is essential to avoid burden shifting.

While the international community has been paying significant attention to the management of individual chemicals, momentum is growing to better understand the complexities associated with chemicals in products and product life cycles, as well as the sustainability dimensions. This chapter sheds light on the interface of chemical and product supply chains, within the broader sustainable consumption and production system. Some of the concepts introduced, such as life cycle assessment and sustainable supply chain management, are further discussed in Part III, Ch. 7 and Part IV, Ch. 6.

4.1 The complexity of global supply chains and management challenges

Global trade of chemicals and products

The evolution of global value chains has significantly affected global trade and supply chains for chemicals and products. Business between companies around the world involves trade in chemicals, materials, and intermediate and final products at various stages of their life cycle, including waste. The trade of chemicals such as benzene, methanol and sulphuric acid

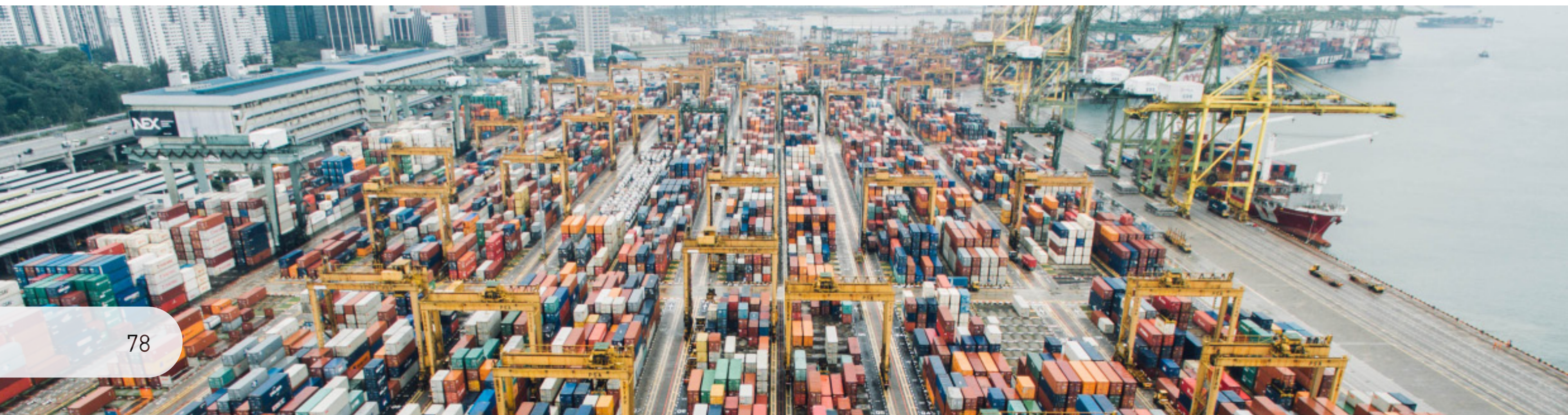
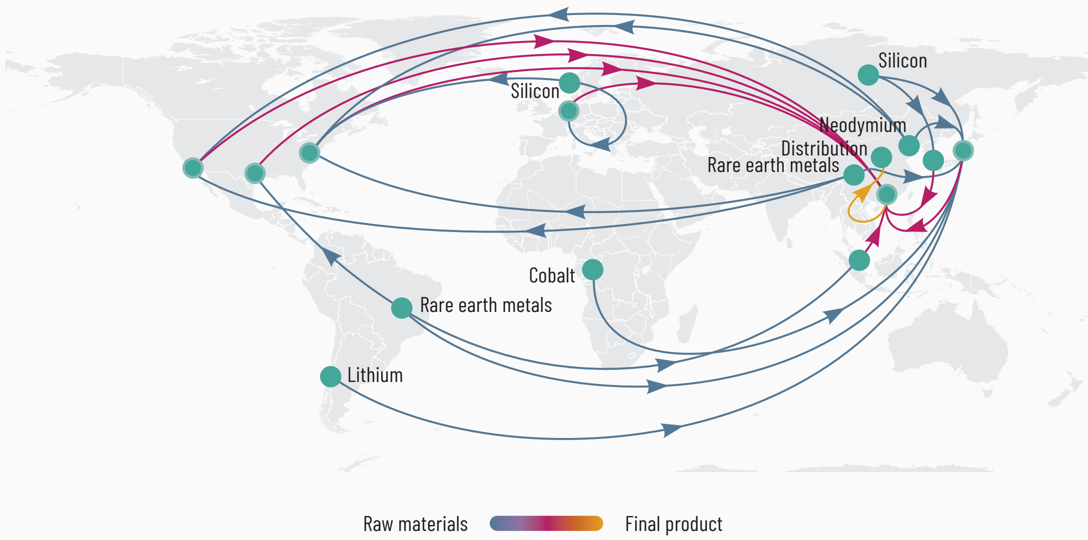


Figure 4.1 **Illustration of the complexity of global supply chains: the case of an electronic product (adapted from Sourcemap 2012)**

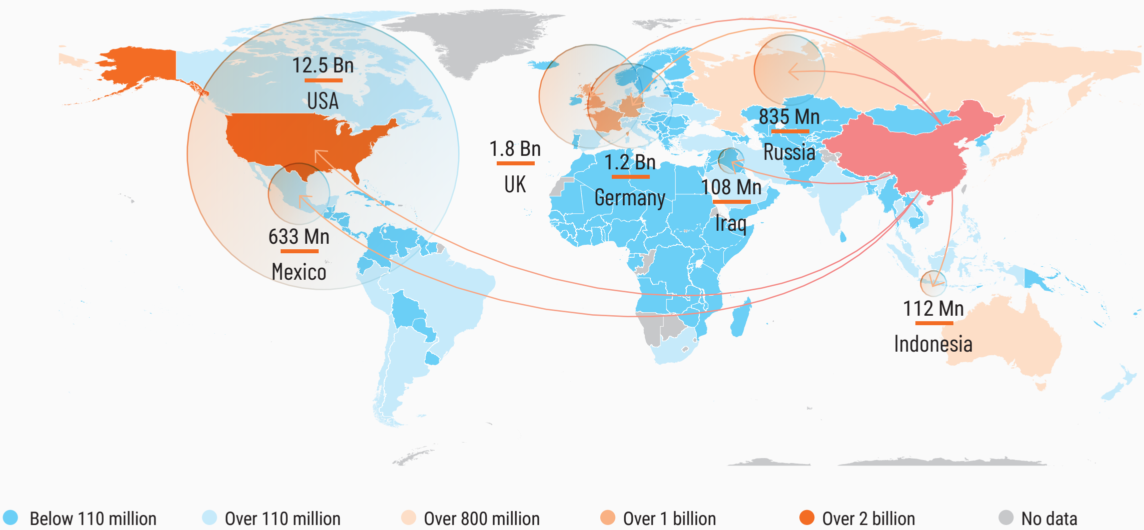


Chemical-intensive products, such as the electronic product depicted here, are traded through increasingly complex global supply chains, spanning many countries and regions. This poses a variety of management challenges.

has increased significantly in the past decades (Chua 2017). This adds further to the complexity of supply chains, particularly where imported chemicals are used in the production of articles and products which are then exported, or where products are recycled and materials are returned to exporting countries for re-manufacturing. This complexity of global supply chains, and the cross-border trade of chemicals and chemical-intensive products across countries with distinct regulatory frameworks, create challenges. The supply chain for electronics illustrates fragmentation in a specific economic sector and across geographic locations (Figure 4.1).

Figure 4.2 shows the relative scale of exports of toys from China by importing market, illustrating the increasing interdependence and global

Figure 4.2 **Relative scale of exports of toys from China by importing market (based on Atlas 2018)**



character of current supply chains. In 2017 China imported more than US dollars 61 billion worth of plastic materials, some of which were used in the manufacture of toys. In the same year it exported approximately US dollars 43.7 billion worth of toys.

The automotive industry is another example. Divestment of large portions of the automotive supply chain has occurred, including outsourcing of cost- and labour-intensive manufacturing portions as semi-independent or wholly independent units (Bitran *et al.* 2006). Such disintegration leads to a more complex, but also more flexible, automotive supply chain network. As a result, the level of interaction and coordination between actors involved in the supply chain increases significantly even if the number of supply chain layers, from components to finished products, remains the same.

Supply chains are fragmented and complex

Global production and supply chain systems span the globe, creating value across entire production and product systems and product life cycles, industries and consumers. The global supply chain of each sector includes various networks around the world for raw materials extraction; production and processing of intermediate goods and materials; final products manufacturing; export and distribution; and marketing of the final products. A generalized global supply chain for the textile sector is presented in Figure 4.3. Some of these networks have introduced innovative management action, such as a sector-specific restricted substance list (Apparel and Footwear International RSL Management Group 2018). (Further examples are provided in Part III, Ch. 4 and Part IV, Ch. 7.)

Figure 4.3 Global supply chain in the textile sector (adapted from Martin 2013, p. 6)

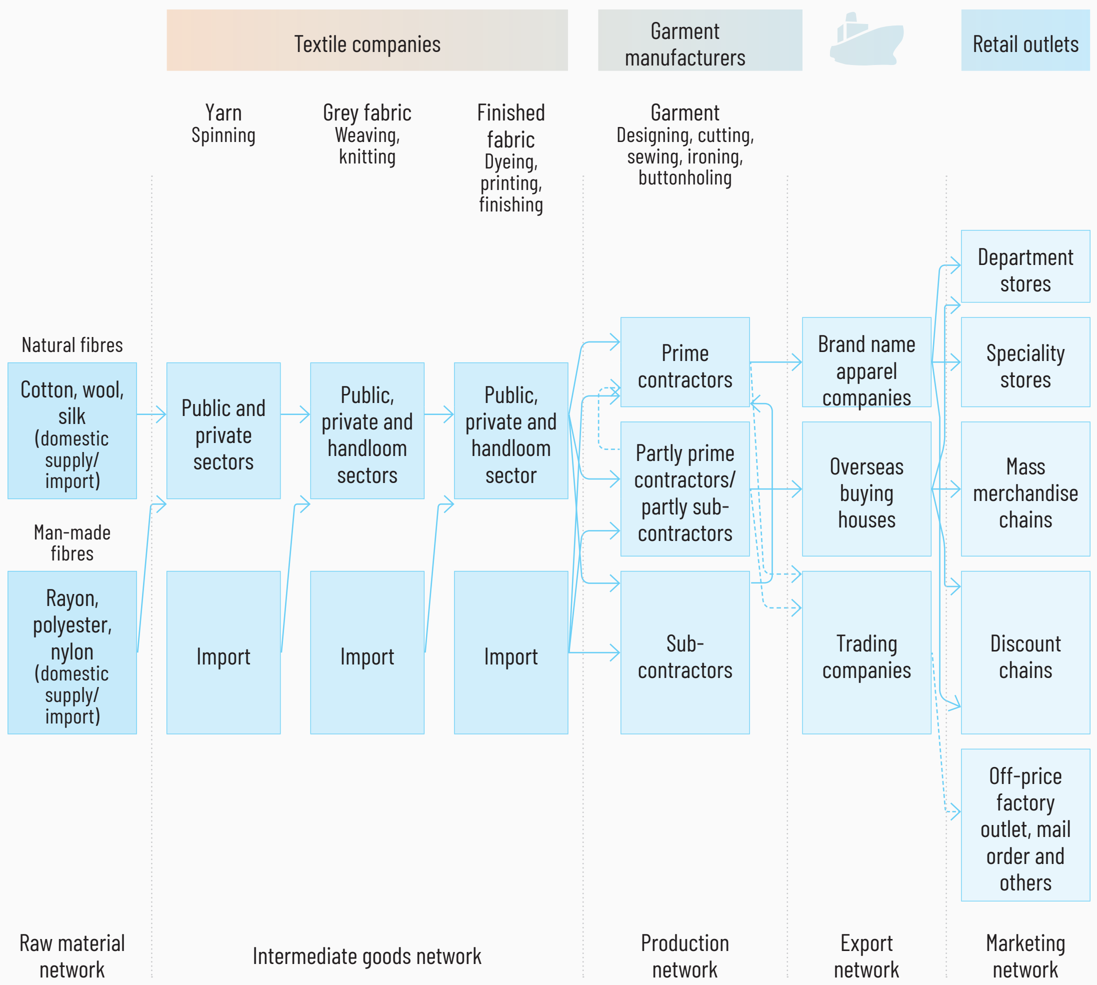


Table 4.1 Actors, main impact drivers and exposure over the product life cycle of toys

Life cycle stage	Actors	Main impact drivers and exposures	Evaluation tools and challenges	Management tools and entry point
Oil extraction and refinery	Oil companies	Worker exposures and industrial releases	Life cycle inventory of raw materials and oil refinery processes	
Chemical and plastic manufacturing	Chemical and plastic manufacturers	Worker exposures and industrial releases	Environmental genome of industrial products (EGIP) (Overcash 2016)	Supply chain management (SCM)
Toy design, manufacturing, assembling	Original equipment Manufacturers, market surveillance enforcement authorities	Product design worker exposure and industrial releases	Design for Environment worker exposure assessment (Kijko, Jolliet and Margni 2016)	SCM, ensure traceability of products, components
Trade – distribution, retail	Retailers, traders, enforcement authorities testing organizations	Transportation	Disclosure of product composition	Retailer disclosure policy labels
Purchase and use	Consumers, NGOs	Near-field exposures to chemicals in products, energy usage	Product Intake Fraction modeling (Fantke *et al.* 2016)	
Recycling	Recyclers – both formal and informal sectors	Chemical residues and contamination of recycled material	Material flow analysis, life cycle assessments (LCAs)	Dismantling as focus for informal sector, recycling and waste treatment for formal sector
Waste management	Municipalities, waste treatment facilities, recycling facilities, etc.	Waste treatment releases	End-of-life LCAs	From waste management to resource management

Traditional hierarchical and one-dimensional supply chains have largely been transformed into fragmented networks, involving strategic partnerships between many companies located in different parts of the world.

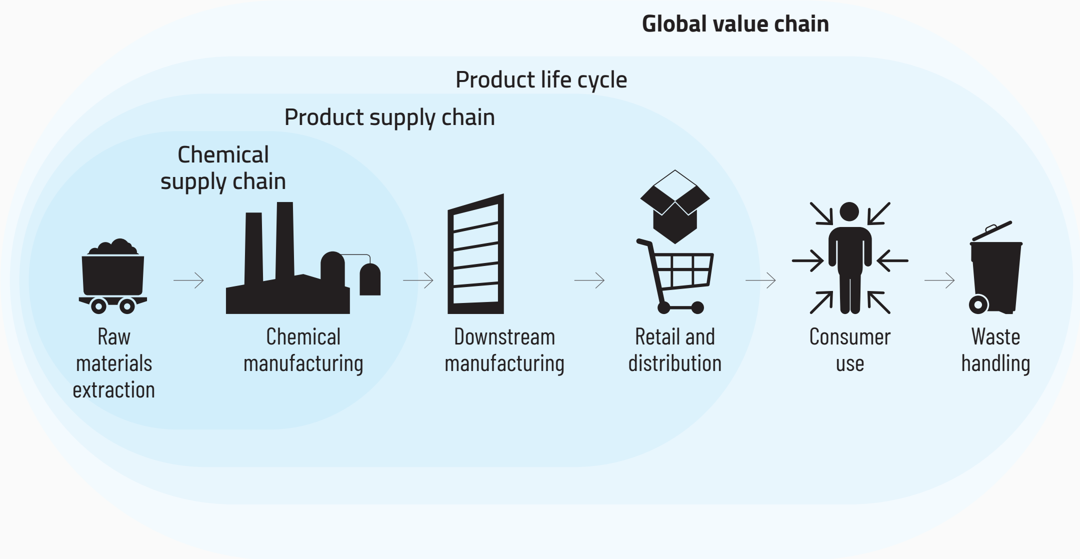
Different commodities involve different key players

The complexity of global supply chains implies that multiple stakeholders are involved, including resource extractors, chemical manufacturers, product manufacturers, bystanders, retailers, consumers, civil society organizations, and governments and international regulators. Table 4.1 shows key actors, drivers of chemicals-related impacts, evaluation tools and challenges, and indicative management options for each life cycle stage of toys. The institutional framework established on the international and national levels must be designed in a way that adequately responds to this complexity (responsive regulation), while the governance mechanisms at company level must address the complexity of its (global) supply chains.

4.2 Understanding chemicals in products and product life cycles

Manufactured chemicals are constituents of materials and products that we encounter in daily life. The global value chain of chemicals and products has several stages: raw materials are extracted and synthesized into chemicals, polymers and materials; products are manufactured and distributed; and, following consumption, products enter recycling or become waste. The life cycles of chemicals and of products are therefore closely interconnected. Each chemical has its own life cycle, from resource extraction, to chemical synthesis, to incorporation into a chemical formulation, composite material or product, to product use, to end-of-life treatment. Products, in turn, have their own resource extraction, product manufacturing

Figure 4.4 **Relationship between global value chains, product life cycles, product supply chains and chemical supply chains in a linear economy**



Supply chains are concerned with the flow (and purchase) of materials from the point of origin (e.g. raw material) to the point of use (product). The product life cycle extends from raw material extraction to waste handling. The global value chain concept refers to the broader system of adding value to an article (e.g. through production, marketing, and after-sales service and product stewardship).

or end-of-life treatment processes. Emissions of, and exposure to, chemicals may occur throughout all stages of the chemical and product supply chains and product life cycle. Figure 4.4 illustrates the relationship between global value chains, product life cycles, product supply chains and chemical supply chains in a linear economy.

Use and functions of chemicals along the product life cycle

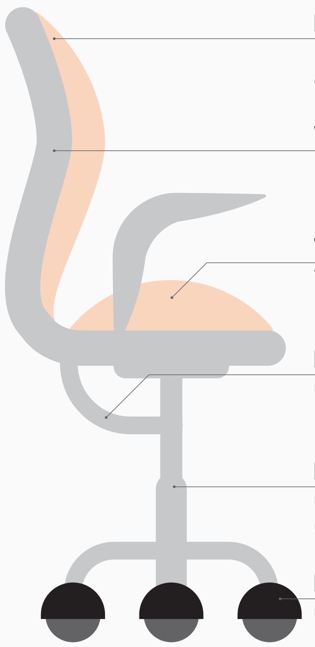
Chemicals fulfil diverse specific functions, as basic constituents of simple and composite materials and polymers (e.g. as stabilizers or adhesives) and to shape the quality of end market products (e.g. colour, viscosity, stability). Furthermore, they fulfil specific functions in the realm of production and product systems within the product life cycle. For example, chemicals are used in auxiliary processes for resource extraction (e.g. potassium chloride to recover crude oil from shale rock), in manufacturing (e.g. hydrogen peroxide in pulp and paper bleaching), during product use (e.g. hydrofluorocarbon refrigerants to run air conditioners) and in waste treatment (e.g. sodium hydroxide to remove paint from disposed products).

Most chemicals are synthesized and manufactured in complex production systems. During this process, some chemicals are used as processing input (e.g. catalyst) while others are generated as intentional co-products or unintentional by-products (Overcash 2016). Unintentional chemical by-products may include persistent, bioaccumulative and toxic compounds, such as dioxins formed as the result of incomplete combustion (Baker and Hites 2000) or during the manufacturing of chlorinated pesticides (Holt *et al.* 2010). In contrast, chemical co-products are subsequently used, for example, as solvents in specialty chemicals. An example is the production of polyethylene from crude oil, which also yields, among others, benzene as chemical co-product.

The chemical content in products varies

Modern-day products often contain hundreds of chemicals (Figure 4.5). Many of these chemicals

Figure 4.5 **Chemicals in an office chair (adapted from Swedish Chemicals Agency [KEMI] 2016a, p. 7)**



may have hazardous properties. The universe of products includes formulated chemical products (often sold as liquids, gels or aerosols with certain performance properties) as well as articles (products whose function is determined primarily by shape rather than by a particular chemical composition). Examples of chemicals in products include formaldehyde in shampoo, microbeads in toothpaste, phthalates in food packaging, certain flame retardants in televisions, and antimicrobials (e.g. triclosan) in soaps. Many formulated products (e.g. personal care products and household cleaners) contain multiple chemical compounds of distinct composition (as a function of brand, regulatory requirements and target consumers), yet fulfil the same desired function.

In a number of cases simple metal or wooden tools, toys and household products have been replaced by products made of complex polymer and composite materials filled with a wide range of functional additives. Some of the intentionally added chemicals in today's complex composite materials may have hazardous properties. For example, in 2013 in the State of Washington in the United States companies were required to disclose the use of chemicals of high concern (e.g. cadmium, mercury, molybdenum, antimony and cobalt) if they were present in children's products that were sold (Uding and Schreder 2013). In the United States textiles, skin products, plastics and other children's items have been found to contain potentially hormone-disrupting chemicals such as certain phthalates, bisphenol A, parabens, nonylphenol and D4; low levels of phthalates have been found in more than 700 products (Kay 2013).

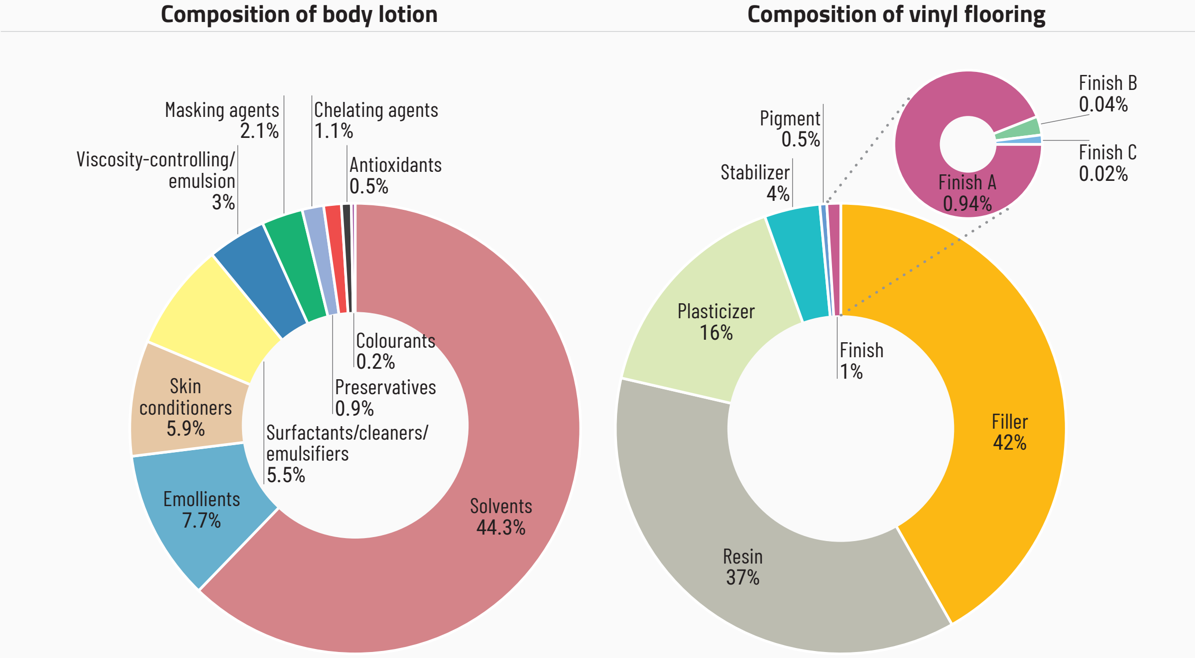
Concentrations of chemicals in products vary widely, depending on the intended function (Isaacs *et al.* 2018), with some formulated products containing chemicals of concern at significant concentrations. For certain classes of products, such as cleaning products, the chemical composition and content have been relatively well-characterized. They are available through different databases (e.g. Goldsmith *et al.* 2014) or can be estimated based on the chemical function (Phillips *et al.* 2017). Concentrations range, for example, from up to 50 per cent in plasticizers or flame retardants to less than 0.01 per cent in pigments or some solvents (Hansen, Nilsson and Ravnholt Vium 2014). Solvents in body lotion account for approximately 60 per cent of mass/volume (Figure 4.6, left side), while colourants account for approximately 0.5 per cent.

However, for many products, such as building materials, the chemical composition is often unknown. This creates challenges for assessing associated exposure and risks. At present,

assessments of such products rely on databases derived from product safety datasheets (e.g. for vinyl flooring) (Figure 4.6, right side) and current composition industry databases (e.g. the Pharos database developed by the Healthy Building Network).

In some cases, products may contain chemicals despite the existence of regulations that limit or prohibit their use. Several such cases have been reported in recent years. For example, the Swedish Chemicals Agency analyzed a number of electrical and electronic products

Figure 4.6 **Variations in chemical content in a body lotion and in vinyl flooring (per cent) (adapted from Fantke *et al.* 2019 and Isaacs *et al.* 2016, p. 728)**



and found 38 per cent to contain too high levels of prohibited chemical substances, including lead and short chain chlorinated paraffins (KEMI 2016b).

Unintentional chemical residues show up in articles and products

In addition to intentionally added chemicals that fulfil a certain performance function, products and their articles may also contain unintended chemical contaminants. These chemicals may be residuals from the chemicals used in product manufacture, or may originate from packaging or other sources such as cross-contamination via recycling. Moreover, chemicals included in pharmaceuticals, pesticide formulations or plastics may become residues in other products such as food products (Fantke, Friedrich and Jolliet 2012). Food contaminants typically include environmental contaminants, food processing contaminants, unapproved adulterants and food additives, and chemical migrants from packaging materials. If they are characterized by a high fat content, food products are likely to absorb chemicals from plastic packaging and other materials. Some persistent environmental contaminants tend to accumulate in meat, poultry, fish and dairy products. Other chemicals, such as perchlorate and pesticides, are present in fruits, vegetables and other agricultural commodities at various concentrations. This is further explored in Part I, Ch. 6.

Table 4.2 provides some specific examples of studies which have identified residues of unintentional chemicals in products. Unintended chemical residues are usually found at trace

Table 4.2 Examples of studies identifying unintended chemical contaminants in products

Product/article	Chemical(s)	Example study
Thermo cups and kitchen utensils	brominated flame retardants, e.g. decabromodiphenyl ether (decaBDE), tetrabromobisphenol A (TBBPA)	Samsonek and Puype 2013
Electrical articles	lead	KEMI 2014
Waste paper and board from households	mineral oil hydrocarbons, phthalates, phenols, polychlorinated biphenyls, and selected toxic metals	Pivnenko *et al.* 2016
Children's toys	polybrominated diphenyl ethers (PBDEs) and phosphate flame retardants (PFRs); plasticizers such as phthalate esters	Ionas *et al.* 2014
Packaging material	hexabromocyclododecane (HBCDD)	Bodar *et al.* 2018
Rubber on playgrounds and football fields	polycyclic aromatic hydrocarbons (PAHs), phthalates, antioxidants (e.g. BHT, phenols), benzothiazole and derivatives	Llompart *et al.* 2013, Bodar *et al.* 2018
Pizza board package	phthalates and synthetic biocides	Pieke, Smedsgaard and Granby 2018
Various food samples	bisphenols	Liao and Kannan 2013
Commercial salt	microplastics (polypropylene, polyethylene and others)	Karami *et al.* 2017
Honey	neonicotinoids (acetamiprid, clothianidin, imidacloprid, thiacloprid and thiamethoxam)	Mitchell *et al.* 2017
Lettuce	various pesticides	Skovgaard *et al.* 2017
Various food samples	DDE (a DDT metabolite), PCB congeners, PFOA and others	Schecter *et al.* 2010
Wine	lead (584 µg/kg, sample taken in 2015)	WHO 2018
Cooked crabs	dioxins (WHO TEF; 740 pg/kg; sample taken in 2010	WHO 2018

Whether the presence of chemical contaminants in products poses a risk depends on exposure and is determined by a number of factors, as further explored in Part III. This overview does not provide an assessment of whether measured concentrations exceeded relevant thresholds set by regulatory bodies (further information is provided in Part I, Ch. 6).

levels and at the lower end of the range of content fractions compared to intentional chemical ingredients, unless there is mishandling or an accident in chemical formulation. Yet they may create challenges for recycling and for ensuring that material cycles are non-toxic.

Chemicals, waste and circularity

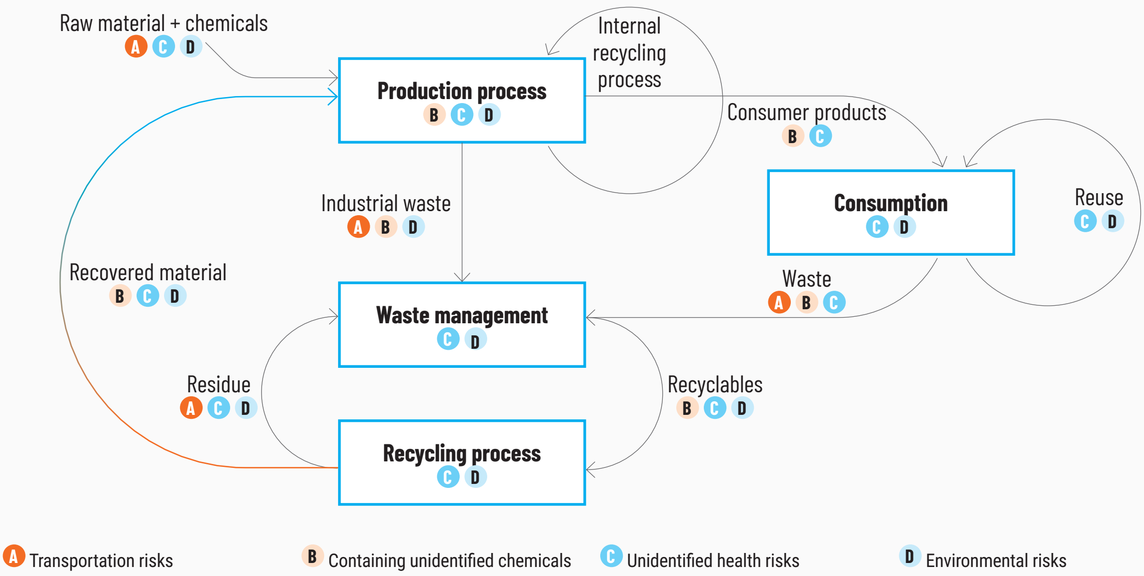
The circular economy concept seeks to minimize the extraction of natural resources, keep the extracted resources in use as long as possible, and promote recovery and regeneration of products and materials at the end of their life cycles. Such reuse and recycling is compatible with international policy objectives that aim at promoting environmental sustainability and resource efficiency (Bodar *et al.* 2018). Despite some differences in interpretation, the circular economy concept has recently been gaining attention in the scientific and policy communities (Homrich *et al.* 2018) as well as the private sector (Accenture 2017).

The increasing trade of chemicals and related products, and the quest to recycle products and materials, create opportunities but also raise concerns regarding the fate of chemicals and chemicals in products once they reach the waste stage or become secondary raw materials. Challenges include the chemical content of products becoming secondary raw materials, as well as the global flows of recycled products often being unknown, potentially impeding management intervention that could ensure undesired chemicals re-entering supply chains are not causing health and safety problems at various stages of the material flow (Figure 4.7).

As various products such as paper and cardboard, plastics and lubricants are recycled, they may become “secondary raw materials”. Products made from recycled materials (e.g. textiles and carpets) may contain, for example, heavy metal traces from the original product applications. Studies have found, among others, flame retardants in consumer products most likely originating from recycled plastics (Schecter *et al.* 2011) and various chemical contaminants in recyclable waste paper derived from households (Figure 4.8) Another study (Llompart *et al.* 2013) found various hazardous substances in rubber playground equipment, including high concentrations of polycyclic aromatic hydrocarbons (PAHs) likely originating from recycled rubber tyres. Furthermore, there is mounting evidence that the demand for black plastics in consumer products is partly met by sourcing materials from the plastic housings of end-of-life waste electronic and electrical equipment. This creates a potential to introduce restricted and hazardous substances into the recyclate (e.g. including brominated flame retardants; antimony, a flame retardant synergist;

Various chemical contaminants have been found in recyclable waste paper.

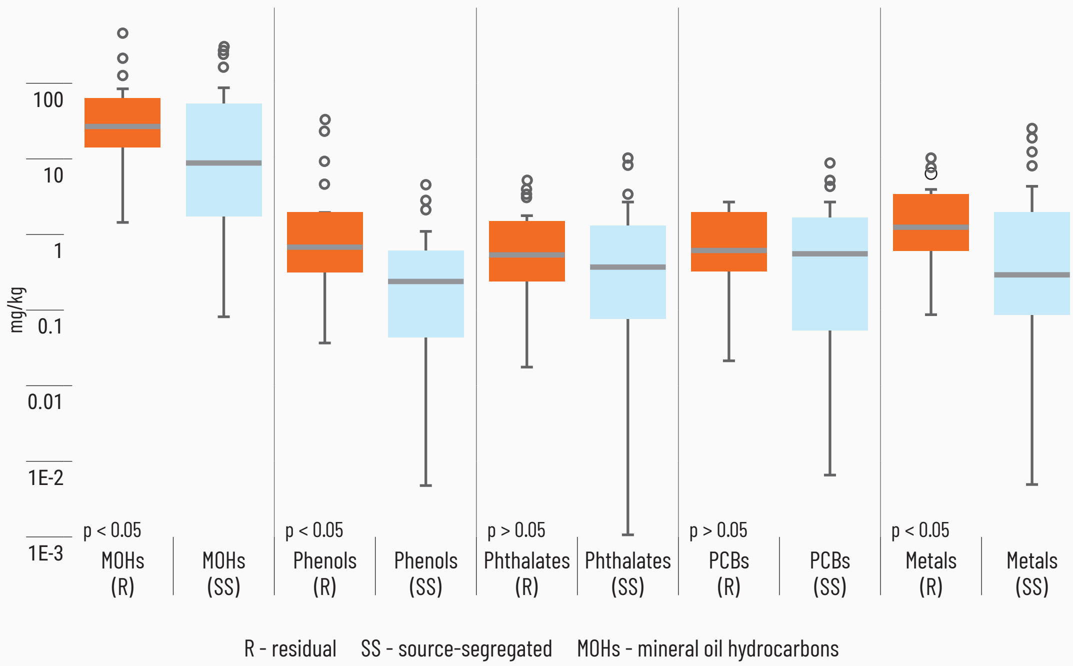
Figure 4.7 **Simplified material flow of a circular economy in a global scale with health and environmental risks (adapted from Grundmann *et al.* 2013, p. 2)**



and the heavy metals cadmium, chromium, mercury and lead) (Turner 2018).

The presence of hazardous substances in products, whether intentional or unintentional, including through recycling, thus poses challenges

Figure 4.8 **Unintended residues found in recyclable waste paper (mg/kg) (adapted from Pivnenko *et al.* 2016, p. 51)**



The values for PCBs are in µg/kg. The p values indicate a significant ($p < 0.05$) or non-significant ($p > 0.05$) difference between residual and source-segregated waste paper.

to circularity and the implementation of the waste hierarchy, which emphasizes source reduction, reuse and recycling. A coherent approach to the sound management of chemicals and waste in a circularity context implies that undesired substances are not used in consumer products, and that potential cross-contamination and related exposures or releases to the environment are avoided. A challenge for all actors engaged in the supply chain is therefore to effectively address potential trade-offs between increasing recycling rates on the one hand, and consumer and environmental exposure associated with cross-contaminated products on the other. At the same time, these considerations create a driver and opportunity for the chemical and engineering sciences to provide the basis for innovative products that can be reused and recycled without sustainability trade-offs. Under this paradigm, substances and chemicals in products are considered as a resource and not as potential wastes (Clark *et al.* 2016).

Further gaps and research needs closely related to achieving the sound management of chemicals and waste throughout the life cycle include the following (Grundmann *et al.* 2013):

- lack of data about chemicals in products;
- risks of chemical mixtures;
- releases of chemicals from materials and goods;
- scarce information on characteristics related to use of chemicals;
- associated uncertainty missing for *in vivo* experiments;
- the need to increase the acceptability of alternative methods;
- lack of information and missing common databases for additives;
- limited specific data about informal recycling processes (e.g. efficiency, emissions);
- lack of more detailed emission models for products; and
- lack of a clear link between emissions and impacts of chemicals.

4.3 Sustainability considerations across chemical supply chains and product life cycles

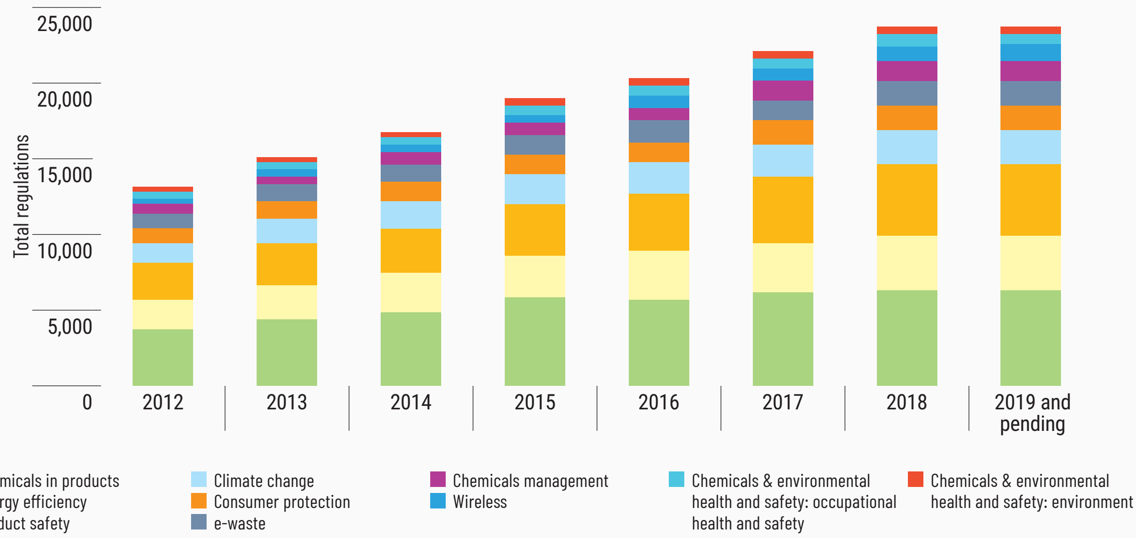
Management challenges across complex supply chains

Global supply chains within and across industry sectors, along with the increasing global trade of goods, have created challenges from a sustainability perspective. These challenges

Box 4.1 An example of challenges related to the interface of chemicals, waste and circularity: the phthalate plasticizer DEHP in PVC (adapted from EC 2018)

Flexible PVC from post-consumer waste can contain up to 20 per cent of the plasticizer substance DEHP. This plasticizer is classified as hazardous due to its adverse effects on the human reproductive system and is subject to certain use restrictions and to authorization in the EU. When PVC containing DEHP is recovered, it is subject to authorization under the EU's Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) Regulation and must comply with the REACH and Classification, Labelling and Packaging (CLP) rules for hazardous mixtures in order to reach end-of-waste status. There are, however, no EU harmonized or national end-of-waste criteria applicable to PVC waste containing DEHP and no relevant national case-by-case decisions. Yet a number of recycling companies have applied for authorization to use the recycled material under REACH, considering their PVC containing DEHP no longer to be in the waste phase. Lack of harmonization and different interpretations of waste classification and end-of-waste provisions have led to uncertainties about the conditions under which operators must continue to manage and trade this material as waste rather than as a product.

Figure 4.9 Concept-to-production (C2P) global regulations by subject, cumulative total (adapted from Compliance and Risks 2018)



include unintended releases of chemicals during resource extraction and manufacturing; occupational exposures during manufacturing; consumer exposures during use; and releases during recycling or disposal at the end of a product's useful life. Many of the companies involved (sometimes SMEs) operate in countries with limited regulatory capacity. In addition, international trade may shift problems from one region to another (Wiedmann and Lenzen 2018).

In complex global supply chains it may be difficult for final product brand-identified corporations, such as Apple, Nike, Adidas, Unilever, Ford and Volkswagen, to manage their suppliers. One challenge is to know what chemicals are in the components or articles that go into the products that they bring onto the market. For example, the lead paint discovered in 2007 on the toy trains Mattel marketed worldwide appear to have been the result of undisclosed activities of second and third tier suppliers in the supply chain (Jennings 2007). The same applies to environmental emissions associated with the different extraction, manufacturing and processing steps along the entire supply chain of a product.

Managing complex supply chains: policy instruments and challenges

The number of standards and regulations to manage global supply chains and extended producer responsibility has increased significantly over the last 15 years (Figure 4.9). These include, but are not limited to, regulations addressing production processes, individual substances and harmful product constituents, product safety measures and waste handling. However, while codes, standards and regulations are mostly national, supply chains are global, complicating effective management. This situation, and the increasing global trade of chemicals and products (described in Part I, Ch. 1, 2), create opportunities to explore approaches for effective global governance that can reduce impacts along the entire supply chain. This includes measures to avoid burden shifting (i.e. avoiding adverse impacts associated with imported goods in the exporting manufacturing countries) (Normile 2017), or avoiding waste from exporting countries creating adverse impacts in importing countries. Agreements that facilitate trade therefore need to foster effective regulations that take into account human health and environmental considerations related to chemicals and waste across countries.

One growing challenge to ensuring compliance with regulatory requirements in different parts of the world, and for complex supply chains, relates to cross-border trade and e-commerce. Recent research shows that imported chemicals or products often do not comply with the chemicals legislation of the importing country (see also Part II, Ch. 3). For example, various products imported into the EU were found to contain illegal amounts of restricted chemicals (ECHA 2018a). Similar challenges have been encountered in the United States. For example, 12 per cent of imported shrimp tested for drug residue and other toxins were rejected (US Government Accountability Office 2017).

As regards e-commerce, many chemicals can now be ordered directly from anywhere in the world by private entities which may be unaware of safety regulations and responsibilities. In 2017 the ECHA conducted an inspection of 1,314 internet advertisements for chemical mixtures to determine whether they complied with EU CLP regulations. It found that 82 per cent did not contain the required hazard information. Most of the advertised chemical mixtures were used in households (37 per cent), were used in construction (16 per cent) or were motor products (14 per cent) (ECHA 2018b).

The trend towards circularity also creates challenges for aligning chemicals and waste standards and regulations. In a non-circular economy, products usually become waste and thus fall under the respective waste legislations. However, in a circular economy recyclable materials and products increasingly become "secondary raw materials" to which different regulatory requirements apply, such as specific end-of-waste criteria. The challenge is to ensure that hazardous materials do not re-enter the life cycle in new materials as a result of a circular approach. In Europe end-of-waste criteria have already been specifically developed for iron, steel and aluminium scrap, glass cullet and copper scrap. Opportunities exist to develop such criteria for a wider realm of recyclable materials and products, such as waste plastic re-entering the market (Villanueva and Eder 2014).

Assessing impacts across supply chains and product life cycles

Addressing chemical and product life cycles in a sustainable way requires proper management of information flows and feedback loops among stakeholders involved in the supply chain. Approaches are emerging which complement market-based supply chain management, measuring the environmental as well as social impacts associated with chemical pollution and working conditions along the supply chain and throughout the life cycle. Measuring environmental and social sustainability upstream and downstream can provide a basis for increasing full supply-chain sustainability (O'Rourke 2014). Advances in life cycle assessment (LCA) and in the calculation of product environmental footprints may help translate impacts into decision support for companies (Hellweg and Milà i Canals 2014). However, LCA is not without its own limitations, challenges and critiques; it should therefore be applied and interpreted with caution (Gutowski 2018). Opportunities also exist to advance the integration of the chemicals dimension in LCA models and tools. Further details are provided in Part III, Ch. 7.

Life cycle management (LCM) encourages a holistic perspective. It covers the entire chemical or product life cycle and calls for managerial decisions that consider environmental and health impacts. LCM provides an opportunity to minimize the environmental and socio-economic burden while maximizing economic and social value (Bey 2018). Applying the life cycle perspective is also of key relevance in advancing a circular economy and closing material loops along chemical and product life cycles and creating self-sustaining production systems. A holistic view in assessing chemical-related releases to the environment, or human exposure, helps identify and avoid performance improvements at one life cycle stage (e.g. decreased raw material extraction through recycling) at the expense of increased impacts at another stage (e.g. increased residues of contaminants in recirculates and related consumer exposure and related human health risks). It helps avoid what is commonly known as burden-shifting (Hellweg and Milà i Canals 2014). Finally, assessing and managing chemicals along entire product life cycles allows environmental performance of products, and their supply chains, to be benchmarked against pollution and exposure reduction targets set by the global sustainable development agenda in support of developing products and technologies that are sustainable in absolute terms (Fantke and Illner 2019).

Enhancing traceability of chemicals in the supply chain

Ensuring the traceability of chemicals along the supply chain has been addressed by the Strategic Approach to International Chemicals Management (SAICM) for many years, and was added in 2015 to the International Organization for Standardization (ISO) 9000 series on quality management and quality assurance management series. It is a key feature to address product stewardship along the supply chain. In this respect, the "Proactive Alliance" is developing criteria for a cross-sectoral global standard heading towards a "Full Material Disclosure" (FMD) as a governance response to the complexity and various interlinks of the global supply chain. Regulatory approaches aiming to support a circular economy, such as the substances of very high concern (SVHC) database to be hosted by the ECHA, have been triggering this development (Global inter-sector standard for Substances in Articles [SiA] communication 2018; Stringer 2018).

5/ Chemical pollution: emissions, releases and wastes

Chapter Highlights

Large amounts of manufactured chemicals continue to be released to the air, water and soil.

Releases of heavy metals continue to pollute soils worldwide.

Total fertilizer and pesticide applications to soil are increasing, but application rates are decreasing.

Globally, atmospheric releases of mercury remain high.

Chemicals of concern are released indoors from consumer products and building materials.

Significant progress has been made in reducing releases of some chemicals of concern, including ozone-depleting substances and some persistent organic pollutants (POPs).

Waste dumps and informal recycling are major sources of pollution in many countries.

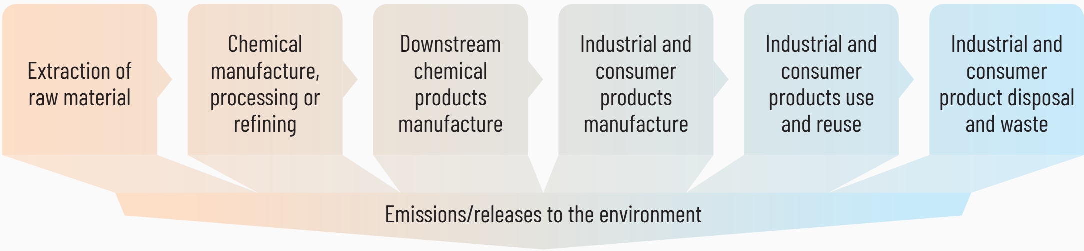
Industrial accidents and natural disasters result in significant pollution.

This chapter compiles and synthesizes available information on the emissions and releases of chemicals to indoor and outdoor environments and on the generation of waste, particularly hazardous waste. Since chemicals are released to various media and released from various sources, both the media and the sources are considered. The first part of the chapter addresses the environmental media as an entry point, using knowledge on releases to air, freshwater and oceans, and soil. The second part takes the source categories as an entry point, exploring releases from products, production processes, municipal and hazardous waste, and industrial accidents and natural disasters. The chapter concludes with a brief discussion of challenges and opportunities in regard to compiling pertinent data and knowledge.

Emissions to air, water and soil

Every year millions of tonnes of manufactured chemicals are released to the environment as air emissions, water discharges, and solid and hazardous waste. While simulation models can be used to estimate the scale of the releases, an accurate assessment of their volumes is inhibited by the multitude of sources. Traces of these emissions and releases are found as pollutants in environmental media in every world region. In many parts of the world emissions and releases of many hazardous chemicals are increasing. Not only do these emissions pose risks to human health and the environment. They also represent lost opportunities to realize economic benefits.

Figure 5.1 The value chain of the chemical industry, with emissions/releases to the environment



Manufactured chemicals can be released at each step in the value chain of the global chemicals economy (Figure 5.1). Large volumes occur as waste materials generated by specific technologies and economic processes. Significant amounts are also released as unintentional leaks, spills and fugitive emissions.

Some of the largest sources of releases of hazardous chemicals are mining, agriculture, wastewater treatment, energy generation, chemical production, and product manufacturing, use and disposal. There is no comprehensive global system for monitoring and tracking these releases. While ambient air measurement and modelling can provide important insights, they cannot replace production or release inventories. Some 30 countries have established national Pollutant Release and Transfer Registers (PRTRs) to track releases of hazardous chemicals from industrial facilities (OECD 2018). PRTRs are useful for monitoring national emissions. However, their usefulness for aggregating data and assessing global trends is restricted by the limited number of chemicals and diverse types of facilities covered, as well as varying reporting thresholds and periods (US EPA n.d. a) (see also Part II, Ch. 3).

5.1.1 Emissions to air

Manufactured chemicals enter the atmosphere through direct emissions, including from stationary point and area sources such as factories and parking lots; mobile sources such as cars and airplanes; diffuse emissions, including pesticide spraying; and fugitive emissions such as those from commercial and household products. Because air emissions travel long distances and have impacts on countries outside the country

of their origin, air pollution is a significant transboundary issue.

Releases of ozone-depleting substances have been sharply reduced

National policies established in conformance with the Montreal Protocol on Substances that Deplete the Ozone Layer, which entered into force in 1989 (see Part II, Ch. 1-3), have led to the phase-out of 99 per cent of ozone-depleting chemicals, resulting in significant reductions in releases (Secretariat of the Vienna Convention and its Montreal Protocol 2018). The remaining 1 per cent consists largely of hydrochlorofluorocarbons (HCFCs), a group of controlled substances with ozone-depleting potential much lower than that of the ozone-depleting substances (ODS) they replace (e.g. chlorofluorocarbons [CFCs] and halons). In 2009 it was estimated that this reduction had contributed to climate change mitigation through averting the emission of 135 billion tonnes of carbon dioxide equivalent (CO_2-eq) to the atmosphere (Molina *et al.* 2009).

In 2007 the Parties to the Montreal Protocol decided to accelerate the phase-out of HCFCs. In 2016 they agreed to phase down the consumption and production of hydrofluorocarbons (HFCs), as stipulated in the Kigali Amendment to the Montreal Protocol (UNEP 2016a). While HFCs are not ODS, they are powerful GHGs that are used as ODS substitutes primarily in air conditioning, refrigeration and foam insulation. HFCs can be thousands of times more harmful to the climate than CO_2. In 2010, however, 5.4 million tonnes of ODS were estimated to be banked in existing refrigeration and air conditioning equipment, and contained in insulation foam, that could gradually be vented into the atmosphere (UNEP 2009).

A recent study published in *Nature* (Montzka *et al.* 2018) indicated that trichlorofluoromethane (CFC-11) still contributes one-quarter of all chlorine reaching the stratosphere, while a timely recovery of the stratospheric ozone layer depends on a sustained decline in CFC-11 concentrations. The rate of decline of atmospheric CFC-11 concentrations observed at remote measurement sites was constant from 2002 to 2012. It slowed by about 50 per cent after 2012. Based on a simple model analysis, an increase in CFC-11 emissions of 13 ± 5 gigagrams per year since 2012 has been suggested, despite reported production being close to zero since 2006. According to the study, the increase in emissions of CFC-11 appears unrelated to past production, suggesting unreported new production. Further research on this matter is being undertaken. However, the recent discovery of the rate of decline of CFC-11 in the atmosphere, and the potential increase in emissions, demonstrate the importance of continued atmospheric monitoring even when global compliance is high.

The chemical industry is a significant source of greenhouse gas emissions

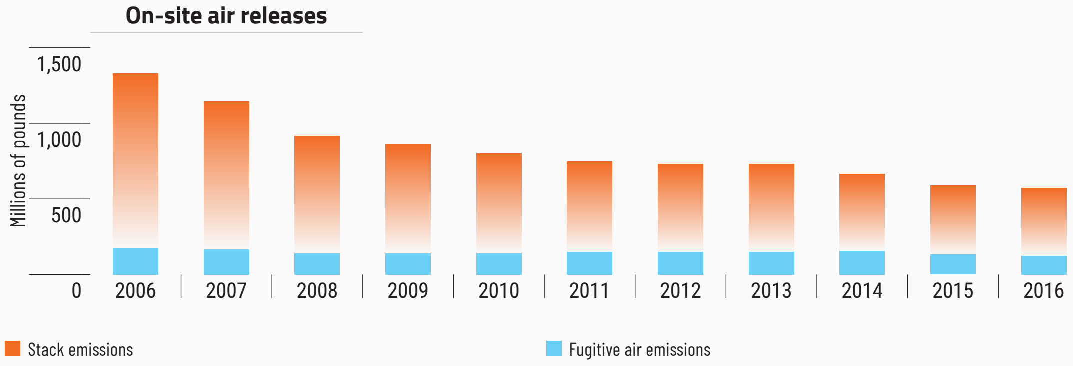
The chemical industry generates about 5.5 per cent of global CO_2 emissions (7 per cent of global GHG emissions) and about 17 per cent of all industrial CO_2 emissions (20 per cent of all industrial GHG emissions). During the past decade it has made significant reductions in its energy consumption and GHG emissions, a trend which is expected to continue (IEA, ICCA and Society for Chemical Engineering and Biotechnology 2013).

Some of the chemicals manufactured by the chemical industry also contribute to GHG emissions. Use of nitrogen-based fertilizers in agriculture (which rose from 11 million tonnes in 1961 to 108 million tonnes in 2014) contributes substantially to emissions of nitrous oxide, an extremely potent GHG. Sulphur hexafluoride, another extremely potent GHG, continues to be used in (and released from) the electronic product manufacturing and magnesium industries, while fluorinated ethers used in degreasing applications are emitted directly to the atmosphere (EEA 2017a).

Releases of hazardous air pollutants vary by region

In middle- and higher-income countries governments monitor and regulate national “priority air pollutants” (e.g. particulate matter, ground level ozone, carbon monoxide, lead,

Figure 5.2 On-site air releases in the United States reported to the Toxics Release Inventory (TRI), 2006-2016 (million pounds) (adapted from US EPA 2019, p. 39)



and sulphur and nitrogen oxides) that are largely generated by combustion. There has been a general long-term decline in releases of these chemicals except in the case of lead, whose emission rates vary between countries (EEA 2017b; US EPA n.d. b). However, emissions of these same chemicals are increasing in the rapidly urbanizing cities of many emerging economies, often leading to highly polluted urban air.

Atmospheric releases of manufactured chemicals from industrial sources are tracked by national PRTRs (see above). Those chemicals with the largest volume releases to air reported under the United States Toxics Release Inventory (TRI) (the PRTR in the United States) include ammonia, hydrochloric acid, methane, sulphuric acid and hydrogen sulphide, along with organic chemicals such as methane, n-hexane, styrene and toluene. Between 2006 and 2016 releases of these chemicals to air decreased by 58 per cent (829 million pounds); the most significant reductions were of hydrochloric acid, sulphuric acid, hydrogen fluoride, methanol, toluene and styrene (US EPA 2019). Figure 5.2 shows trends for hazardous chemicals released to the atmosphere by regulated facilities, as reported to the TRI.

The European Environment Agency (EEA) PRTR has reported that emissions of nitrous oxide, sulphur dioxide and ammonia decreased significantly in most European countries between 1990 and 2012 (EEA 2015). Emissions of industrial air pollutants such as heavy metals and volatile organic compounds (VOCs) also declined, while emissions of lead, cadmium and mercury, dioxins and furans, hexachlorobenzene and PCBs decreased by 67 per cent or more compared with 1990 (Guerreiro *et al.* 2015). Around 94 per cent of air emissions of ammonia in Europe are from agriculture. According to a recent EEA report, these emissions decreased by 23 per cent between 1990 and 2015 but increased between 2014 and 2015 by 1.8 per cent, with much of that increase occurring in France, Germany and Spain (EEA 2017b).

The extent of atmospheric releases of manufactured chemicals from industrial sources in lower-income countries is difficult to determine in the absence of national monitoring systems, such as national PRTRs, in many of these countries.

Emissions of some POPs have decreased but those of others continue

Atmospheric emissions of various POPs have decreased significantly since 1990 among Parties to the Convention on Long-range Transboundary Air Pollution (e.g. 95 per cent for hexachlorobenzene, 75 per cent for PCBs, 70 per cent for dioxins and furans and 83 per cent for PAHs) (EEA 2018). A review of monitoring data from the Arctic Monitoring and Assessment Programme (AMAP) collected over 20 years reveals that primary emissions of most of the POPs first listed under the Stockholm Convention

are declining. Trends are less positive for other POPs, notably polybromated diphenyl ethers (PBDEs), HCB and PCBs, among others, due in part to their remobilization (Hung *et al.* 2016).

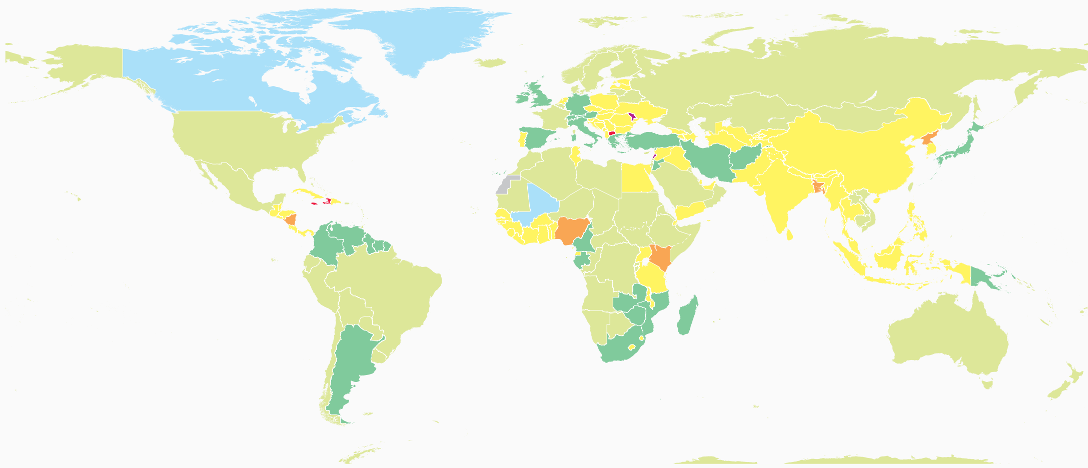
While releases of the POPs first listed under the Stockholm Convention have decreased in most higher-income countries, some compounds continue to be manufactured and released in lower-income countries. For example, DDT is manufactured in India and continues to be used also in some African countries for disease vector control. According to the effectiveness evaluation of the Stockholm Convention, the Convention is expected to result in decreasing levels of unintentional POPs in all regions. Data on releases of unintentionally produced POPs at different times, especially from developing countries and economies in transition, is limited, although initial results show positive trends (UNEP and Secretariat of the Stockholm Convention 2017).

PCDD/PCDF (classified as human carcinogens by the International Agency for Research on Cancer) are not commercially produced, but are formed as trace amounts of undesired impurities in the manufacture of other chemicals or during combustion processes. PCDD/PCDF are released from a variety of sources, with open burning of waste by far the most significant source of emissions to air, particularly in developing countries (Fiedler 2007). According to the effectiveness evaluation of the Stockholm Convention, reported releases of PCDD/PCDF remained almost unchanged between the baseline (2001-2011) and the update (2001-2015). The Asia-Pacific region reported the highest increase and the Western Europe and Others region the strongest decline (Secretariat of the Stockholm Convention 2017). A 2016 study (Wang *et al.* 2016) provided a global estimate of PCDD/PCDF releases. Figure 5.3 shows the releases per unit area that account for the observation that the environmental burden from the release of a certain amount of PCDD/PCDF generally depends on the size of the area to which the release occurs. While the highest releases were estimated to be in Asia, per capita releases in that region were below the global

Box 5.1 Outcomes of the effectiveness evaluation of the Stockholm Convention (UNEP and Secretariat of the Stockholm Convention 2017, p. 4)

The effectiveness evaluation of the Stockholm Convention made available in 2017 found, among other outcomes, that "monitoring results indicate that regulations targeting POPs are succeeding in reducing levels of POPs in humans and the environment. For POPs listed in 2004 under the Convention, concentrations measured in air and in human populations have declined and continue to decline or remain at low levels due to restrictions on POPs that predated the Stockholm Convention and are now incorporated in it. For the newly listed POPs, concentrations are beginning to show decreases, although in a few instances, increasing and/or stable levels are observed".

Figure 5.3 **National/regional PCDD/PCDF releases per unit area (adapted from Wang *et al.* 2016, p. 307)**



Release per unit area (mg Toxic Equivalent (TEQ) km^{-2} yr^{-1})

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0.001–0.1 (4) 0.1–0.5 (41) 0.5–1 (32) 1–5 (79) 5–10 (21) 10–15 (9) 15–28.2 (10)

average; by contrast, while the lowest releases were estimated to be in Oceania, this region was estimated to have the highest releases per capita (also due to non-anthropogenic sources).

Atmospheric emissions of mercury are a significant source of air pollution

It is estimated that cumulative global anthropogenic releases of mercury to the environment up to 2010 amounted to about 1.54 million tonnes, 73 per cent of which had been emitted since 1850 (Streets *et al.* 2017). Anthropogenic mercury emissions to the atmosphere are currently more than 2,000 tonnes per year, or about 30 per cent of total annual global atmospheric mercury emissions. A significant share of these emissions comes from industrial areas in East and South Asia, Central Europe, South Africa and eastern North America. The remainder come from natural processes (60 per cent) that result in re-emissions of mercury previously deposited to soils and water (much of which are derived from earlier anthropogenic emissions and releases) and from natural sources (10 per cent) (UNEP and AMAP 2017).

Artisanal and small-scale gold mining (ASGM) is also a significant source of mercury released to air: 37 per cent of global air emissions of mercury are produced by ASGM. Mercury vapour in the air around amalgam burning sites almost always exceeds the WHO limits for public exposure (Gibb and O'Leary 2014). Other important sources of mercury emissions include stationary coal combustion, power plants, vinyl chloride monomer production, industrial uses and domestic/residential burning. These are followed by emissions from non-ferrous metal production and from cement production. Emissions associated with the disposal of mercury-containing product waste make up some 7.6 per cent of the air emissions (UNEP and AMAP 2017).

Global mercury emissions show a slow decline with regional differences. Significant decreases in emissions in Europe and North America are offset by increases in Asia. Trends observed in North America and Europe reflect the phase-out of mercury from commercial products, the closing of coal-fired power plants, and improved pollution controls on remaining coal-fired utilities (Zhang *et al.* 2016).

Releases from waste dumps are a key source of air pollutants

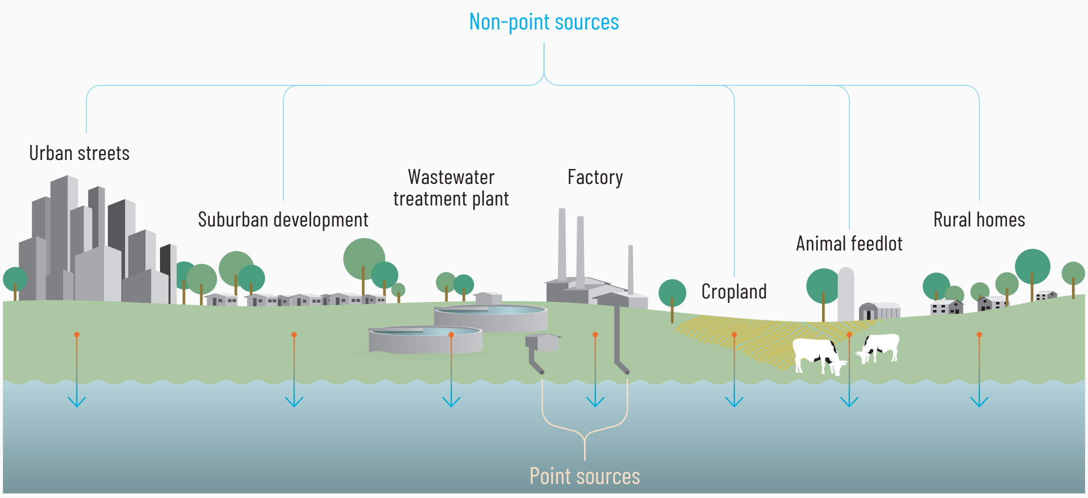
Roughly 33 per cent of the world's solid waste ends up in open dumpsites. Decomposition of waste in dumps and landfills releases various volatile chemicals originating from decomposing products, as well as a heavy mix of methane and CO_2. It is estimated that GHG emissions of 1.6 billion tonnes CO_2-eq. were generated from solid waste treatment and disposal in 2016, driven primarily by open dumping and disposal in landfills. This is about 5 per cent of total global GHG emissions (Kaza *et al.* 2018). As urbanization and population growth continue, it is expected that these dumpsites will increase in size and number and that, by 2025, municipal and domestic dumps will account for 8-10 per cent of global anthropogenic GHG emissions (International Solid Waste Association [ISWA] 2015).

Open burning is common in many low-income countries (Kumari *et al.* 2017; Wang *et al.* 2017). An estimated 620 million tonnes of global domestic waste are burned openly every year (Cogut 2016). Burning of this waste, typically at low temperatures and in an uncontrolled manner, releases large amounts of hazardous substances to the environment, making dumps a major source of some substances of high concern such as carbon black, dioxins and furans (Zhang *et al.* 2017). Given the difficulty of including open dump burning in inventories, air emissions from waste dumps are significantly underestimated (Wiedinmyer *et al.* 2014).

Hazardous chemicals are also released indoors

In many lower-income countries fuel combustion for cooking and heating is the primary source of indoor air contamination in homes (WHO 2014). However, in higher-income consumer economies the most common sources of indoor air contaminants (in addition to cigarettes) are building materials, household furnishings and products. For example, formaldehyde volatilizes from pressed wood products and biocides leach from indoor carpeting. Phthalates such as DEHP are widely released to indoor air, including dust from flooring materials (Jeon, Kim and Choi 2016). The growing use of building insulation materials, which are increasingly installed to conserve energy, has introduced new health concerns related to contaminates in household dust coming from the aging of the insulation. Products such as perfumes, hairsprays, air fresheners, furniture polish, cleaning solvents, hobby and craft supplies, pesticides, glues, adhesives, sealants, and carpet and fabric dyes and fibres are all likely sources of VOCs in indoor air (Apte and Salvi 2016).

Figure 5.4 Potential sources of chemical water pollution (adapted from Arefin and Malik 2018, p.100)



The WHO has identified the most common chemicals emitted to household indoor air globally. These include benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polyaromatic hydrocarbons, trichloroethylene and tetrachloroethylene (WHO 2010).

5.1.2 Releases to freshwater and oceans

Manufactured chemicals contaminate water bodies through direct discharges from industrial facilities and municipal wastewater treatment plants, as well as indirect discharges from landfills and leaking pipes and storage tanks. Non-point sources such as agricultural fields, roadways and parking lots are harder to identify and control (Arefin and Malik 2018) (Figure 5.4). Chemicals are also released to water through wastewater containing commonly used commercial products such as soaps, detergents and personal care products flushed through municipal sewage treatment facilities.

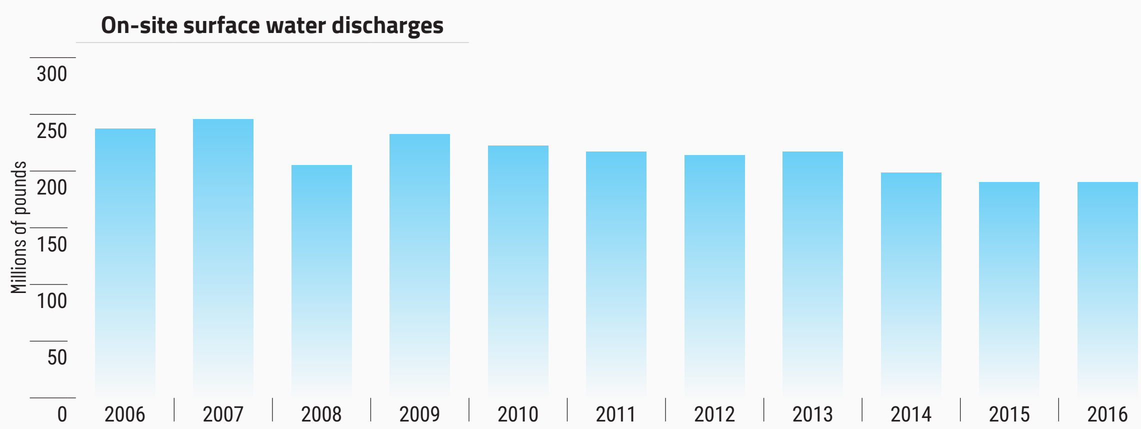
Releases of chemical wastes to water bodies throughout the world remain significant

It is estimated that globally more than 80 per cent of municipal and industrial wastewater is released to the environment without adequate treatment (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2017). In lower-income countries the rates are even higher. Up to 90 per cent of industrial and agricultural wastewater in these countries flows untreated into rivers, lakes and coastal zones; it is also estimated that globally 2 million tonnes of sewage and industrial and agricultural wastes are discharged into freshwater bodies every day. Facilities thus represent a major point source of releases. For example, 80-90 per cent of PFOS/PFOA contamination in the Chinese environment has been estimated as originating from manufacturing and industrial facilities, primarily via wastewater discharges (Liu *et al.* 2017). Agriculture is a leading source of nitrogen pollution and nitrate has been identified as the most common chemical contaminant in the world's groundwater aquifers (Shukla and Saxena 2018).

"China has been the largest producer and emitter of perfluorooctanoic acid and its salts (PFOA/PFO)" (Meng *et al.* 2017, p. 11254). A study showed that in 2012 most PFOA releases in China are due to the activities of the fluorochemical industry (94 per cent) rather than releases from consumer products containing PFOA (Li *et al.* 2015); however, this situation may have changed over the past years.

While releases of hazardous chemicals to surface waters remain high in most countries, rates are falling in the United States, Japan and northern Europe. According to the TRI in the United States,

Figure 5.5 **On-site hazardous surface water discharges in the United States reported to the Toxics Release Inventory (TRI) (millions of pounds), 2006-2016 (adapted from US EPA 2019, p. 44)**



hazardous surface water discharges in that country fell by 24 per cent (60 million pounds) between 2006 and 2016. Most of the decrease was due to reductions in water discharges of nitrate compounds from agriculture, which declined by 25 per cent (56 million pounds) and were attributable to reduced nitrification and nitric acid formation in wastewater treatment facilities (US EPA 2019) (Figure 5.5).

Agricultural production is the primary source of surface water pollution globally

In many higher-income countries and most lower-income ones, pollution from agriculture exceeds that from municipal and industrial discharges. Farming and food processing generate some 40 per cent of water pollution in higher-income countries and 54 per cent in lower-income countries (UNESCO 2009). In the United States agriculture is the main source of water pollution of lakes, rivers and streams, the second largest source in wetlands, and the third largest source in lakes (Mateo-Sagasta *et al.* 2017). In the EU water quality in 38 per cent of water bodies has been degraded by agricultural runoff (UNESCO 2015). Agriculture is the source of a large share of surface water pollution in China, where it is responsible almost exclusively for groundwater pollution by nitrogen (Mateo-Sagasta *et al.* 2017).

Herbicides, insecticides, fungicides and bactericides applied directly in fields can wash off soil into nearby surface water or percolate to lower soil layers and groundwater. However, the intensity of pesticide use globally has been falling (see Part I, Ch. 5). The growth of intensive livestock production has introduced a new class of agricultural pollutants released to the environment: veterinary medicines such as antibiotics, vaccines and growth promoters contaminate both surface and groundwater. Such pollution has become significant as soil and water contaminants near large-scale animal feed lots and industrial-scale egg and meat production facilities (Boxall 2012).

Releases of pharmaceuticals to water are an emerging concern

About 4,000 active pharmaceutical ingredients are administered worldwide in prescription medicines, over-the-counter therapeutic drugs and veterinary drugs. Globally some 100,000 tonnes of active ingredients are produced every year (Weber *et al.* 2014). A large number of studies document the pollution of rivers and groundwater (as well as soil and sediment) with active pharmaceutical ingredients from pharmaceutical manufacturing in different regions (Larsson 2014). Conventional wastewater treatment facilities are often ineffective in fully removing pharmaceuticals from wastewater, with removal efficiencies ranging from 20 to 80 per cent for individual pharmaceuticals (Owens 2015; Beek *et al.* 2016). Antibiotics and synthetic hormones are widely used in humans and animals; once excreted, they are released directly to surface water or waste treatment facilities. Additional burdens to water arise

when unused medicinal products in domestic settings are disposed of in sinks and toilets (Review on Antimicrobial Resistance [Review on AMR] 2016). Yet another critical source of antibiotics is animal husbandry, including fish farming (Singer *et al.* 2016; Wall *et al.* 2016; Topp 2018). In some countries the use of antibiotics in agriculture exceeds its use in humans (Review on AMR 2016). Scientists have highlighted the need to address knowledge gaps regarding the role of the environment in the transmission of antibiotic resistant pathogens, including regarding release pathways (Larsson *et al.* 2018).

Groundwater pollution resulting from chemical discharges remains significant

Despite considerable progress globally in reducing discharges of chemical pollutants to aquifers and water collection basins, pesticides, industrial chemicals and household chemicals continue to affect the quality of regional groundwater in many areas. Hazardous chemicals used in industry and commercial products such as solvents (particularly trichloroethylene, perchloroethylene and methylene chloride) are a common source of groundwater contamination. There are growing concerns about groundwater contamination by the chemicals used in hydraulic fracturing (Michalski and Ficek 2016; Luek and Gonsior 2017) (Box 5.2).

Discharges from land-based sources into oceans

Roughly 80 per cent of ocean pollution comes from land-based sources. This includes much of the world's urban sewage, which is often discharged untreated into the ocean. In many lower-income countries between 80 and 90 per cent of municipal sewage entering coastal zones is estimated to be raw and untreated. Nearly 50 per cent of the urban sewage discharged to the Mediterranean Sea is untreated (EC 2006). This sewage often contains heavy metals such as lead, cadmium and mercury, as well as a variety of POPs found in conventional domestic and commercial products (US NOAA 2018). In addition, plastic waste washed through wastewater treatment facilities contains a broad range of additive chemicals. Contaminants may also be re-emitted/remobilized in the marine environment. Tornero and Hanke (2016) lists 276 substances potentially released into the sea from sea-based sources.

Box 5.2 **Releases of chemicals used in fracking**

Hydraulic fracturing (fracking) has expanded natural gas production, particularly in the United States. The use of additives in the fluids used to fracture rock formations is causing increasing concern. Some of these additives have been shown to migrate into groundwater (i.e. drinking water resources) (USGS 2016). While the oil and gas industry has been reluctant to divulge the ingredients of these fluids, it has been suggested that upwards of 750 substances could be found in fracking fluids, ranging from benign salt and citric acid to benzene, toluene, xylene and lead. Methanol is the most common component, but other chemicals include hydrochloric acid, isopropyl alcohol, 2-butoxyethanol and ethylene glycol (United States House of Representatives 2011; Michalski and Ficek 2016). Hydraulic fracturing involves five stages, each of which potentially causes water pollution (US EPA 2016; Luek and Gonsior 2017).

Large amounts of plastic are released to water bodies along various pathways

Plastic enters the oceans along various pathways. Land-based sources (e.g. waste disposed at beaches) are the largest source of releases to the marine environment; others include marine-based sources (e.g. due to aquaculture and fishing) and other environmental media (rivers and atmospheric transport) (Lebreton *et al.* 2017). Studies suggest that about 6-10 per cent of global plastic production is released to the ocean (Essel *et al.* 2015). Van der Wal *et al.* (2015) found that the Danube River released between 530 and 1,500 tonnes of plastics into the Black Sea each year. It has been estimated that 275 million tonnes of plastic waste were generated in coastal countries in 2010, of which 4.8 to 12.7 million tonnes entered the ocean (Jambeck *et al.* 2015). The total mass of plastic debris added to the marine environment from 2010 until 2025 is expected to grow by an order of magnitude and may amount to some 100-250 million tonnes (UNEP and Grid Arendal 2016).

Macroplastic litter originates from various sources, including poorly managed plastic recycling, packaging, agriculture, construction and coastal tourism (UNEP 2016b). Recent modelling studies suggest that the largest share of microplastic wastes that end up in the ocean are secondary wastes generated from the breakdown of clothing and textiles during machine washing (around 35 per cent) and erosion of tyres on roadways during normal vehicular travel (around 29 per cent). A smaller but significant share comes from primary microbeads added as functional constituents to detergents and personal care products (Boucher and Friot 2017) (Figure 5.6).

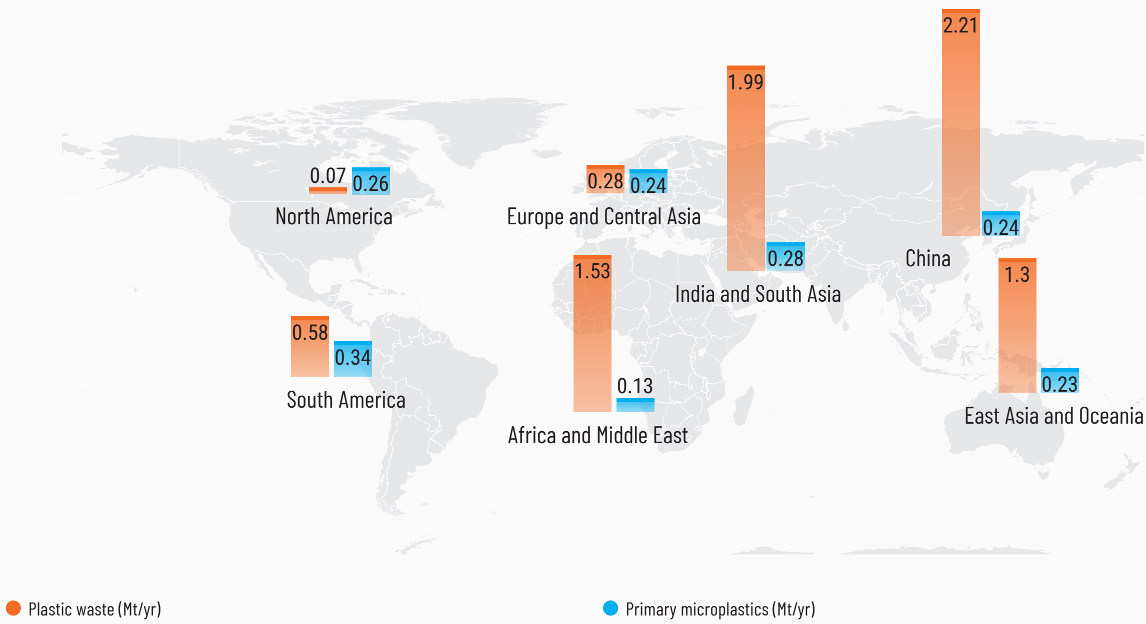
5.1.3 Releases to soil

Hazardous chemicals are released to soil during activities such as agriculture, mining, manufacturing and treatment of sewage sludge, or as solid and hazardous wastes deposited in dumps and landfills. Conventional applications of pesticides and fertilizers in agriculture result in direct releases of pesticides to soil (Rodríguez Eugenio, McLaughlin and Pennock 2018).

Releases to soil through mining and metal processing are very significant

The mining industry generates large amounts of overburden and mining wastes. The mining and metal processing industries are responsible for the largest releases of hazardous pollutants in

Figure 5.6 Global releases of plastic and microplastic waste to oceans (million tonnes per year) (adapted from Boucher and Friot 2017, p. 28)



North America. The top five pollutants in 2013 reported to PRTRs In North America (Canada, the United States and Mexico) were zinc and its compounds, lead and its compounds, manganese and its compounds, copper and its compounds, and nitric acid and its compounds, all of which are found in mining wastes (Commission for Environmental Cooperation 2016). Of the reported chemicals released to the environment in the United States, 44 per cent (1.52 billion pounds) came from the metal mining industry; most of this was deposited on land as overburden and waste (US EPA 2018).

Wastes from mining often contain hazardous chemicals such as arsenic, lead and cyanide in concentrations that pose serious hazards to ecosystems and human health. Acid mine drainage (AMD) is one of the largest sources of the mining industry's soil and water pollution (Hudson-Edwards *et al.* 2011). In many parts of the world gold, gems, precious stones and metals are extracted by artisanal and small-scale miners. About 25 per cent of the world's gold is produced through artisanal and small-scale gold mining (ASGM) operations in over 55, mostly lower-income countries. Mercury releases from tailings and vaporized mercury at these mines exceed 1,000 tonnes per year, making ASGM responsible for the largest releases of mercury to the soil of any sector globally (Esdaile and Chalker 2018).

Total fertilizer and pesticide applications to soil are increasing, but application rates are decreasing

Because use of fertilizers and pesticides typically involves direct application to crops, trends in their use are a rough indicator of the volumes released to soils. As explored in Part I, Chapter 2, the market for pesticides and fertilizers is increasing globally. Between 2018 and 2022 the fertilizer industry is expected to add 78 million tonnes of production capacity. Global manufacture of pesticide active ingredients increased from 1.9 million tonnes in 2008 to 2.8 million tonnes in 2016.

Meanwhile, it has been estimated that use rates have declined over the past decades. A 2018 report (Phillips McDougal 2018), estimated average application rates in the 1950s at 1,200, 1,700 and 2,400 grams of active ingredient used per hectare (g ai/ha) for fungicides, insecticides, and herbicides, respectively. By the 2000s the average use rates were reduced to 100, 40, and 75 (g ai/ha) (Figure 5.7). Schreinemachers and Tipraqsa (2012) studied levels and trends in agricultural pesticide use for a large cross-section of countries using FAO data for the period 1990-2009. Their analysis showed that a 1 per cent increase in crop output per hectare was associated with a 1.8 per cent increase in pesticide use per hectare, and that the growth in intensity of pesticide use levelled off as countries reached a higher level of economic development. On the other hand, few higher-income countries had significantly reduced the

Figure 5.7 Average active ingredient application rates over time as a function of the decade of introduction, 1950s-2000s (adapted from Phillips McDougal 2018, p. 6)

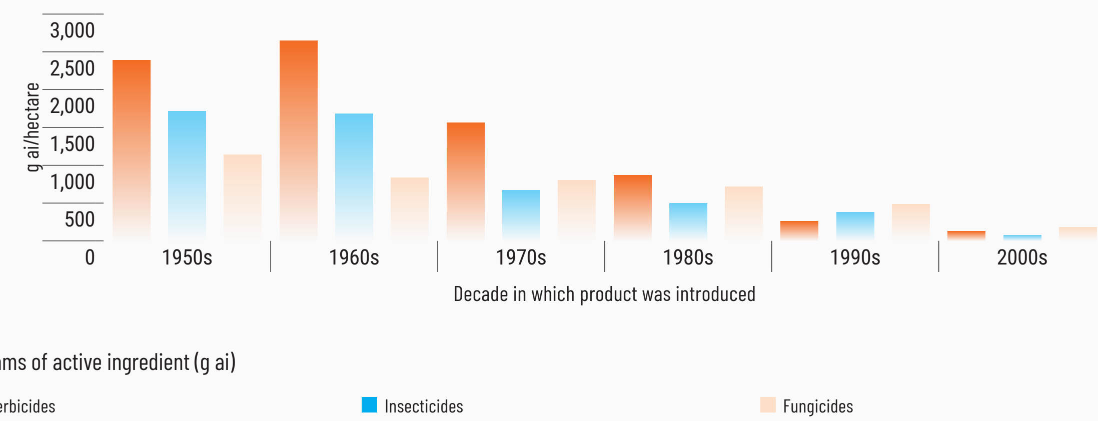
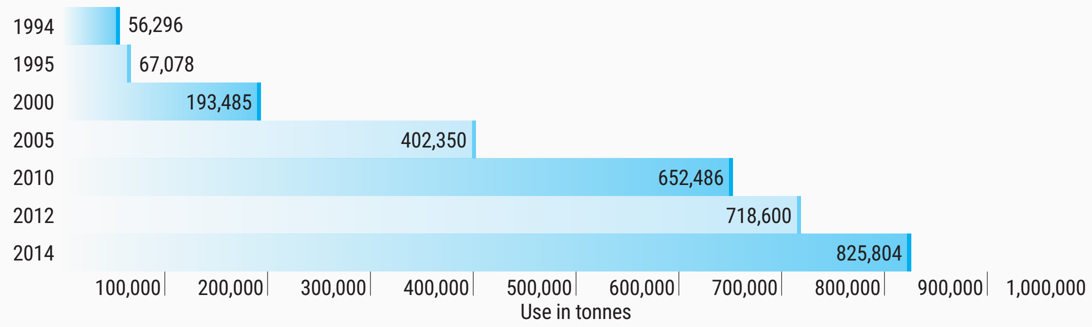


Figure 5.8 Global glyphosate use, 1994-2014 (tonnes) (based on Benbrook 2016)



level of intensity of their pesticide use since decreases in insecticide use were largely offset by increases in herbicide and fungicide use.

The FAO maintains a database for the purpose of tracking pesticide use by country, but few data have been uploaded. A study in the United States on trends in pesticide use for 21 of that country's largest-volume crops found that use increased from the 1960s to 1980 and levelled off thereafter, at some 500 billion pounds per year. Herbicides made up the largest share of the pesticides, and the most common herbicides were glyphosate-based (Fernandez-Cornejo *et al.* 2014). Glyphosates are the largest-volume herbicides in use today (Benbrook 2016). Figure 5.8 shows the significant growth of glyphosate use worldwide.

Trace elements such as cadmium, boron and iron are increasing in agricultural soils where there has been prolonged use of rock phosphate and phosphorus-containing fertilizers (Kratz, Schick, and Schnug 2016). Increased use of treated municipal sewage can also distribute various heavy metals, including lead and cadmium, to soil (Najam *et al.* 2015).

Microplastics are another source of soil pollution

If discarded plastic is not incinerated, most of it ends up in dumps and landfills where it may disintegrate into microplastic particles (commonly understood to be 5 millimetres in diameter or less) that break down further into nanoparticles (between 1 and 100 nanometres [i.e. between 0.001 and .01 micrometre] in size). According to de Souza Machado *et al.* (2018) one-third of all plastic waste ends up in soils or freshwater. Municipal sewage systems distribute microplastics both in wastewater and sludge. It is estimated that 80-90 per cent of the microplastics in municipal sewage ends up in the sludge that is typically spread on farms or forests (de Souza Machado *et al.* 2018). Zhang and Liu (2018) identified soil amendments and irrigation with wastewater as important sources. Application of sewage sludge was also identified by the Norwegian Institute for Water Research (2018) as an important source of releases of microplastics to agricultural soils and estimated that 110,000-730,000 tonnes of microplastics are released each year to agricultural soils in Europe and North America.

5.2 Chemical releases from products

Chemicals are released during production, use and disposal of products

Chemicals in products are released during product manufacturing, expected use and disposal, or during product transportation, storage, accidents or unintended uses. Releases from products are diffuse, and quantifying the amount of these releases is challenging. However, some releases from products have been well-studied. For example, mercury-containing products were recognized as significant contributors to global mercury releases to air, soil and water from the late 19th century onwards. Given the diversity and magnitude of the products currently in commerce, chemical releases from products are receiving yet further attention. New research is examining the respective contributions of consumer products to total global emissions, as well as the contributions of specific chemicals such as those used as flame retardants (Wei *et al.* 2015) and plastic articles (Steinemann 2015; Cousins *et al.* 2018).

Releases from products are a substantial part of total emissions

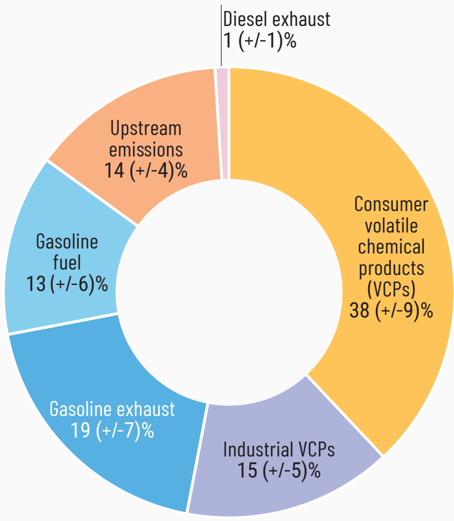
Volatile and non-volatile organic compounds (VOCs and NVOCs) released from products are a major source not only of indoor air pollution, but also of pollution of outdoor air and freshwater and marine environments. A recent study suggests that releases of chemicals from consumer products (e.g. cosmetics and paints) have become the primary source of VOCs from petrochemical sources in some industrialized cities (McDonald *et al.* 2018) (Figure 5.9). The amount of chemicals released to the environment from products varies substantially, depending on product applications and chemical properties. A combination of modelling and empirical approaches has been used to trace specific chemical sources from products to environmental media (e.g. flame retardants in products that can reach water bodies) (Csiszar *et al.* 2014; Melymuk *et al.* 2014).

Volatile and semi-volatile compounds volatilize from articles and building products

Chemically-intensive products such as furniture, carpets, textiles, toys and building products contain a diverse collection of chemical ingredients. These products are important sources of chemical releases. People are in regular proximity to or in contact with such products. Plastic products, in particular, are a common source of chemical releases indoors and outside. Because polymerization of monomers is rarely complete, and additives may not be chemically linked into the polymeric structure, unreacted monomers, plasticizers, binders, flame retardants, dyes, colorants, nanoparticles, biocides and contaminants from processing can leach from plastic products (Rydberg *et al.* 2011). Direct human exposure to plastic components also occurs, especially in the case of children through toy mouthing or dermal contact (Bouma and Schakel 2002; Babich *et al.* 2004).

VOCs such as phenol or benzene diffuse relatively rapidly through a product and are

Figure 5.9 **Contributors to VOC emissions to ambient air in Los Angeles, California, 2010 (adapted from McDonald *et al.* 2018, 763)**



Volatile organic compound emissions = 350 +/- 50 Gigagrams (Gg).
Reprinted with permission from the American Association for the Advancement of Science (AAAS).

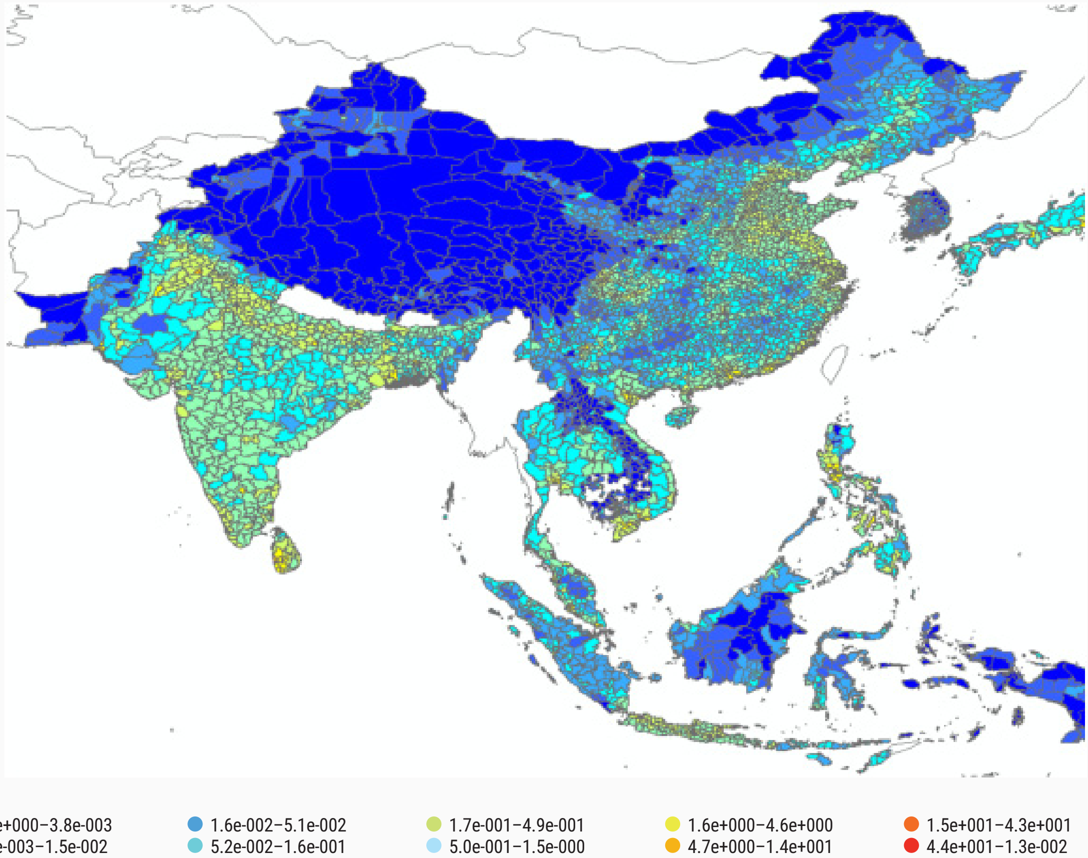
often entirely released to indoor air over the product lifetime, leading to emissions to ambient urban air (McDonald *et al.* 2018). The amount and rate of release of such VOCs are driven by the diffusion characteristics within the material, which depends on chemical properties, material type and temperature (Huang and Jolliet 2016; Huang *et al.* 2017).

Semi-volatile organic compounds (SVOCs), such as phthalates and several classes of flame retardants, are released to indoor air from products more slowly and in smaller fractions due to their lower atmospheric vapour pressure. Exposure to these compounds can, however, cause concern due to their relatively large content in products and to exposure via dust or gaseous dermal uptake (Weschler and Nazaroff 2014; Morrison *et al.* 2016). In addition, a substantial part of SVOCs is present at the end of the product lifetime. It can then be released to the environment during disposal (e.g. landfilling or incineration).

Personal care and household chemical releases

In many consumer economies indoor air is increasingly polluted with releases of VOCs from products such as perfumes, hairsprays, air fresheners, furniture polish, cleaning solvents and household biocides. Chemicals in personal care products are directly released during normal use through dermal contact. Of particular concern are skin lightening creams that contain mercury, which are commonly used in some Asian and African countries. In one study the WHO found that 40 per cent of women in China, 61 per cent in India and 76 per cent in Nigeria used such creams (WHO 2011). A large share of the substances in personal care products can be washed off. They may then reach freshwater and marine environments. Figure 5.10 presents findings on the geographical distribution of releases of linear alkylbenzene sulphonate (LAS), primarily from the use of biodegradable laundry detergents in China. Spatially explicit chemical release inventories are becoming available at the global level to estimate releases

Figure 5.10 Spatial distribution of releases of linear alkylbenzene sulphonate (LAS) due to household emissions in Asia, in mg/m²/day (underlying data from Wannaz *et al.* 2018, elaborated according to Hodges *et al.* 2014)



from household products to the freshwater environment, accounting for the presence or type of wastewater treatment processes (Hodges *et al.* 2014; Wannaz *et al.* 2018) (Figure 5.10).

Migration from packaging to food

Chemical releases to food occur unintentionally from packaging materials (e.g. releases of bisphenol A [BPA] or bisphenol S [BPS] from plastic water bottles). The EU's Rapid Alert System for Food and Feed (RASFF) shows a significant upward trend in the migration of hazardous chemicals from materials in contact with food, including migration of lead from ceramic ware; releases of chromium and nickel from metal ware; migration of isopropyl thioxanthone from carton packages; and releases of aromatic amines from kitchen utensils (EC 2014). Research indicates that food packaging contributes to measurable levels of phthalates in take-out foods in the United States (Varshavsky *et al.* 2018).

Product distribution transports chemicals throughout the world

Many products formulated or assembled in one region are transported worldwide. If they contain hazardous chemicals, they may become a vehicle for transporting these chemicals to distant users and landfills. There the chemicals may be released and pollute local ambient and indoor environments. Where supply chains are long and involve transporting chemicals or components across continents, they can be responsible for a significant share of the transfer of hazardous chemicals throughout the environment. This is further explored in Part I, Ch. 4.

Chemicals accumulate in human-made material stocks, creating potential legacies

A significant share of materials accumulates in "human-made material stocks" (buildings, infrastructure and machinery). It was estimated that 36 billion tonnes of such materials were added to the global material stock in 2015 alone (Krausmann *et al.* 2017a). The total mass of the human-made infrastructure has been estimated at about 30 trillion tonnes (Zalasiewicz *et al.* 2016). Large quantities of chemicals are thus stored in the accumulated products of societies around the world and, over time, may lead to substantial releases to the environment (Rydberg *et al.* 2011). In many cases these materials contain chemicals of concern (e.g. certain building materials containing asbestos).

When products are disposed, the majority of materials (and the chemicals in them) are dispersed as releases to the environment and/or unrecoverable wastes. Only around 8.4 billion tonnes or 9.1 per cent of global material resources used in 2015 were recycled (de Wit *et al.* 2018). Consistent with this trend, less than 9 per cent of the 6.3 billion tonnes of plastic waste generated up to 2015 has been recycled, while 12 per cent has been incinerated and 79 per cent has been disposed in landfills or in the environment (Geyer, Lambeck and Law 2017). Where persistent chemicals such as brominated and fluorinated compounds, and metals such as mercury, lead and other heavy metals, are incorporated into products that are disposed in the environment as wastes, the potential for exposures of people and biota may persist for decades.

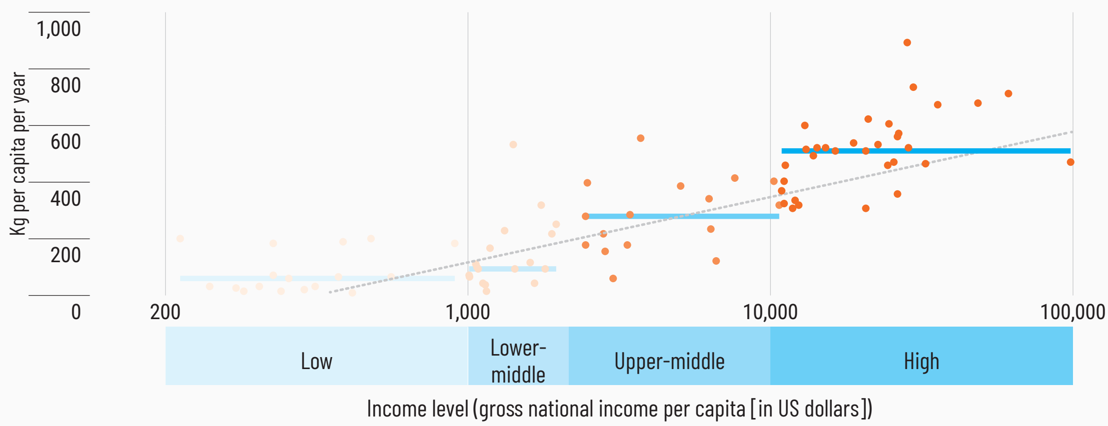
5.3 Releases from municipal and hazardous waste

Large volumes of manufactured chemicals are deposited on soil as hazardous or solid wastes. Industrial wastes that are flammable, reactive, corrosive or toxic to human health or the environment are considered to be hazardous wastes. Solid wastes are typically divided into municipal (or household) wastes, commercial wastes, industrial wastes, and construction and demolition wastes. As the proportion of discarded chemically intensive products (e.g. motor oil, batteries, paints and varnishes, cleaning agents, electronic products, solvents and pesticides) increases, municipal wastes are becoming as hazardous as hazardous wastes.

Municipal solid waste is increasing, particularly in lower-income countries

The best estimate of the global amount of municipal solid waste is around 2.1 billion tonnes per year with at least 33 per cent of that amount not managed in an environmentally safe manner (Kaza *et al.* 2018). If commercial, industrial, and construction and demolition wastes are included, the estimates grow to 7 to 10 billion tonnes per year. Globally, some 37 per cent of municipal solid waste is disposed of in some form of a landfill, 8 per cent of which is disposed of in sanitary landfills with landfill gas collection systems. Open dumping accounts for about 33 per cent of waste, 19 per cent is recovered through recycling and composting, and 11 per cent is incinerated for final disposal. (Kaza *et al.* 2018). In lower-income countries indiscriminate dumping of solid and liquid waste by industry, small-scale

Figure 5.11 **Waste generation by level of national income (US dollars) (adapted from UNEP and ISWA 2015a, p. 2)**



Note: Data for selected countries

artisans and automotive garages is common, as proper waste collection and disposal facilities are lacking. In rural areas most wastes are burned in open dumps or directly released to unmanaged landfills, leading to contaminated soils, surface waters and groundwater (ISWA 2015; ISWA 2016).

Although waste generation rates and measures vary significantly across countries, there is generally a positive correlation between waste generation and national income level. In 2010 the traditional higher-income countries, with 16 per cent of the world population, accounted for about 34 per cent (or 683 million tonnes) of the world's solid waste. Low-income countries accounted for 9 per cent of the world population, but generated 93 million tonnes or about 5 per cent of global solid waste (UNEP and ISWA 2015a; Kaza *et al.* 2018) (Figure 5.11).

China generated some 203.6 million tonnes of municipal solid (consumption) waste in 2016 (National Bureau of Statistics of China 2017). By 2030 it will likely produce twice as much municipal solid waste as the United States. Sub-Saharan Africa generates approximately 174 million tonnes per year. The total amount of waste generated per year in Latin America and the Caribbean is 231 million tonnes, while In East Asia and the Pacific the amount generated per year is at least 468 million tonnes (Kaza *et al.* 2018).

In terms of chemical-intensive products in global municipal waste streams, plastics are estimated to make up 8 to 12 per cent across most countries, while the proportion of paper varies from a high of 23 per cent in higher-income countries to 11 per cent in middle-income countries and a low of 7 per cent in lower-income countries. Metals and textiles make up about 12 per cent of municipal waste generated in higher-income countries, 9 per cent in middle-income countries and 6 per cent in lower-income countries. Estimates suggest that household hazardous wastes make up less than 1 per cent of municipal wastes, but up to 5 per cent if electronic waste (e-waste) is included (UNEP and ISWA 2015a).

Global solid waste is expected to grow to 3.40 billion tonnes by 2050. In projecting trends beyond 2015, the *Global Waste Management Outlook* (UNEP and ISWA 2015a) shows a flattening of the growth curve and, in some cases, a decline of municipal waste generation rates in higher-income countries, while such rates are growing and expected to continue to grow

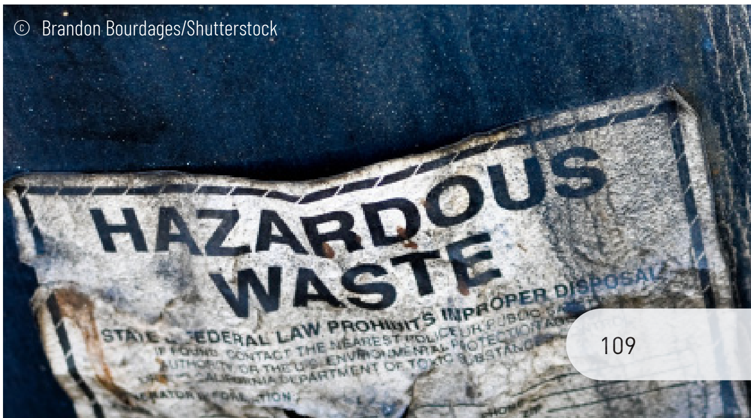


Table 5.1 Hazardous and non-hazardous wastes from six African countries (tonnes/year), 2012 (based on United Nations Economic and Social Commission for Western Asia 2015, p. 19)

	Non-hazardous waste (tonnes/year), 2012	Hazardous waste (tonnes/year), 2012
Algeria	10,430,000	2,910,000
Morocco	69,070,000	1,910,400
Egypt	51,000,000	6,528,300
Tunisia	6,555,000	166,000
Mauritania	540,000	126,000
Sudan	1,528,000	not available

in middle- and lower-income countries. Daily per capita waste generation in higher-income countries is projected to increase by 19 per cent by 2050, compared to lower- and middle-income countries where it is anticipated to increase by approximately 40 per cent or more.

Asian counties are expected to become the largest generators of municipal waste by 2030, while Africa is expected to exceed even these rates by later in the century (UNEP and ISWA 2015b; Kaza *et al.* 2018). The social and economic megatrends driving African development are affecting the continent's waste generation. 125 million tonnes of municipal solid waste was generated in African countries in 2012 and that amount is expected to double by 2025. Table 5.1 presents data on hazardous and non-hazardous wastes from six African countries (United Nations Economic and Social Commission for Western Asia 2015).

On average, some 57 per cent of these wastes are organic material while 13 per cent are plastic. More than 90 per cent are disposed in uncontrolled dumpsites and landfills. An estimated 70-80 per cent are recyclable, but only 4 per cent are reported to be currently recycled (Figure 5.12).

Solid waste recycling is increasing around the world

Waste recycling is considered a benefit to environmental sustainability and a critical component of a circular economy. The rates of municipal waste recycling vary considerably among countries, from a high of 65 per cent in

Figure 5.12 Composition of municipal solid waste in Sub-Saharan Africa (per cent) (adapted from UNEP and Council for Scientific and Industrial Research [CSIR] n.d., p. 2)

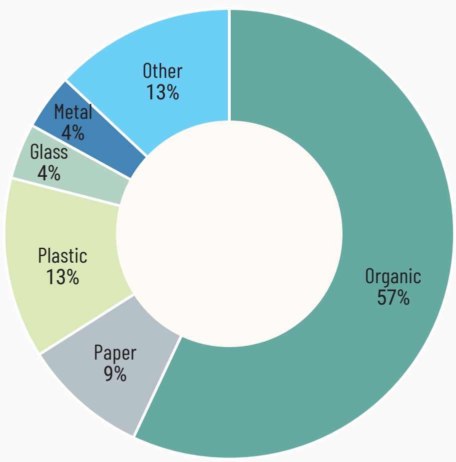
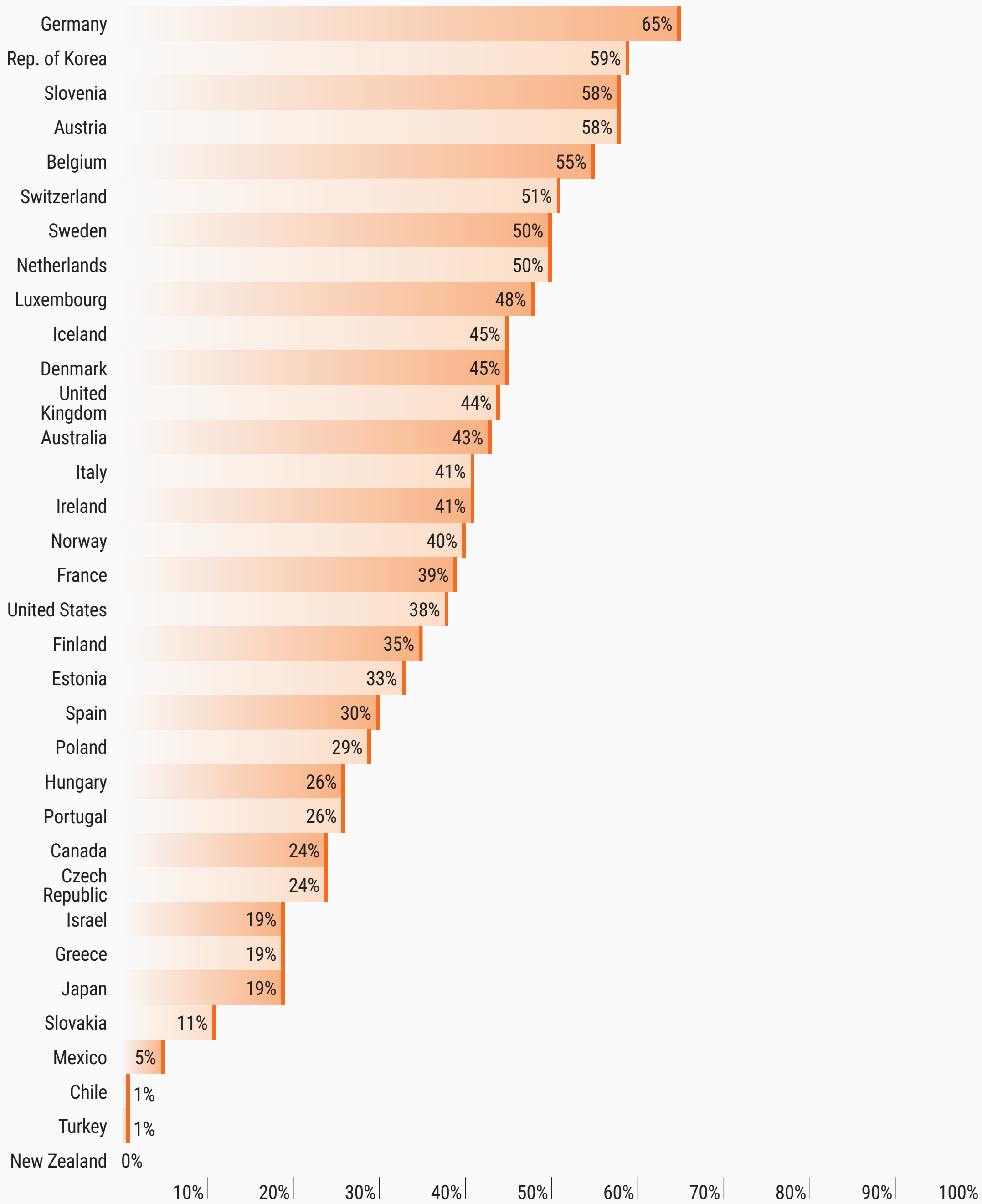


Figure 5.13 Recycled and composted waste as a share of total municipal waste in OECD countries (per cent), 2013 (adapted from McCarthy 2016)



Germany in 2013 to less than 1 per cent in Turkey, with Estonia and Spain at 33 and 30 per cent (McCarthy 2016) (Figure 5.13).

Waste recycling is increasing in many countries, for example through the growth of waste material separation and accessible municipal recyclable product collection services as well as collection and disposal fees for wastes not recycled. Local and national bans on plastic bags, cups and packaging are another incentive to recycle and reuse. However, separation and collection for recycling only makes economic sense if the material is actually recycled.

The waste industry depends closely on the secondary materials industry to provide the market for recycling. It is estimated that some 700 to 800 million tonnes of "waste" are recycled as "secondary commodities", derived from municipal solid waste and other waste streams. In terms of tonnage, recycling markets are dominated by ferrous scrap (steel) followed by paper and board. In terms of value, steel ranks first while non-ferrous metals such as aluminium and copper rank second. The main traded secondary materials represent around 10-15 per cent of overall world waste generation, excluding construction and demolition, agricultural and forestry, and mining and quarrying wastes (UNEP and ISWA 2015b).

Informal sector recycling generates significant releases of hazardous substances

Where wastes are exported from wealthy countries for recycling in lower-income countries, the potential for adverse environmental and health exposures is present. In some regions and countries, up to 95 per cent of electronic waste is treated and processed informally and by untrained workers lacking appropriate equipment. This often results in significant releases of chemicals such as heavy metals (lead, cadmium, mercury, etc.), PCBs, brominated flame retardants, PAHs and dioxins and furans to the environment (Annamalai 2015; Heacock *et al.* 2016). Heavy metals and other pollutants are routinely released from e-waste recycling operations to air, water and soil (Awashthi, Zeng and Li 2016; He *et al.* 2017).

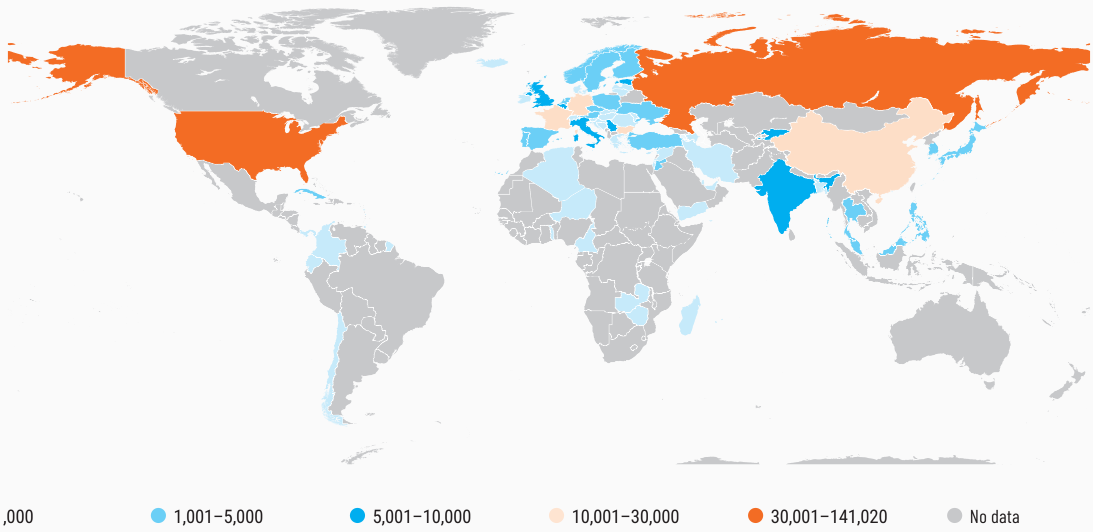
A good example involves lead battery recycling. Non-regulated, informal battery recycling practices occur in many countries and have resulted in lead exposure and poisoning, with young children being particularly at risk (Daniell *et al.* 2015; WHO 2017). Where such recycling is carried out in urban areas with high population densities, large numbers of people may be exposed to high levels of lead.

China recently instituted a series of import restrictions on "foreign wastes" that were previously exported to China for potential treatment and recycling. This ban covers imports of 24 types of materials, including unsorted paper and the low-grade polyethylene terephthalate used in plastic bottles. Before this, China had been processing at least half of the world's exports of waste paper, metals and used plastic (7.3 million tonnes in 2016) (de Freytas-Tamura 2018).

Hazardous waste is generated worldwide

Data on the generation and management of hazardous waste are lacking or remain weak for many countries. Furthermore, comparisons are difficult when the types of hazardous waste covered and the definitions and methods used differ. Global data on hazardous waste generation are therefore not exhaustive despite the progress made by many countries (UNEP and ISWA 2015a). Figure 5.14 provides a global overview of hazardous waste generation by major country.

Figure 5.14 **Global hazardous waste generation in 2009 (thousand tonnes) (adapted from United Nations Statistics Division 2011)***



Units: thousand tonnes *Note that data correspond to the latest year available Last update: March 2011

Data from the EU PRTR show that the waste and wastewater management sectors account for the largest total transfers of hazardous waste in Europe, followed by the chemical industry and the metal production and processing sector (EEA n.d.). Some 20.3 to 28.8 million tonnes of hazardous waste are reported to be generated every year in the United States, of which 5-10 per cent goes to landfill and some 90- 95 per cent is deep well injected (US EPA 2018). The chemical industry is the largest source of the country's hazardous waste, but much of this waste is treated on-site. The oil, gas and coal industries are the next largest source (UNEP and ISWA 2015a). Figure 5.15 and Figure 5.16 show the sources of hazardous wastes in the United States and the EU.

Figure 5.15 **Sources of hazardous waste in the United States by sector, 2011 (per cent of volume) (adapted from UNEP and ISWA 2015a, p. 93)**

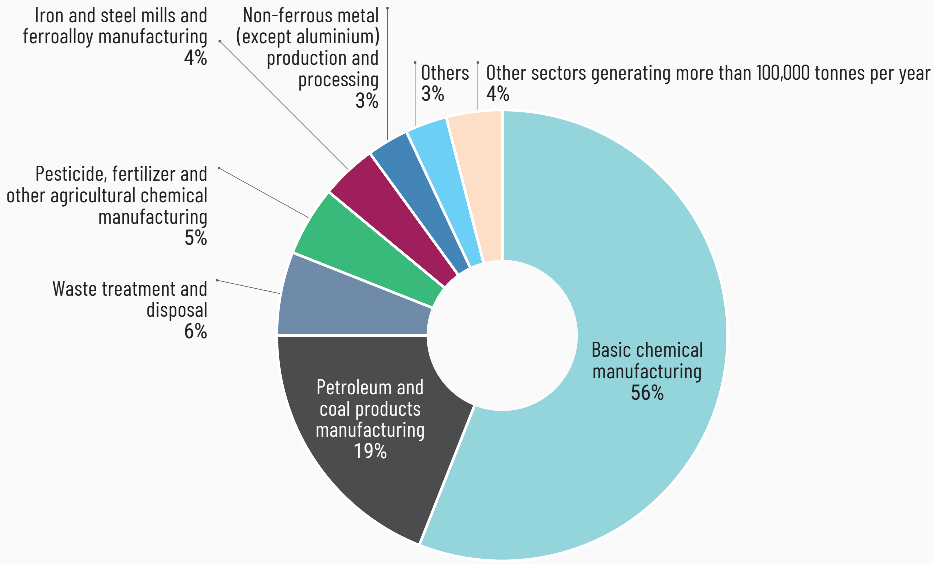
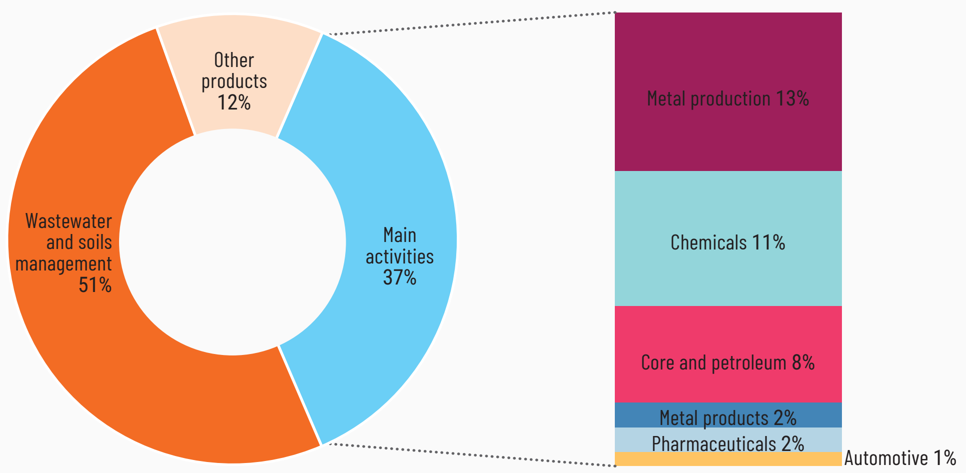


Figure 5.16 Sources of hazardous waste in EU countries by sector, 2015 (per cent) (adapted from EEA n.d.)



Regional hazardous waste generation largely reflects the degree of industrialization

Asian countries report that they are generating increasingly large volumes of hazardous waste. The National Bureau of Statistics of China reported that in 2014 China produced 3,256.7 million tonnes of industrial solid waste, including 36.3 million tonnes of hazardous waste (of which 20.6 million tonnes were treated and further used and 9.3 million tonnes were disposed) (National Bureau of Statistics of China 2015). Table 5.2 shows hazardous waste generation data in selected countries that provided updated figures as of September 2016 (Secretariat of the Basel, Rotterdam and Stockholm Conventions [BRS Secretariat] 2016). China reports the generation of the largest volumes of hazardous wastes.

Whatever the region of the world, there is a gap between the generation of hazardous waste and the treatment capacity for the waste and proper information on its chemical composition. As an example, in the EU, where hazardous waste is largely well-handled and treated, the gap between the amounts of hazardous waste generated and treated is 28 per cent (up to 29 million tonnes).

Table 5.2 Hazardous waste generation in selected countries, 2014 (tonnes) (BRS Secretariat 2016)

Country	Volume (tonnes)
Australia	10,031,053
Austria	1,252,125
Bulgaria	17,792,272
China	36,335,236
Estonia	10,484,292
Germany*	17,000,000
Iran	1,099,215
Malaysia	1,665,347
Morocco	5,900,000
Norway	1,380,000
Philippines	1,712,394
Poland	1,974,866
South Africa	11,353,856

Data rounded to the nearest integer. Many countries provided no data. Data cannot be used to draw conclusions about regional or global patterns, or about countries not listed here.
* Preliminary figure, subject to verification

Generation of electronic waste is increasing throughout the world

The enormous growth of the electronic technologies of the "Digital Age" has created a significant impact on global waste generation in the form of electronic product waste, or e-waste. Electronic waste often contains toxic chemicals such as mercury, lead and brominated flame retardants, as well as a variety of precious metals and rare materials. Large quantities of this waste are disposed of illegally when electronic waste is transferred within and between countries, misrepresented as second-hand products (Rucevska *et al.* 2015). The unregulated international transfer of hazardous wastes has been reduced since the signing of international agreements such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal and the Bamako Convention; however, unregulated electronic waste trade continues across national borders (Obradović *et al.* 2014).

In 2016 the global economy generated some 44.7 million tonnes of e-waste, which is expected to grow to 52.2 million tonnes by 2021. Of the generated waste, approximately 1.7 million tonnes are disposed in municipal waste in higher-income countries and are likely to be incinerated or landfilled. Globally, only 8.9 million tonnes of e-waste are documented to be collected and recycled, corresponding to 20 per cent of all the e-waste generated. In 2016 Asia was the region that generated the largest amount of e-waste (18.2 million tonnes), followed by Europe (12.3 million tonnes), the Americas (11.3 million tonnes), Africa (2.2 million tonnes) and Oceania (0.7 million tonnes) (Baldé *et al.* 2017).

Informal recycling markets in China, India, Pakistan, Viet Nam and the Philippines handle 50-80 per cent of this e-waste. Much of the recycling processes involves shredding, burning and dismantling products, often in "backyards". According to a study carried out in India, over 30,000 computers were estimated to have been decommissioned every year in the city of Bangalore alone. This resulted in waste containing more than 1,000 tonnes of plastics, 300 tonnes of lead, 0.23 tonne of mercury, 43 tonnes of nickel and 350 tonnes of copper (Needhidasan, Samuel and Chidambaram 2014). During the 2000s more than 20 million tonnes of e-waste was recycled per year, mostly within the informal sector in and around Guiyu, China (Rucevska *et al.* 2015). Today much of the most hazardous recycling has been closed at Guiyu and replaced with more regulated operations. However, e-waste recycling in the informal sector still continues in other parts of Asia and Africa.

Significant amounts of waste are generated in the chemical industry

An analysis shows that the amount of waste generated per kg of chemical product increases up the chemical value chains from oil refining via bulk (basic) chemicals to fine chemicals and pharmaceuticals. In the production of pharmaceuticals, for example, at least 25 kg of emissions and waste (and at times more than 100 kg) are generated for every kg of product, highlighting resource inefficiencies (Sheldon 2017) (Table 5.3).

Table 5.3 Resource efficiency in the chemical industry: ratio of products and waste generation (Sheldon 2017, p. 19)

Industry segment	Tonnes per year	e-factor (kg waste per kg product)
Oil refining	10^6-10^8	< 0.1
Bulk chemicals	10^4-10^6	< 1-5
Fine chemicals	10^2-10^4	5-50
Pharmaceuticals	10-10^3	25- >100

The e-factor is a measure to indicate the amount of waste created for each unit of product manufactured. An e-factor of 10 means that 10 kg of waste is generated for 1 kg of product.

5.4 Chemical releases: industrial accidents and natural disasters

5.4.1 Releases from chemical accidents are significant

Chemical accidents often cause significant impacts on human health and the environment and severely disrupt community and economic life (see also Part III, Ch. 6). The best known example is the exposure of more than half a million people, including thousands fatally, to methyl isocyanate gas released from the Union Carbide pesticide plant in Bhopal, India in 1984 (Broughton 2005).

Accidents at mining sites also cause significant chemical releases to the environment. Tailing ponds often hold large amounts of hazardous chemicals, and the greatest releases occur when dams burst. It is estimated that 3,500 tailings impoundments exist globally, and that every year two to five major failures and 35 minor failures occur (Martin and Davies 2000). The magnitude of such incidents was illustrated in the case of the Baia Mare spill, when some 100,000 m^3 of cyanide and other contaminated waste were released into nearby rivers in Romania (Soldán *et al.* 2001). More recently, the catastrophic failure of the Bento Rodrigues iron mine tailings dam in Brazil caused a toxic flow of mud into the Doce River region, killing 19 people and disrupting the livelihoods and adversely affecting livelihoods of more than 1 million people (Fernandes *et al.* 2016). In the same year the fire and explosion of a hazardous goods warehouse at Tianjin Port resulted in the deaths of 165 people and the injury of nearly 800 others. The incident caused euros 1 billion in damages without taking account of the vast economic costs to neighbouring businesses and residents (China State Administration of Work Safety 2016).

Chemical accident trends in emerging economies are difficult to assess because of a lack of data. Some data are available regionally. For example, a recent review of sudden chemical leakage accidents in China identified 666 incidents between 2006 and 2011. Ninety-five per cent of the pollution came from industrial facilities. Petroleum accidents made up the largest number of these incidents, followed by those involving corrosives and ammonia liquids (Li *et al.* 2014). In addition, the Work Accident Map of the China Labour Bulletin shows 42 accidents involving gas or chemical exposure, 33 explosions and 28 fires occurring in workplaces in China in 2017 (China Labour Bulletin 2018). Some accident data are also available regarding specific industries, collected either by government regulators or by industry associations. The EU tracks chemical accidents through its Major Accident Reporting (eMARS) System.

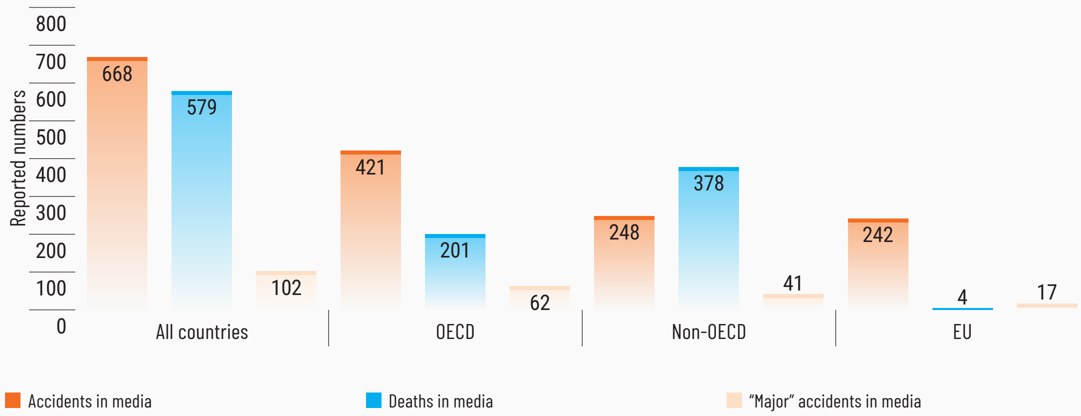
A review of chemical accidents reported in the news media between October 2016 and September 2017 identified 667 facility accidents, with 184 taking place at chemical processing sites (Wood 2017). The great majority of these incidents occurred at fixed facilities (454) and a smaller number during transport (147), followed by pipelines (37) and offshore (9). The study also looked at the differences in incident data between OECD, non-OECD and non-EU countries. The reports indicate that chemical accidents and near misses continue to occur frequently in OECD countries, but have lower fatality rates than those in non-OECD countries. According to the study, OECD countries accounted for nearly two-thirds of events (421 out of 668), but barely one-third of deaths (201 out of 579). The study also looked at reports from EU countries (many of which belong to OECD). Similarly, EU countries accounted for one-third of incidents collected but only four deaths (Figure 5.17).

A similar study of accidents with significant releases to the environment in OECD and EU countries undertaken by the Major Accident Hazards Bureau of the European Commission identified 86 accidents between 1986 and 2013 that resulted in measurable pollution, notably releases to watercourses but also to soil and air (Gyenes and Wood 2014) (Figure 5.18). The majority (30 per cent) of the identified accidents occurred in the chemical industry.

Chemical releases are also caused by natural disasters

In a recent report the WHO has drawn attention to chemical releases that may be directly and indirectly triggered by the increasing frequency of

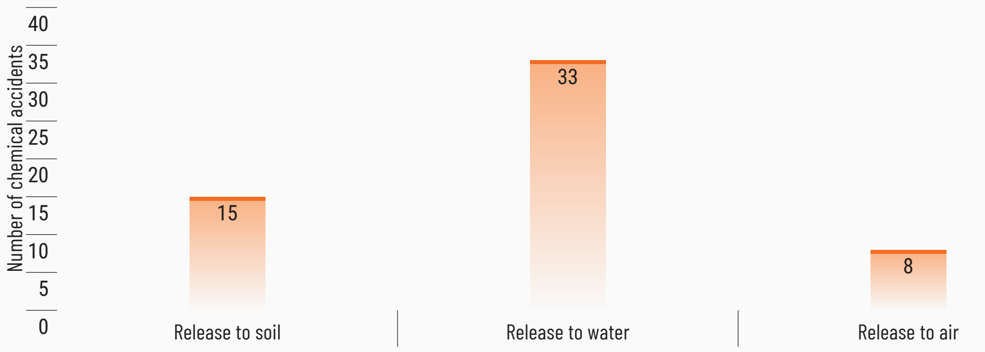
Figure 5.17 Chemical accidents reported in news media in OECD, non-OECD and EU countries, October 2016-September 2017 (adapted from Wood 2017, p. 10)



natural hazards such as earthquakes, hurricanes, tsunamis, floods and forest fires (WHO 2018). Such natural hazards may cause releases of chemicals from damaged fixed chemical installations, oil and gas pipelines, storage sites, transportation links, waste sites and mines (Krausmann *et al.* 2017b).

The recent effects of Hurricane Harvey on petrochemical facilities in Texas in 2017 provides an example. (Griggs *et al.* 2017; Tabuchi and Kaplan 2017; Horney *et al.* 2018) (see also Part III, Ch. 6). In more than a dozen chemical plants and refineries in the Houston area damaged storage tanks, ruptured containment systems and broken pressure relief valves were reported. At least 14 tanks failed when their floating roofs sank under the weight of the heavy rain; others floated or toppled over, tearing flowlines and spewing thousands of barrels of oil and waste water. A

Figure 5.18 **Number of chemical accidents in OECD countries with significant releases to the environment (adapted from Gyenes and Wood 2014, p. 10)**



spill of almost 11,000 barrels of gasoline into the floodwaters occurred at a storage terminal where tanks had floated and released their content (Texas Commission on Environmental Quality 2017). At a chemical facility fires and explosions occurred when the site lost power and therefore its refrigeration capabilities (Sutherland *et al.* 2018). Benzene, vinyl chloride, butadiene and other known human carcinogens were among the dozens of tonnes of toxic substances released, which polluted the air in the Houston area in the wake of the hurricane (US EPA n.d. c).

Removing wastes after a disaster in a timely and environmentally sound manner is also a significant challenge. These wastes can be highly heterogeneous. They may include not only construction materials (e.g. concrete, steel and timber), but also hazardous substances such as asbestos, pesticides, oils and solvents (Greenwalt *et al.* 2018).

5.5 Chemical pollutant and waste data: challenges and opportunities

Global systems to track and quantify chemical releases to the environment are lacking

There are substantial gaps in data on chemical releases and on global pollution worldwide. Available data concerning chemical releases at the national or regional levels are often inconsistent, incomparable and incomplete, while their availability is regionally varied. Published data are available for a few higher-income countries, but not for most low- and middle-income countries. Consistent data are available across some countries on five to seven priority air pollutants, but not on industrial chemical air emissions or water discharges. Information on the global and regional use and release of pesticides is very limited. Despite efforts to systematically collect information about chemical accidents, a consolidated database does not exist, creating challenges for researchers (Hemmatian *et al.* 2014).

Reporting data on the uses of ozone-depleting chemicals, and modelling data on GHG emissions, provide some broadly accepted global trend metrics. New initiatives such as the Global Mercury Observation System, the Stockholm Convention Global Monitoring Plan and the Global Atmospheric Passive Sampling (GAPS) for monitoring and modelling mercury, POPs and other pollutant concentrations offer useful indications of releases. These systems could provide models for tracking programmes that cover releases of chemicals in pesticides, fertilizers and other manufactured products at the global level. There is a growing literature on the global mass flows of materials and releases of some chemicals, such as perfluorinated and brominated compounds that rely on analytical models. These are also promising.

In some countries PRTRs provide reliable data on chemical releases. However, there is no common list of chemicals, thresholds for reporting, or units by which the data can be aggregated or made available to the public. There is a significant opportunity to create a global PRTR, or an internationally harmonized network of national PRTRs.

Opportunities exist to improve global waste generation and treatment data

Solid and hazardous waste data are collected by various national governments, and some shipments are reported under international agreements. However, these data are limited due to variations in terms, classification categories and data collection methods. The *Global Waste Management Outlook* (UNEP and ISWA 2015b) and the World Bank's *What a Waste* and *What a Waste 2.0* reports (Hoornweg and Bhada-Tata 2012; Kaza *et al.* 2018) chart comprehensive directions for assessing global solid waste generation, but also admit to the data collection limits raised by inconsistencies in waste definitions, metrics for measurement, and reporting procedures. Collecting data on hazardous wastes is even more difficult. There are no international surveys. Under national reporting obligations, Basel Convention data cover hazardous waste trade. Providing total amounts for hazardous waste generation is optional. National reporting on hazardous waste generation varies by country and is often incomplete (see Part II, Ch. 2).

More Information is needed on chemicals in products

Product labelling and safety data sheets have increased the amount of information available on the chemical ingredients of formulated products. However, UN Environment's Chemicals in Products Programme has revealed that this information is often incomplete, particularly for low-volume chemicals and unintended contaminants (UNEP 2015). Information is seldom available on the chemical make-up of articles. While there are new models for predicting releases from products, there is no public information on chemical releases, and little global information on the number and volume of products on regional or global markets. More national or international product registries could provide repositories for such information.

6/ Concentrations of chemicals in the environment and humans

Chapter Highlights

A broad range of chemical pollutants are widely found in air, soils, sediments, oceans, freshwater bodies, biota and humans throughout the world.

Concentrations vary widely according to substance, region and environmental media.

Available data indicate positive trends in reducing concentrations of chemicals regulated or restricted by governments (e.g. lead) and multilateral treaties (e.g. some POPs and mercury).

Concentrations of other hazardous chemicals have been identified in various media and are in many cases increasing.

Several chemicals which have long been banned are present in the remotest regions of the world.

Plastic particles are found in water bodies, soils, air and human faeces.

Chemicals of concern concentrate inside buildings and jeopardize indoor air quality.

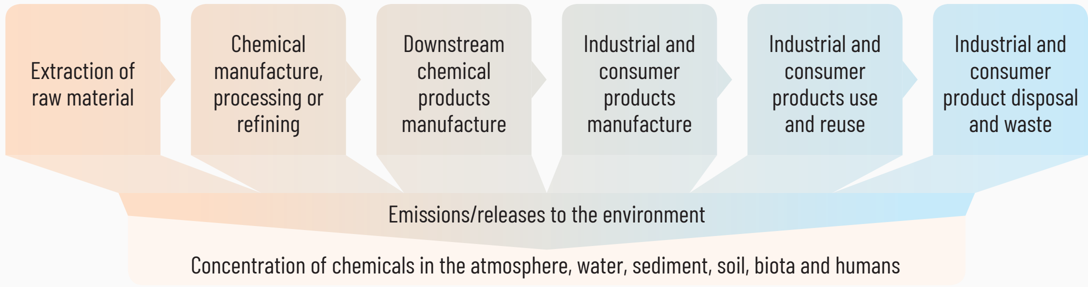
Following the discussion of chemical pollution, this chapter seeks to compile existing data and knowledge on concentrations of chemicals in the environment and humans. It begins with a brief discussion exploring the interface between releases, exposure and concentrations. The remainder of the chapter is structured according to the respective media, beginning with environmental media, then proceeding with biota and concluding with humans. Releases of chemical pollutants from products, production processes and wastes have resulted in a global environment where an increasing number of hazardous chemicals – including lead, bisphenol A, bisphenol S, brominated flame retardants and per and poly-fluorinated compounds – are nearly ubiquitous (Wu *et al.* 2018). Frequently, however, limited data make it difficult to identify trends.

6.1 The interface of releases, exposures and concentrations

Chemicals in the environment: fate and exposures

Once manufactured chemicals are released to the environment, their fate is determined by their molecular properties and the biochemical and physicochemical properties of the receiving medium. “Fate” refers to the transformation processes, as chemicals transfer across different indoor and outdoor environmental media and build up in chemical concentrations in humans and the environment. Chemicals often transfer from one environmental medium to others for which they have a greater affinity and travel long distances through these media. The potential for human exposure to these chemicals is

Figure 6.1 Value chain of the chemical industry, showing emissions and concentrations



determined by the proximity, frequency and duration of contacts between the chemicals and susceptible populations. It may involve different doses taken in through various exposure routes. Exposures can occur throughout a chemical's life cycle, from its original extraction or production, through its processing and integration into a product, during product distribution and use, and on to its ultimate disposal (Figure 6.1).

Concentrations around point source releases vs. long-range transport of chemicals

Chemical pollutants may concentrate in air, surface and groundwater, soils and sediments, and living organisms (including people). These concentrations tend to be higher near the point of release and to decrease with distance, owing to

dilution, chemical transformations, and microbial or chemical degradation.

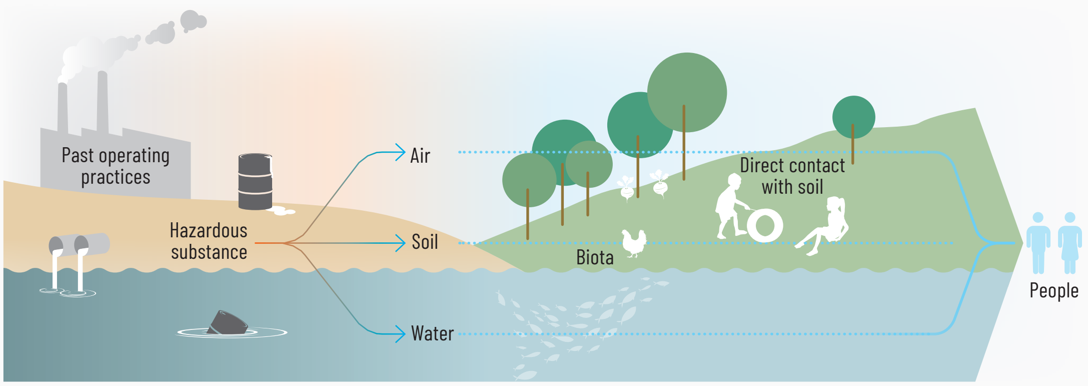
Persistence is a key determinant of fate, with substantial variations in the environmental elimination half-lives of chemicals, which range from a few minutes to hundreds of years. Long-range transport of chemicals via atmospheric or surface water currents may distribute persistent chemicals far from the originating source. The transport of chemical-intensive products internationally provides a new and relatively unstudied way in which manufactured chemicals are distributed throughout the global environment. Manufactured chemicals may be found in physical and ecological niches such as polar regions, where air, river and ocean currents, drifting sea ice and migrating wildlife transport these chemicals long distances and where their degradation is restricted (Beyer *et al.* 2000).

The potential effects of bioaccumulation on chemical intake

People are exposed to manufactured chemicals either directly from products or indirectly through releases to the environment. Exposure routes include ingestion, inhalation, dermal uptake and injection (the latter usually in the case of pharmaceutical products). Ingestion occurs through multiple exposure pathways (e.g. directly though drinking water, eating food or sucking on objects) or indirectly through swallowing dust (Figure 6.2).

Food intake is a major source of chemical exposure. The magnitude of exposure from food depends on the amount of the chemicals and their persistence and/or their bioaccumulative potential. Fat soluble, lipophilic chemicals tend to accumulate in fish, meat or dairy products and

Figure 6.2 Exposure pathways



Box 6.1 Bioaccumulation and biomagnification (Naik 2018)

Bioaccumulation and biomagnification often occur in conjunction with each other.

- *Bioaccumulation* is the process by which chemical toxicants build up in individual organisms.
- *Biomagnification* is the process by which chemical toxicants pass from one trophic level to the next and, in doing so, increase in concentration in higher-level trophic organisms.

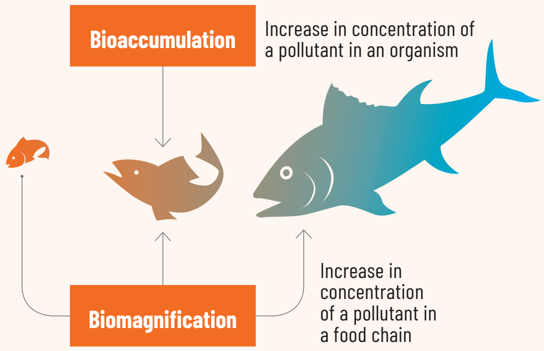
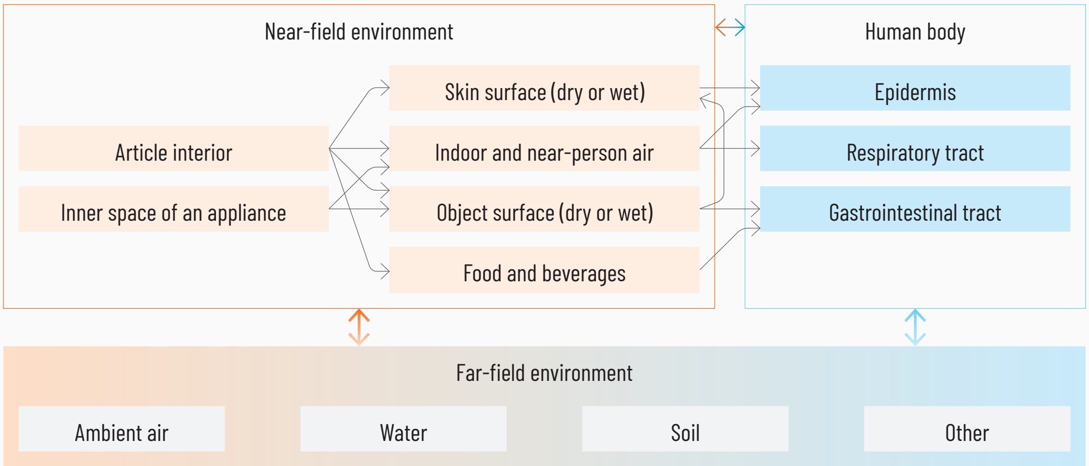


Figure 6.3 Links between the near-field environment and compartment of entry, the far-field environment, and the human body (adapted from Huang *et al.* 2017, p. 185)



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to biomagnify throughout the food web; their concentrations can be up to a million times higher in fish than in the fish's water habitat (Arnot and Gobas 2006). Lipophilic chemicals also tend to be persistent and to have long half-lives and thus contribute to high internal exposures in humans. Non-bioaccumulating chemicals such as certain phthalates (Ferguson *et al.* 2017), parabens (Fisher *et al.* 2017) and triclosan (Weiss *et al.* 2015) can be identified in biomarker sampling studies where exposures may be continuous (Box 6.1).

Exposures to consumer products can increase chemical concentrations in people

For many people in higher-income countries (and some in middle- and lower-income countries) the most significant exposures to hazardous chemicals may come from consumer products. Since the frequency of consumer contact with products and the exposure duration are often high (Wambaugh *et al.* 2013), these exposures can result in significant chemical concentrations in human bodies, especially during pregnancy (Lang *et al.* 2016). Exposure depends not only on chemical properties, but also on how the product is used and the manner in which the body is exposed (Huang *et al.* 2017) (Figure 6.3).

A number of chemicals of concern are found in food products

Food is a particularly significant vehicle for chemical exposure. Sampling data compiled by the WHO (2018a) on food contaminants include lead in wine at up to 584 micrograms/kilogram (μg/kg), dioxins in cooked crabs at 740 picograms/kilogram (pg/kg), and the neonicotinoid imidacloprid in lettuce at 10,790 μg/kg. A study of common foods in the United States (Liao and Kannan 2013) found several bisphenols contaminants in 75 per cent of analyzed food samples. Plastic particles have been found in salt, beer and honey (Hartmann 2018; Kosuth, Mason and Wattenberg 2018), soft drinks (Qunitili 2018), and bottled and tap water (Kosuth, Mason and Wattenberg 2018; Mason, Welch and Nertko 2018) as well as in human faeces (Eurekalert 2018; Parker 2018; Schwab *et al.* 2018). Contaminants have also been found in baby and infant food. For example, a 2017 study found methylmercury and inorganic arsenic in rice baby foods (Rothenberg *et al.* 2017).

Pesticides may be present in food in various concentrations. A recent study of honey collected across the world found evidence of neonicotinoids in most samples. (Mitchell *et al.* 2017). A 2019

compilation of United States Department of Agriculture and United States Food and Drug Administration data (Environmental Working Group [EWG] 2019) found that almost 70 per cent of produce sold in the that country contained pesticide residues and that there were “225 different pesticides and pesticide breakdown products on popular fruits and vegetables”. However, most of these were at “very low levels” (Bernhardt *et al.* 2019). The data set includes, for example, kale contaminated with Dacthal, classified by the US EPA as a possible human carcinogen (US EPA 2018). Compiling data on the analysis of 85,000 samples for 791 pesticides, the European Food Safety Authority (EFSA) concluded that more than 96 per cent of the tested samples fell within the legal limits, a slight decrease compared to the previous reporting year (EFSA 2018). This 2016 report further notes that more than 50 per cent of the tested samples were free of quantifiable residues. While 2.4 per cent of the samples from EU and European Economic Area (EEA) countries were above legal limits, 7.2 per cent of the samples from non-EU countries exceeded legal limits. Data availability for developing countries is limited, but limited management, surveillance and regulatory capacity is likely to cause more concerns. For example, a study sampling foods purchased at a local market in Bolivia found pesticide residues in 20 per cent of lettuce samples to be above the maximum residue limits. The study also observed that “no samples contained concentrations of pesticides which alone or together would lead to exposures that exceeded the acceptable daily intake or the acute reference dose” (Skovgaard *et al.* 2017).

Highly exposed and susceptible populations

Depending on the dominant exposure pathways, different subpopulations are exposed to hazardous chemicals in different ways (Hunt *et al.* 2016; UNEP 2016a; Secretariat of the Strategic Approach to Chemicals Management [SAICM Secretariat] 2018; Undeman *et al.* 2018). In the case of exposure to PCBs contained in fish, subsistence fishermen and high-end fish consumers are among those most highly exposed (United States Agency for Toxic Substances and Disease Registry [US ATSDR] 2014). In the case of dermal uptake of parabens, frequent

consumers of personal care products will have higher exposure levels. Children can be exposed through direct contact with chemicals in various articles (e.g. phthalate plasticizers via mouthing, swallowing dust or direct contact) (Dewalque *et al.* 2014; Guo, Wang and Kannan 2014). Workers can be highly exposed to chemicals in their work environments and to chemicals used in product manufacturing (Kijko *et al.* 2015), especially where protective measures are limited (Arastoo *et al.* 2015). The burden of direct workplace exposure to hazardous chemicals is often unevenly distributed between women and men, who have different sensibilities to these chemicals, play different gender roles and may be exposed in different ways (UNEP 2016a; Women in Europe for a Common Future [WECF] 2016).

Generic and multi-media models are available to predict chemical fate and exposure. Results from these models help predict the distribution of environmental concentrations for a wide range of substances (and the proportion of human intake via multiple pathways) (MacLeod *et al.* 2011; Webster *et al.* 2016; Wannaz, Fantke and Jolliet 2018; Wannaz *et al.* 2018). More recently, new approaches have become available to evaluate exposure to a wide range of chemical-product combinations, accounting for both environmental and indoor exposures (Isaacs *et al.* 2014; Fantke *et al.* 2016). However, further research is needed to better understand and quantify product-specific exposure pathways such as dust, gaseous dermal uptake, and direct contact with textiles and other articles.

6.2 Concentrations in environmental media

Concentrations of manufactured chemicals in the environment are found around the world. Much of these concentrations come directly from industrial facility releases, or municipal landfill leakage, air deposition, contaminated water run-off, land applications of pesticides and fertilizers, and commercial products. However some also come from complex chemical transformations in environmental media. Global, regional and local monitoring studies reveal both increasing and decreasing trends.

6.2.1 Air

Concentrations of priority air pollutants are decreasing in some regions

Air concentrations of most priority air pollutants arising from combustion sources in higher-income countries are on a long-term decline. In the past two decades sulphur dioxide concentrations in North America and Europe have fallen by more than two-thirds because of improved energy efficiencies, shifts in fuel mixes, and widespread application of end-of-pipe desulphurization in the power sector (EEA 2015; US EPA n.d.). Average air concentrations of lead in air have decreased in regions where government regulations have restricted lead additives in fuel. In the United States, for example, airborne lead concentrations declined 92 per cent between 1980 and 2013, largely due to reduced lead content in gasoline (US EPA 2014; US EPA 2017a). Furthermore, Canada implemented the Air Quality Management System, which is a comprehensive and collaborative approach by all levels of government to reduce the emissions and ambient concentrations of various pollutants of concern (air pollutants that case smog and acid rain). These reductions have contributed to the reduction of the air pollutants that Canadians breathe every day (Canadian Council of Ministers and of the Environment 2014).

However, concentrations of the same air pollutants are increasing in lower-income countries

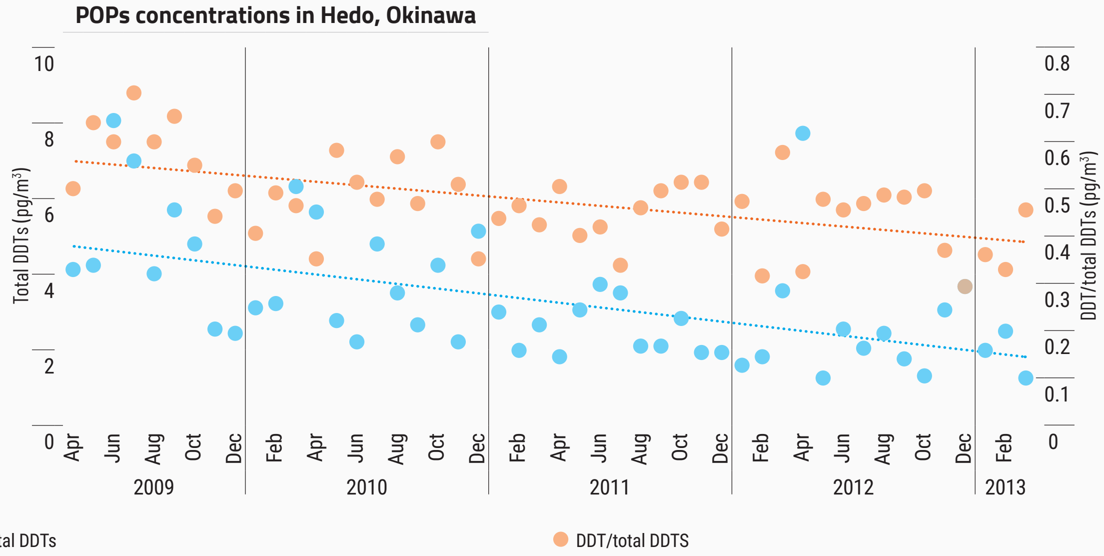
The WHO estimates that around 90 per cent of people worldwide breathe polluted air with an annual mean value of particulate pollution higher than the WHO air quality guideline levels (WHO 2018b). The highest ambient air pollution levels are in the Eastern Mediterranean region and Southeast Asia. Particulate pollution levels in low- and middle-income cities in Africa and the Western Pacific are also high. In a WHO survey of 795 cities in 67 countries, 98 per cent of cities with more than 100,000 inhabitants in lower- and middle-income countries did not meet WHO air quality guidelines. The main sources of particulate matter (PM) air pollution include cooking (the principal source of household air pollution), industry, agriculture, transport and coal-fired power plants (WHO 2018c).

Some studies show concentrations of certain persistent organic pollutants in the atmosphere are declining in some regions

The second *Global Monitoring Report* of the Global Monitoring Plan for Persistent Organic Pollutants (POPs) under the Stockholm Convention concludes that concentrations of listed POPs in air have largely decreased, and that concentrations

© UNEP/Victor Estellano, passive air sampling

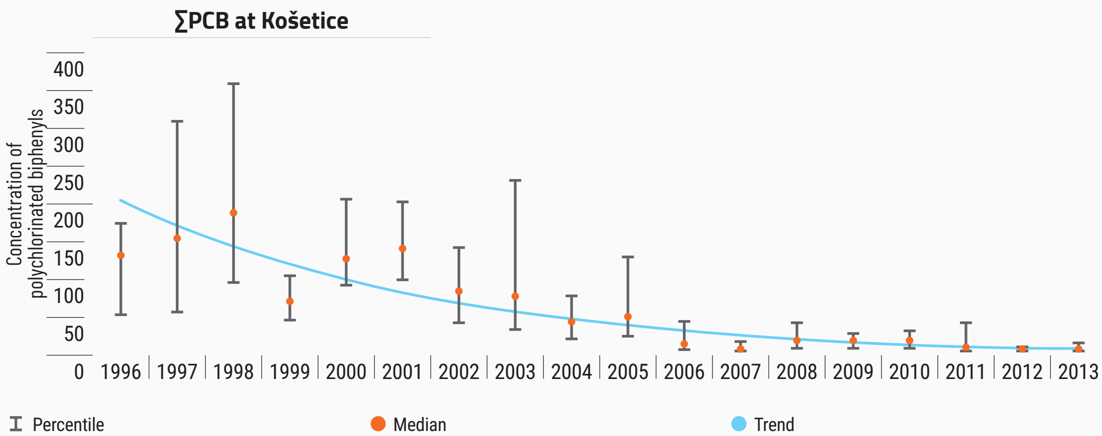
Figure 6.4 **Trends in DDT concentrations in air, and ratios between DDT and total DDTs (pg/m³), in Hedo, Japan, 2009-2013 (adapted from Nagai *et al.* 2015, p. 41)**



Air monitoring undertaken at a site in Japan between 2009 and 2012 showed deceasing concentrations for total DDT (sum of six isomers, including the major breakdown products of DDT) as well as for the ratios of DDT (sum of p,p'- and o,p'-DDT, the major components of commercial DDT) and total DDT, which suggests a reduction in DDT input during the sampling period.

of so-called "legacy POPs" (organochlorine pesticides, PCBs and PCDD/PCDF) have decreased strongest since the 1980s (Šebková *et al.* 2014). Figure 6.4 and Figure 6.5 show trends in PCBs and dichlorodiphenyltrichloroethanes (DDTs) concentrations at two sites: Košetice in the Czech Republic and Hedo in Japan. Concentrations of chemicals more recently listed in the Stockholm

Figure 6.5 **Trends in concentrations of PCBs in Košetice, Czech Republic (pg/m³), 1996-2013 (adapted from Šebková *et al.* 2014, p. 61)**



Over a period of 18 years, concentrations of sum PCBs gathered through active sampling showed decreasing trends at a station in the Czech Republic, pointing towards the effectiveness of national and international action taken on PCBs, including through the Stockholm Convention.

Convention as POPs (e.g. PBDEs, PFOS, HBCD and PeCBz) increased through the 1990s, subsequently stabilized, and then started to decrease in the early 2000s.

Atmospheric concentrations of PCBs, DDT, chlordanes, and polybrominated diphenyl ether (PBDE) congeners (such as BDE-209) are slowly declining in Arctic air. Atmospheric monitoring in other regions of the world has revealed that, among all POPs, pesticides were found at the highest concentrations in Africa and in Latin America and the Caribbean. Specifically, concentrations of DDTs, hexachlorocyclohexane (HCH) and endosulfan were dominant in Africa while lindane was detected at the highest concentrations in Latin America and the Caribbean. These concentrations were all decreasing in the Asia-Pacific region, Central and Eastern Europe and Western Europe (UNEP and Secretariat of the Stockholm Convention 2017).

Concentrations of some flame retardants are decreasing, but those of others are increasing

A recent study analyzing air monitoring data in the Great Lakes Basin in Canada found that PBDE concentrations had declined between 2005 and 2014 (Shunthirasingham *et al.* 2018). While these PBDE concentrations show declining trends, concentrations of other flame retardants present increasing concerns. Data from the Global Atmospheric Passive Sampling (GAPS) Network suggest that concentrations of atmospheric PBDEs are similar across regions, although lower concentrations are observed in Latin America and the Caribbean in comparison to North America and the Asia-Pacific region. These differences may be due to the influence of local sources, as well as historically higher usage of PBDEs in North America (UNEP and Secretariat of the Stockholm Convention 2017; Rauert *et al.* 2018). Minimal differences in concentrations were identified across urban, agricultural and polar regions for PBDEs, and for their POPs-like flame retardant replacements, organophosphate esters (OPEs) and other more recently introduced flame retardants (Rauert *et al.* 2018). Despite positive declining trends for PBDEs across the globe, monitoring in the Arctic has revealed uncertain trends for other flame-retardant chemicals (Figure 6.6).

In some studies elevated concentrations of chlorinated flame retardants in the Arctic are now being detected which are comparable to those found in urban air, while organophosphate-based flame retardants (PFRs) are being detected at higher concentrations than PBDEs. Moreover, air concentrations of chlorinated PFRs are commonly reported at concentrations higher than those of other classes of flame retardants in the same samples, often 100 times higher (AMAP 2017).

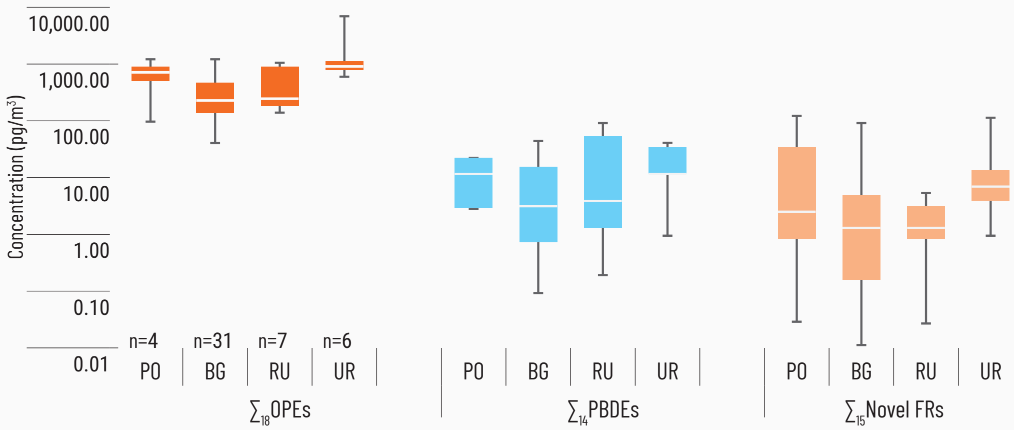
Atmospheric concentrations of mercury are still of concern

It is estimated that over the past century anthropogenic activities cumulatively have increased atmospheric mercury concentrations by 300-500 per cent. There is a clear gradient in concentrations of mercury in air driven by local and regional sources, with higher concentrations in the northern hemisphere compared to the southern hemisphere. Most monitoring sites in the northern hemisphere show a downward trend in mercury concentrations between 2007 and 2014, while sites in South Africa show a slight increase. In North America and Europe, concentrations in air declined 10-40 per cent between 1990 and 2010 and have more recently plateaued. In the Arctic, concentrations have also been declining, although at a slower rate than elsewhere possibly due to mercury released during permafrost melt from climate change. (Schuster *et al.* 2018). Atmospheric mercury concentrations at remote sites in China are elevated compared to those at remote sites in Europe, North America and other locations in the northern hemisphere. It is assumed that regional anthropogenic emissions and long-range transport of mercury are driving these elevated mercury concentrations (UNEP and AMAP 2018).

Chemicals concentrate inside buildings, affecting indoor air quality

Manufactured chemicals released from building materials, home and workplace furnishings, and

Figure 6.6 Global atmospheric concentrations of polybrominated diphenyl ethers (PBDEs) and of organophosphate esters (OPEs) and other novel flame retardants (FRs) at four location types: polar, background, rural and urban, 2014 (adapted from Rauert *et al.* 2018, p. 2778)



Analysis of passive air samples from the Global Atmospheric Passive Sampling Network suggested that "global atmospheric concentrations of PBDEs have not declined since regulatory measures were implemented" (Rauert *et al*. 2018). The study found organophosphate esters in concentrations at least an order of magnitude above those detected for PBDEs.

household and personal care products can result in higher concentrations inside residential and workplace facilities than outside (EEA 2016). New buildings or recently redecorated environments, where the frequency of air exchanges has been reduced, have been associated with high concentrations of these chemicals in household and interior dusts (Mercier *et al.* 2011).

A recent study of concentrations of chemicals – including phthalates, flame retardants, chlorinated solvents and others – in new and recently renovated housing found indoor air concentrations exceeding available risk-based screening levels in all sampled homes for at least one of the targeted chemicals (Dodson *et al.* 2017). This study not only identified chemicals from building materials (e.g. certain flame retardants), but also chemicals used in personal care products such as dibutal phthalate (DBP). A recent review of semi-volatile organic compounds (SVOCs) in indoor air found significant concentrations in residences, schools and office buildings at sites throughout the world (Lucattini *et al.* 2018). Another study analyzing concentrations of volatile organic compounds (VOCs) in newly renovated residences in Shanghai found a dozen VOCs classified by the International Agency for Research on Cancer as confirmed or probable carcinogens in more than 60 per cent of samples (Dai *et al.* 2017).

Indoor dust is a reservoir for chemicals released from commercial consumer products. Heavy metals such as lead and cadmium have been identified in household dust. Lead is a common constituent in dust from older homes in India where lead paint may still be present (Kumar and Scott 2009). The Canadian House Dust Study found elevated concentrations of lead in dust samples from Canadian homes in central urban areas (Rasmussen *et al.* 2011). Permethrin and cypermethrin were the most common pesticides identified in a review of 15 published studies of floor wipes and dusts in residential environments in the United States (Morgan 2012). A recent study of indoor dust samples taken from residential settings in the United States identified chemicals of recognized health concern. Phthalates occurred in the highest concentrations, followed by phenols, chemicals used to replace regulated flame retardants, fragrances and PFASs (Mitro *et al.* 2016)

6.2.2 Freshwater and oceans

Continuous discharges of hazardous chemicals into freshwater bodies and oceans, atmospheric

deposition, and the dynamic nature of water cycles results in the presence of chemical contaminants in rivers, streams, lakes, reservoirs, groundwater and oceans.

Globally, clean drinking water is available to most people but not all

The WHO has reported that 91 per cent of the world population has access to clean drinking water. However, some 660 million people remain without safe water while chemical contamination from pesticides, landfill leachate and industrial discharges continues to be a local problem in low- and middle-income countries (United Nations International Children's Emergency Fund and WHO 2015). Although over 200 chemicals in drinking water are regulated by some governments, there is growing public concern about the presence of chemicals such as perfluorinated compounds, dioxane, siloxanes, pharmaceuticals, perchlorate, musks, illicit drugs, pesticide degradation products and sunscreens (Villanueva *et al.* 2013).

Chemical pollutants occur in freshwater bodies throughout the world

A recent analysis of over 800 scientific studies on 28 common insecticide compounds in surface waters in 73 countries found that of the 8,186 insecticide concentrations detected, over 68 per cent were above regulatory thresholds, sometimes by as much as 10,000 times (Stehle and Schulz 2015). A review (Lapworth *et al.* 2012) of the sources of emerging organic contaminants, such as pharmaceuticals, personal care products and selected industrial compounds, in groundwater found microgram-level concentrations of a large range of these contaminants (Lapworth *et al.* 2012). Glaciers also carry pollutants: a recent study (Ferrario *et al.* 2017) determined the occurrence of various POPs (including DDTs and PCBs), pesticides and other contaminants in Alpine glaciers. Certain organochlorine pesticides regulated under the Stockholm Convention have also been found in the Himalayan glaciers (Li *et al.* 2017a).

European water monitoring studies have found that river basins in northern Europe pose higher chemical risks than in the south. Of the 223 chemicals included in monitoring efforts, pesticides, tributyltin, PAHs and brominated flame retardants were the major contributors to chemical risk (Malaj *et al.* 2014). A recent survey of river water samples in 41 cities in 15 countries found detectable concentrations of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) in nearly every region studied (Kunacheva *et al.* 2012). In addition to river contamination, many

Box 6.2 Concentrations of legacy chemicals in water bodies: the Mariana and Kermadec trenches and Lake Geneva

Certain hazardous chemicals whose production and use were banned years ago may still be found at high concentrations in the environment. A recent study (Jamieson *et al.* 2017) analyzed small animals (called amphipods) captured from some of the deepest ocean trenches – the Mariana and Kermadec trenches of the Pacific Ocean – at a depth of more than 10 km. The PCB and PBDE concentrations tested in the animals were at "extraordinary levels", higher than those of animals living in in highly polluted rivers in industrialized regions. This can be explained by the high persistence and accumulation of POPs in fat. In another study (Filella and Turner 2018) several thousand samples of diverse plastic litter of various sizes, age and composition were collected from shores around Lake Geneva in Switzerland. The researchers found a number of banned/restricted hazardous chemicals, including cadmium, mercury, lead and bromium (most likely from brominated flame retardants).

studies in Western Europe and the Asia-Pacific region report concentrations of PFOS in lakes/reservoirs, estuaries and coastal waters (UNEP and Secretariat of the Stockholm Convention 2017) (Box 6.2). A study reviewing available literature and databases on concentrations of chemicals in rivers in the United Kingdom found evidence for the presence of a large variety of hazardous chemicals, including a range of heavy metals, triclosan and lindane. The highest median river water concentrations in order of magnitude were detected for iron, aluminium, zinc and manganese (Donnachie *et al.* 2014).

Climate change may significantly increase concentrations of POPs in ocean water

It is anticipated that climate change will alter concentrations of POPs. With the melting of Arctic sea ice, previous reservoirs for POPs are expected to release these chemicals back to the environment. Modelling of future POPs concentrations suggests that ocean waters could be particularly impacted, with up to a four-fold increase in concentrations of some POPs even after their production and use have been phased out (Wöhrnschimmel *et al.* 2013).

Pharmaceuticals are found in water across the world

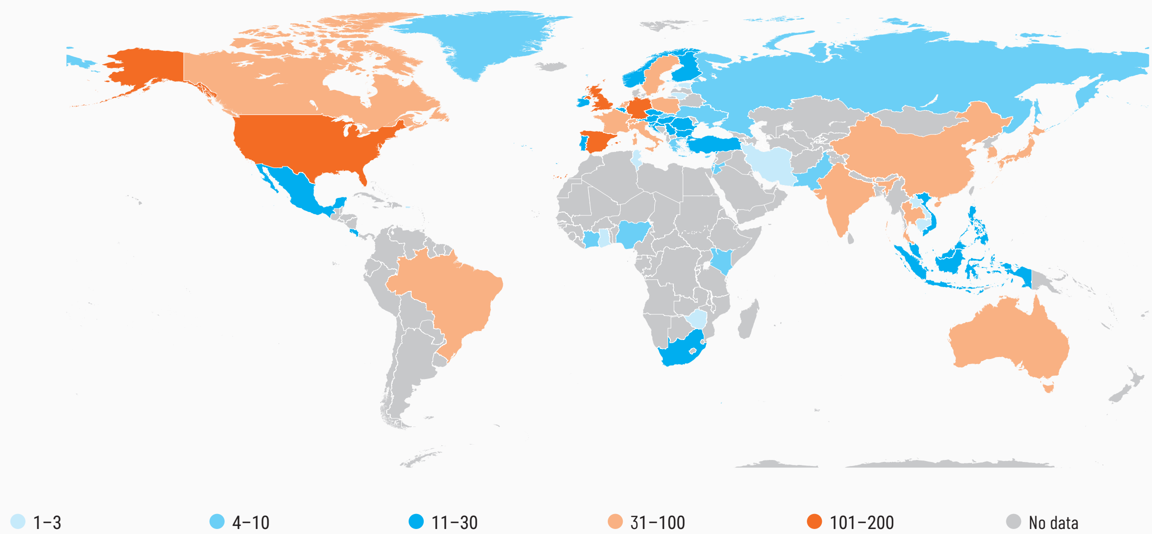
Pharmaceuticals and their metabolites are released to the environment from a variety of sources, including medicinal drugs and agricultural feedlots. A study of 203 pharmaceuticals across 41 countries showed that pharmaceutical residues are present at significant levels in surface and tap water in many countries and regions (Hughes *et al.* 2013). Another study, by the German Environment Agency (UBA), found that in 71 countries in all regions there were more than 600 active pharmaceutical substances or their metabolites and transformation products in surface water, groundwater, tap water and/or drinking water and other environmental matrices (Figure 6.7). Seventeen pharmaceuticals were found in all five United Nations regions, including the anti-inflammatory drug diclofenac (which was detected in 50 countries) (Weber *et al.* 2014; UBA n.d.).

A wide range of chemical contaminants are present in oceans

A recent review of studies of chemical contaminants in marine environments identified 276 manufactured chemicals, including nine metals/metalloids, 10 organometallic compounds, 24 inorganic compounds, 204 organic compounds and 19 radionuclides. The source of these chemicals ranged from oil and gas operations, and shipping and marine aquaculture, to accidental spills and on-shore discharges (Tornero and Hanke 2016). An analysis (Ho *et al.* 2016) of organotin contamination in the marine environment of Hong Kong in the period 1990-2015 found that, in some cases, there were increasing concentrations of several organotins. Another study (Liao and Kannan 2018) found elevated concentrations of parabens in China's Bohai Sea, with gradual increases documented between 2006 and 2012.

Of the anthropogenic emissions of mercury that have accumulated over the centuries, 50 per cent remains in the oceans, of which 36 per cent is in sea water (Zhang *et al.* 2014). One study suggests that concentrations of mercury in the surface layer of the ocean have doubled over the last 100 years, increasing by 25 per cent in intermediate waters and 10 per cent in deep waters. This variation is likely due to the time it takes surface waters to circulate to the depths (UNEP 2013). Mercury concentrations appear to have increased at depths between 200 and 1,000 metres in the North Pacific Ocean over the last few decades and to have decreased In the North Atlantic. The Mediterranean Sea, in contrast, showed a decrease in mercury concentrations between 1990 and 2004 (UNEP 2013).

Figure 6.7 **Number of pharmaceuticals detected in surface water, groundwater, tap water and/or drinking water (adapted from Weber *et al.* 2014, p. 6)**



Ocean and freshwater body sediments store and concentrate chemicals

Studies show that concentrations of currently used brominated flame retardants are increasing in freshwater sediments. Samples drawn from the Great Lakes in North America found that the sediment concentration of decabromodiphenyl ethane (DBDPE) doubles every three to five years in Lake Michigan, and approximately every seven years in Lake Ontario (Yang *et al.* 2012). Sediments in the Adriatic Sea that were deposited within the last two decades represent a 40-80 per cent reduction in peak levels of PCBs, corresponding to national production bans on PCBs in late 1970s (Combi *et al.* 2016).

An increasing amount of plastic particles is widely found in the world's rivers, lakes and oceans

Microplastics have been found in freshwater bodies, including rivers (Moore *et al.* 2011) and lakes (Eriksen *et al.* 2013). Concentrations in rivers vary significantly, depending on factors such as river basin population densities (Lebreton *et al.* 2017). It has been estimated that some 80 per cent of anthropogenic litter along the shorelines of the Laurentian Great Lakes is comprised of plastics (Driedger *et al.* 2015).

Floating plastic debris, including microplastics, has been reported in the gyres of the North Atlantic and Pacific Oceans since the early 1970s (Moore *et al.* 2001; Eriksen *et al.* 2013). Plastic debris and microplastics are transported by ocean currents across borders and are found even in very remote areas such as the deep ocean (UNEP 2016b). While some microplastics float, others sink. Plastic bags and containers that decompose make up a large share of floating plastic wastes. Lighter weight polyethylene, polypropylene and polystyrene are the most common types of plastic litter in surface waters. This debris tends to degrade under the stress of sunlight, heat and agitation into tiny fragments that may be swept into gigantic gyres on the surface of several oceans. The amount of microplastics floating in the oceans has been estimated at 93,000-268,000 tonnes (Eriksen *et al.* 2014; Sebille *et al.* 2015). Denser polymers such as polyester and polyvinyl chloride tend to sink into the sediment of the marine environment and accumulate on the ocean floor, which means that a significant amount of microplastics may eventually accumulate in the deep sea and ultimately in marine and human food resources (Seltenrich 2015). It has been estimated that some 94 per cent of the plastic that enters the oceans ends up on the sea floor and about 1 per cent is found at or near the ocean surface (Lebreton *et al.* 2017).

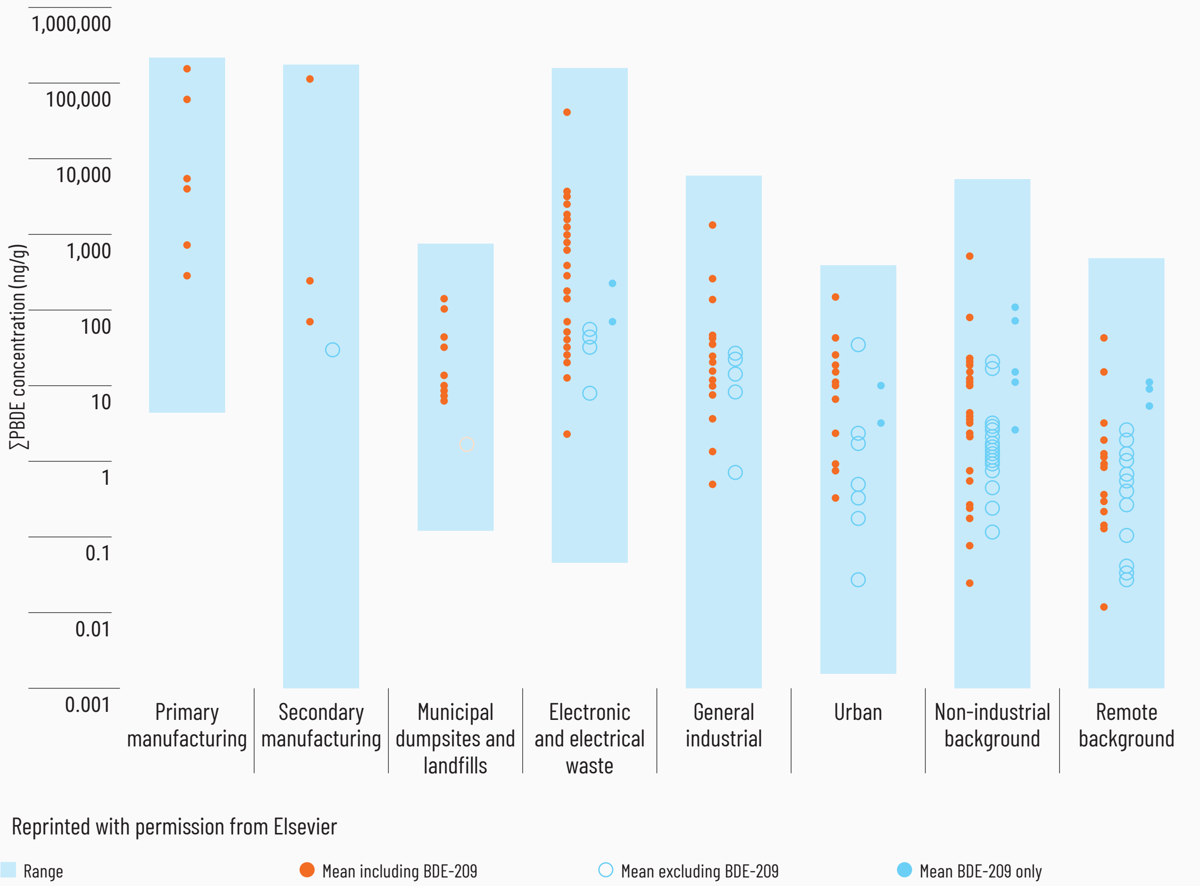
6.2.3 Soils

Soils throughout the world are contaminated by a broad range of hazardous chemicals

Based on the analysis of soil samples from six countries (the United States, China, Japan, Norway, Greece, and Mexico), a global median soil concentration for PFOA and PFOS was estimated to be 0.124 ng g^{-1} and 0.472 ng g^{-1} respectively (Strynar *et al.* 2012). Higher concentrations of PFOA and PFOS for soils from Shanghai, China and Kampala, Uganda have been reported (Li *et al.* 2010; Dalahmeh *et al.* 2018). Perfluorinated compounds have been found in all soil and water samples in a recent national survey in the Republic of Korea of agricultural soils near wastewater treatment plants. Significant mean concentrations of PFOA and PFOS were found in samples from all 81 cities where these were drawn (Choi *et al.* 2017).

Soil acidification is now a major problem in China, where soil has long used for intensive agriculture. Large amounts of metals (e.g. cadmium, arsenic and chromium) have found their way to farmland through air deposition, synthetic fertilizers and livestock manure application (Chen *et al.* 2018). A 2017 study reviewing 465 published papers found that almost 14 per cent of grain production in China was affected by heavy metal pollution in agricultural soil (Zhang *et al.* 2015). In the Republic of Korea, monitoring data reveal an unexpected increase in average soil concentrations of dioxins and furans over a 10- year period (1999-2009). Soils from the country's industrialized regions showed a 10- fold increase in the same period (Kim and Yoon 2014). In a recent study in Mali, hazardous pesticides, including DDT, endosulfan

Figure 6.8 Concentrations of polybrominated diphenyl ethers (PBDEs) in surface soil by land use category (ng/g) (adapted from McGrath *et al.* 2017)



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and profenofos, were detected in 77 per cent of soil samples collected from damaged cotton production sites (Dem *et al.* 2007).

Polybrominated diphenyl ethers (PBDEs) are commonly detected at background locations in surface soils, including in Antarctica and the northern polar regions. As shown in Figure 6.8, PBDEs emitted from numerous land use categories are routinely detected in surface soils.

POPs are present in soils near recycling sites

In India, PCBs and PCDD/PCDFs have been found in soils near informal e-waste recycling sites and nearby open dumpsites of large cities (Chakraborty *et al.* 2018). This is attributed to the burning of wire during the copper extraction process, as well as combustion of plastic materials. In China, Leung *et al.* (2007) found that surface soils at a site where computer parts (e-waste) had been dismantled and recycled for a decade had high concentrations of PBDE and PCDD/PCDFs, with open burning among the major causes.

Heavy metals are present in soils across regions

Various studies have identified heavy metals in soils. For example, a study of the impacts of industrial and agricultural activities on soil concentrations of copper, cadmium, mercury and lead in Zhangjiagang City, in a rapidly developing region of China, revealed high metal concentrations in local areas near industrial locations (Shao *et al.* 2014). Another study of soils along major roadsides in the Kwara State of Nigeria found high concentrations of heavy metals including lead, copper and zinc (Ogundele *et al.* 2015). An Australian study tracked reductions in lead soil samples following the government-

© UNEP/Ludovic Bernaudat, artisanal and small-scale gold mining site

required phase-out of lead additives in fuels. There had been a significant decline over a decade, although legacy concentrations were found to be subject to remobilization (Kristensen *et al.* 2017).

Plastic particles are widely found in soils

Plastic particles are widely found in soils (Bläsing and Amelung 2018; Scheurer and Bigalke 2018; Weithmann *et al.* 2018). The density of microplastics in soil has been found to be significantly higher than in marine environments (up to 23 times, depending on the environment) (de Souza Machado *et al.* 2018). Recently in China, plastic particles were found in all sampled soils, of which 95 per cent were in the microplastic size range (Zhang and Liu 2018). According to Boucher and Friot (2017), “about 52 per cent of the microplastic loss is trapped in soils when wastewater treatment sludge is used as fertilizer and/or when particulates are washed from the road pavement”.

6.3 Concentrations in biota

Concentrations of many manufactured chemicals build up in wildlife and increase as they move up food chains, where bioaccumulation results in the highest concentrations occurring in animals at the highest levels of the food web.

Concentrations of POPs in some fish are declining, but unevenly

Data from Canadian Arctic monitoring reveal that concentrations of poly- and perfluoalkyl substances (PFASs) in landlocked freshwater fish are declining. However, some benthic species such as burbot (*Lota lota*) show increasing trends in some regions (AMAP 2017). Although concentrations of the sum of PCBS congeners (∑PCBs) in Great Lakes fish show continued declines (3-7 per cent per year since the 1970s), concentrations of penta- and hexa-bromodiphenyl ethers appear to have plateaued in fish from the Great Lakes, beginning in the early 2000s, and concentrations are declining (Environment Canada and US EPA 2014; Gandhi *et al.* 2017). The sum of these PBDEs measured between 2008 and 2012 was highest in Lake Ontario, followed by Lake Superior; the lowest concentrations were observed in fish from Lake Erie (McGoldrick and Murphy 2016). The most abundant organochlorine pesticides measured were DDT and its metabolites (DDE and DDD), the highest average concentration of which was measured in fish from Lake Ontario.

Halogenated chemicals are found in birds worldwide

Global reviews of PBDE contaminations in birds have revealed that concentrations of PBDE are generally higher in terrestrial birds than in freshwater or marine birds, and that concentrations in terrestrial birds – particularly of the chemical mixture deca-bromodiphenyl ether(deca-BDE) – were highest in North America and China (Chen and Hale 2010; Law *et al.* 2014). In one study (Chen and Hale 2010) terrestrial birds had higher deca-BDE concentrations than aquatic birds. In another study examining perfluorinated compound concentrations in five different bird species from the same geographic region in Belgium, the highest mean liver perfluorooctane sulfonate (PFOS) concentrations were found in the grey heron with the lowest concentrations in the Eurasian collared dove (Meyer *et al.* 2009).

Mercury is a common contaminant in wildlife

In recent surveys, marine fish species have generally had substantially lower mercury concentrations than freshwater fish. Increasing trends in mercury concentrations have been found in species in North America (Figure 6.9) and west Greenland, while decreasing trends in methylmercury concentrations have been found in east Greenland and the European Arctic (UNEP and AMAP 2018) (Figure 6.10). Egg mercury concentrations for marine birds from the Canadian Arctic indicate that mean mercury concentrations in ivory gulls are above threshold levels for adverse effects on reproduction.

Mercury concentrations are decreasing in polar bears in several regions, including Svalbard, Norway and the southern Beaufort Sea. However, concentrations in the brain tissue of polar bears and beluga whales are generally lower than the levels associated with neurotoxicity in other mammals, although they remain high enough to cause neurochemical changes that can precede overt neurotoxicity (Scheuhammer *et al.* 2015). Harbour seals from the western Hudson Bay had elevated mean liver mercury concentrations, along with comparatively high muscle mercury concentrations (Scheuhammer *et al.* 2015).

Long-term monitoring of mercury concentrations in Sweden, Finland, Norway and the Kola Peninsula of Russia show a consistent and significant decreasing trend in a number of lake fish species, paralleling a similar decline in atmospheric concentrations in the region (Braaten *et al.* 2017). In North America studies often report inconsistent, diverging or mixed trends in concentrations, particularly among aquatic biotic factors. Early declines are attributed to decreases in atmospheric mercury concentrations and deposition rates. Explanations for subsequent reversals or plateaus in concentrations include increasing local emissions, food web changes and climate change (UNEP and AMAP 2018). Overall, however, the updated *Global Mercury Assessment* concludes that “mercury loads in aquatic food webs are at levels of concern for ecological and human health around the world” (UNEP and AMAP 2018).

Figure 6.9 Mercury concentrations in large lake trout collected from the East Arm of Great Slave Lake, Canada (µg/g), 1992-2012 (adapted from Evans *et al.* 2013, p. 12794)

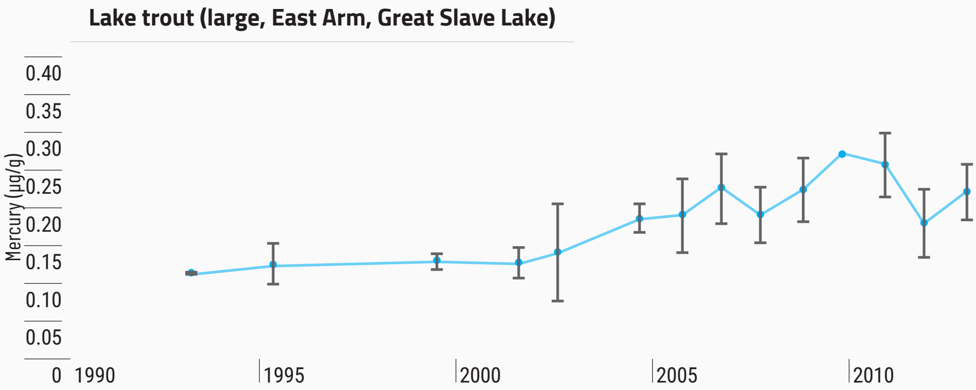
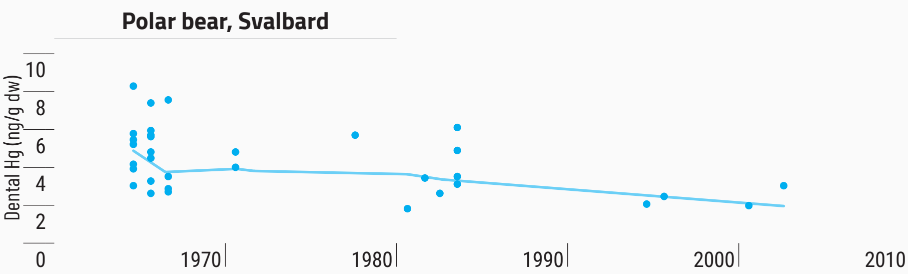


Figure 6.10 Mercury concentrations in polar bears, Svalbard, Norway (ng/g dw), 1960s-2000s (adapted from Aubail *et al.* 2013, p. 60)



Dry weigh (dw)

Plastic particles accumulate in fish

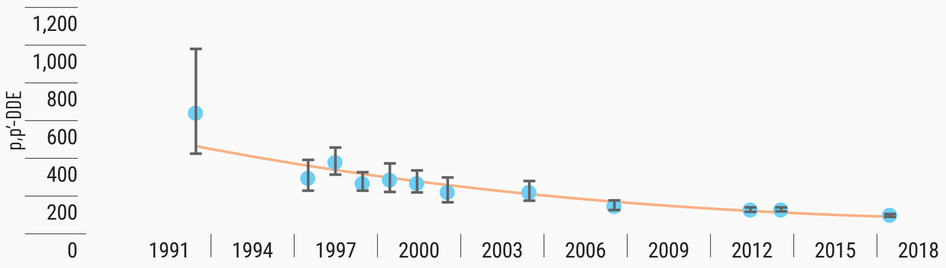
Microplastic particles are found in a wide variety of marine organisms, including species consumed as seafood (UNEP 2016b). One analysis of seafoods from different countries found plastic debris and fibres from textiles in most samples (Rochman *et al.* 2015). Another study found plastic pellets in the stomachs of 22 per cent of marine fish (Miranda and de Carvalho-Souza 2016). It has been estimated that fish in the North Pacific ingest 12,000 to 40,000 tonnes of plastic waste per year (Rios *et al.* 2007). A 2016 study (Rummel *et al.* 2016) found that 5.5 per cent of all investigated fish in the North and Baltic Seas had ingested plastic, the majority of which was microplastics.

6.4 Concentrations in humans

People throughout the world are exposed to low-dose mixtures of broadly heterogeneous manufactured chemicals. Evidence of concentrations of manufactured chemicals in humans is largely dependent on biomonitoring, which typically focuses on blood, breast milk, urine and hair. Biomonitoring studies show that some concentrations of manufactured chemicals in humans are decreasing, while others are increasing.

Continued, but mixed, progress is being made in reducing human blood lead concentrations. Monitoring studies across the world, including in the United States, Canada, South Africa and

Figure 6.11 Blood concentrations (µg/kg plasma lipid) of p,p-DDE in pregnant Inuit women from Nunavik, Canada, 1992-2017 (adapted from AMAP 2015b, Appendix p. 65)



China, show declines. In Canada over the last two decades, a reduction in the level of lead in bone, an indicator of chronic exposure, has been observed (McNeill *et al.* 2017). Blood lead concentrations in children in some countries are declining, but less so in lower-income countries. Average blood lead concentrations (37.17 µg/litre), as measured in children aged 0-6 years from 11 cities throughout China in 2013, revealed continued high concentrations (Li *et al.* 2017b). A study of 2,861 children in the rural Philippines reported that 21 per cent had elevated blood lead concentrations (above 100 µg/litre) (Riddell *et al.* 2007). Hotspot lead exposure remains a concern for children globally. Mass lead intoxication events in Senegal (2008) and Nigeria (since 2010) illustrate the potential severity of such exposures in children (Clune *et al.* 2011).

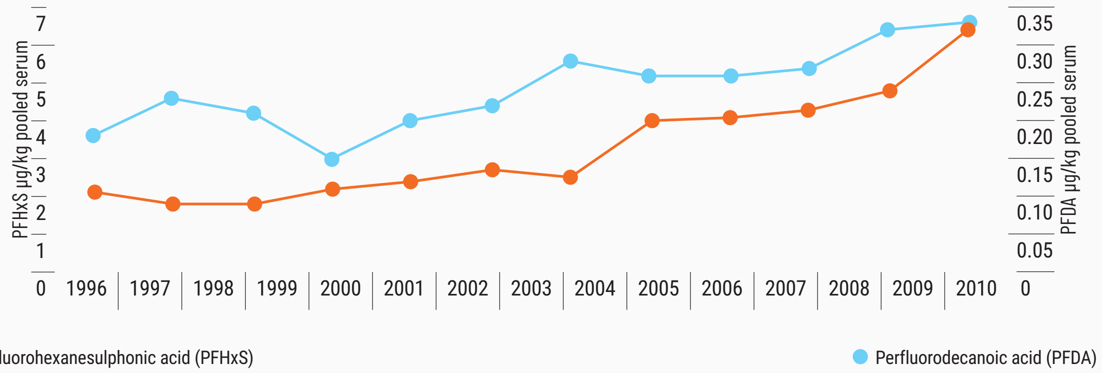
Concentrations of some POPs in blood are falling in some countries, but not in others

The Arctic Monitoring and Assessment Programme's 2015 Assessment found that concentrations of most POPS regulated under the Stockholm Convention, including PCB and DDT in the blood of Arctic populations, had declined in past decades, while concentrations of some others such as HCB might still be increasing (AMAP 2015a). Figure 6.11 shows temporal trends for blood concentrations of dichlorodiphenyldichloroethylene (DDE), one of the compounds formed as a result of the breakdown of DDT in the environment. Concentrations of some POPs not regulated under the Stockholm Convention could also be increasing, for example perfluorodecanoic acid (PFDA) and perfluorohexane sulfonic acid (PFHxS) (Figure 6.12).

There are significant variations in POPs concentrations in human milk across POPs, time, countries and regions

The second *Global Monitoring Report* on POPs (UN Environment and Secretariat of the Stockholm Convention 2017) found concentrations of PCDD/PCDF at relatively similar levels across both higher- and lower-income countries. The highest concentrations were found in the Africa and Western European and Others Group (WEOG) regions. Significant differences were observed among African countries, with Kenya and Uganda having the lowest observed concentrations of PCCDs and PCDFs in human milk while West and Central African countries including Côte d'Ivoire, the Democratic Republic of the Congo, Ghana, Mali, Nigeria, Sudan and Senegal had much higher concentrations. As regards indicator PCB in human milk, significant variations were found across regions, with much higher concentrations in the Central and Eastern Europe (CEE) and Western European and Other Groups (WEOG) regions compared to the Africa, Asia-Pacific and Group of Latin American and Caribbean Countries

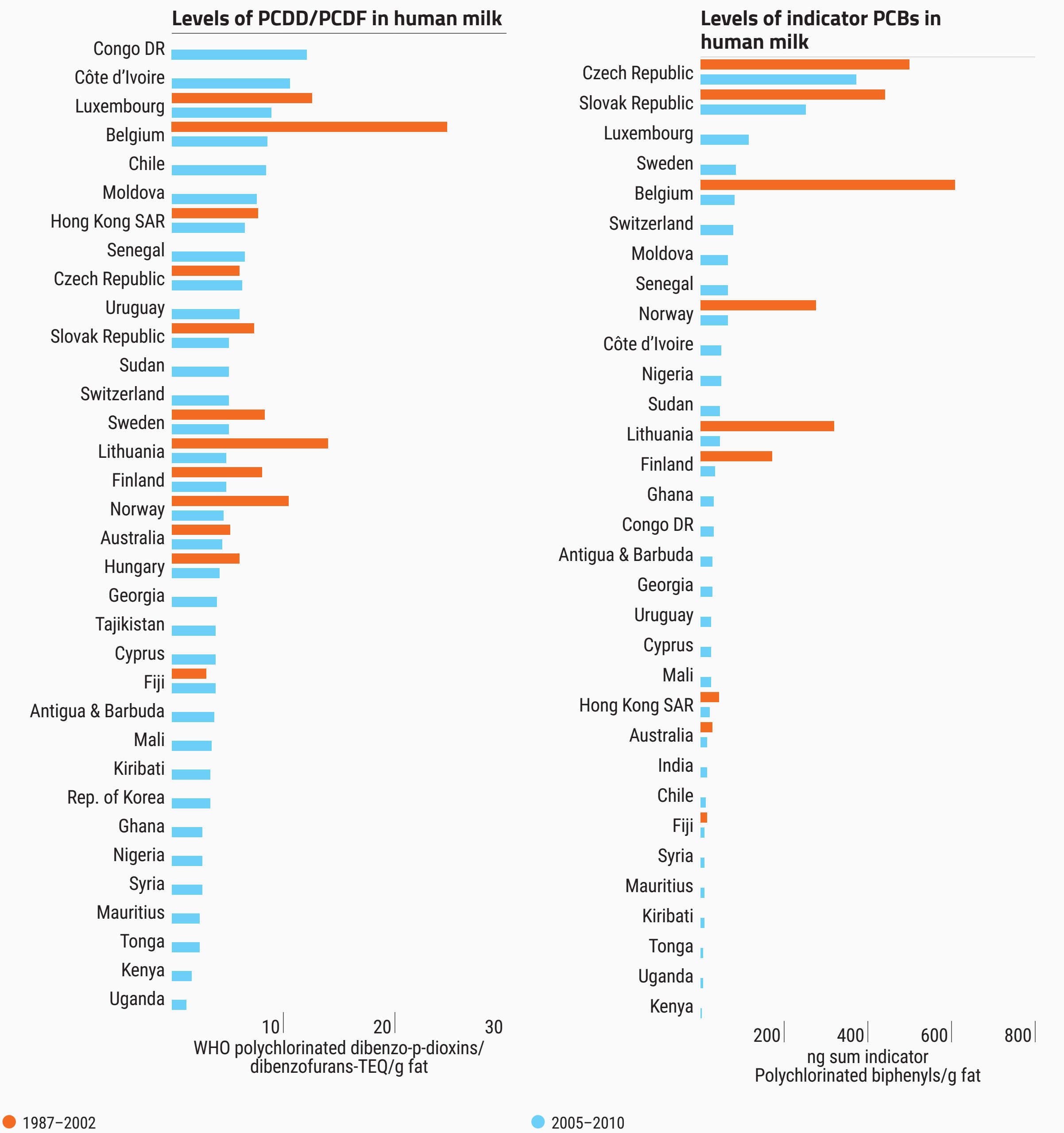
Figure 6.12 Concentrations of PFHxS and PFDA (µg/kg) in the blood of Swedish first-time mothers, 1996-2010 (adapted from AMAP 2015b, p. 49)



(GRULAC) regions. The highest concentrations of ΣDDTs were found in less industrialized countries, including Côte d'Ivoire, Ethiopia, Hong Kong SAR, Uganda, Mali, Mauritius, Haiti, India, Solomon Islands, Sudan and Tajikistan. This distribution reflects DDT use in relation to the occurrence and prevention of malaria in these countries. Concentrations of PBDE in human milk also vary significantly across regions (UNEP and Secretariat of the Stockholm Convention 2017).

Data presented in the second *Global Monitoring Report* suggest positive trends over time for various POPs, although not consistently. Where concentrations of PCDDs and PCDFs in human milk have been measured at multiple time intervals over a decade (e.g. in Belgium, Ireland, New Zealand and Hong Kong), concentrations are steadily declining. Overall, data from the last decade suggest that PCDD/PCDF concentrations in human milk have fallen steadily from their earlier high levels, indicating the effectiveness of measures implemented to reduce environmental releases (Figure 6.13). In the case of PCBs the picture is less clear for some countries, although generally declining concentrations are observed (UNEP and Secretariat of the Stockholm Convention 2017).

Figure 6.13 Levels of PCDD/PCDF (Sum 17 PCDD/PCDF) and indicator PCB (Sum 6 PCB) in human milk: survey results in 2005-2010 and comparison with 1980s levels (adapted and updated based on UN Environment and Secretariat of the Stockholm Convention 2017, p. 66)

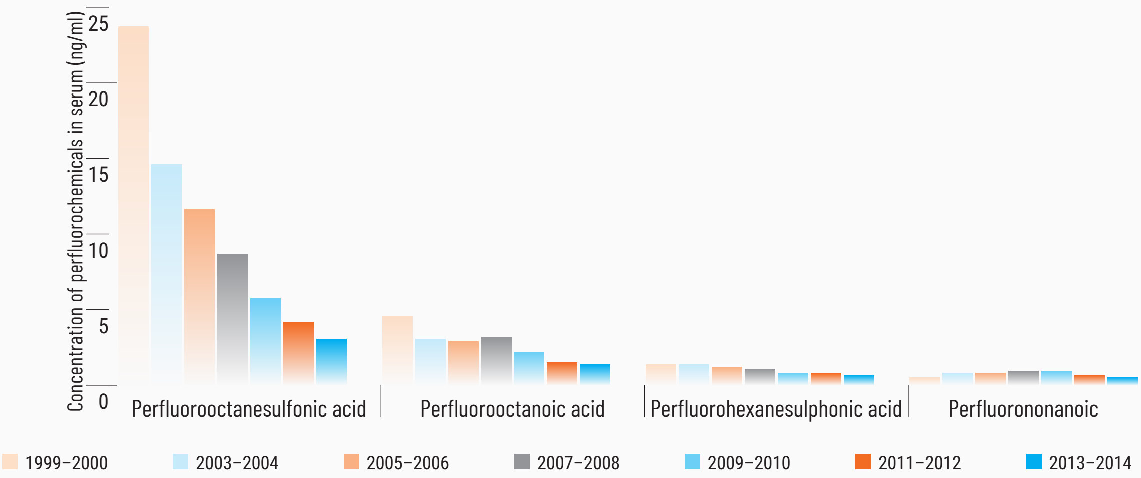


A recent review of the WHO/UNEP global surveys of PCDDs, PCDFs, PCBs and DDTs in human milk found that while the highest absolute concentrations were measured for DDT (more than 20,000 ng/g lipid), only a small share of the surveyed mothers had concentrations above the WHO safety levels. By contrast, virtually all mothers had concentrations of PCDD/PCDF as well as PCB above the WHO safety levels (van den Berg *et al.* 2017).

Perfluorinated chemicals are ubiquitous, but concentrations appear to be declining in some countries

Both PFOS and PFNA are being detected in more than 98 per cent of serum samples from Alaskan Natives, and 92 per cent have shown concentrations of PFOA (Byrne *et al.* 2017). However, studies examining serum concentrations of the long-chain PFASs chemicals

Figure 6.14 **Concentrations of perfluorinated compounds in the blood serum of women in the United States, 1999-2014 (median ng/ml) (adapted from US EPA 2017b)**



Note: To reflect exposures to women who are pregnant or may have become pregnant, the estimates are adjusted for the probability (by age and race/ethnicity) that a woman gives birth.

PFOA and PFOS over time have observed declines in countries where these chemicals have been phased out (US EPA 2013; Nøst *et al.* 2014; Stubleski *et al.* 2016; Eriksson *et al.* 2017; Schoeters *et al.* 2017). Studies of PFOA and PFHxS in human blood, archived by the German Environmental Specimen Bank, also documented mixed but gradual declines between 2001 and 2012 (Schröter-Kermani *et al.* 2013). Biomonitoring studies in Sweden and the United States of PFOA, PFOS and related long-chain compounds document similar declines in other cohorts, including pregnant women (Stubleski *et al.* 2016; Hurley *et al.* 2018) (Figure 6.14).

Concentrations of flame retardants are highest in higher-income countries and are falling unevenly

Studies examining concentrations of flame retardant in mother's milk in the United States show high concentrations of polybrominated diphenyl ethers (PBDEs) (van den Berg *et al.* 2017). However, PBDE concentrations may be decreasing since they were phased out, as shown in analysis of concentrations in children between 1998 and 2013 (Cowell *et al.* 2018). Studies have detected previously banned flame retardants in the umbilical cord blood of newborn children in the United States, indicating one pathway, among others, for the transfer of legacy substances to new generations (EWG 2005; EWG 2009; Terry *et al.* 2017).

Studies examining organophosphorus flame retardants in some Asian countries show concentrations in the Philippines 1.5-2 times higher than those measured in Swedish populations (Kim *et al.* 2014). However, concentrations in Japan and Viet Nam are 4-20 times lower, suggesting that differences are likely attributable to differences in the use of flame-retarded products in each country (Kim *et al.* 2014). A recent study (Hoffman *et al.* 2017) that analyzed urine samples in the United States found that concentrations of the organophosphate flame retardant bis(1,3-dichloro-2-propyl) phosphate (BDCIPP) had increased strongly since 2002, with concentrations measured in 2014/2015 15 times higher than in 2002/2003.

National biomonitoring surveillance programmes in higher-income countries demonstrate recent declines in concentrations of brominated flame retardants. These declines are also being experienced in areas of China where these chemicals are produced (Li *et al.* 2017c). However, concentrations in some populations are notably elevated. For example, in California (United States) biomonitoring studies have revealed that PBDE concentrations among a cohort of firefighters (Park *et al.* 2015) were dramatically higher than national averages. Studies suggest that some PBDE concentrations in pregnant women in Canada may be lower than those in pregnant women in the United States (Fisher *et al.* 2016). Areas of China where flame retardant chemical manufacturing is occurring continue to have high concentrations of some PBDE congeners (Li *et al.* 2017c).

Mercury concentrations in blood in some Arctic regions are declining, but are still among the world's highest

Although there has been a decline in the number of people living in the Arctic with mercury blood concentrations exceeding Canadian and United States guidelines, some (particularly those living in Indigenous communities, or those consuming large quantities of specific species of freshwater fish or marine mammals) have among the highest concentrations of blood mercury in the world. A significant proportion of women of child-bearing age from Indigenous communities living in the Eastern Canadian Arctic and Greenland still exceed these guidelines (AMAP 2011). However, declines are being observed: studies of pregnant Inuit and Nunavik women show decreasing concentrations, averaging a 4 per cent decrease per year since 1992 (AMAP 2015b) (Figure 6.15).

A review of national data available from nine countries found blood and urinary concentrations of mercury in most participants below 5 and 3 µg/litre, respectively, with concentrations significantly higher in adults than in children. Where data were available, overall decreasing trends in both blood and urinary concentrations could be observed. Birth cohort studies undertaken in a number of countries found the highest concentrations of methylmercury among populations consuming large amounts of fish and seafood or marine mammals (UNEP and AMAP 2018) (Figure 6.16). However, some of these countries have experienced strong decreases in methylmercury concentrations. Mercury concentrations also tend to be high (in some cases extremely high) among artisanal and small-scale gold miners (UNEP and AMAP 2018).

Phthalate concentrations are decreasing in some countries, but increasing in others

Biomonitoring data from the United States in 2013-2014 demonstrate that urinary metabolites of diethylhexyl phthalate (DEHP) were detected in 62 per cent of women and 54 per cent of children, while dibutyl phthalate (DBP) metabolites were detected in 94 per cent of women and 98 per cent of children (US EPA 2013). Studies of trends in urinary metabolites of phthalates are seeing a rise in frequency and concentrations of the metabolite of Di-iso-nonylcyclohexane 1,2-dicarboxylate (DiNCH), often being used to replace DEHP and DiNP (Gyllenhammar *et al.* 2016).

Figure 6.15 Concentrations of mercury and selenium in women's blood, Nunavik (Canada) (µg/L), 1992-2012 (adapted from AMAP 2015b, p. 31)

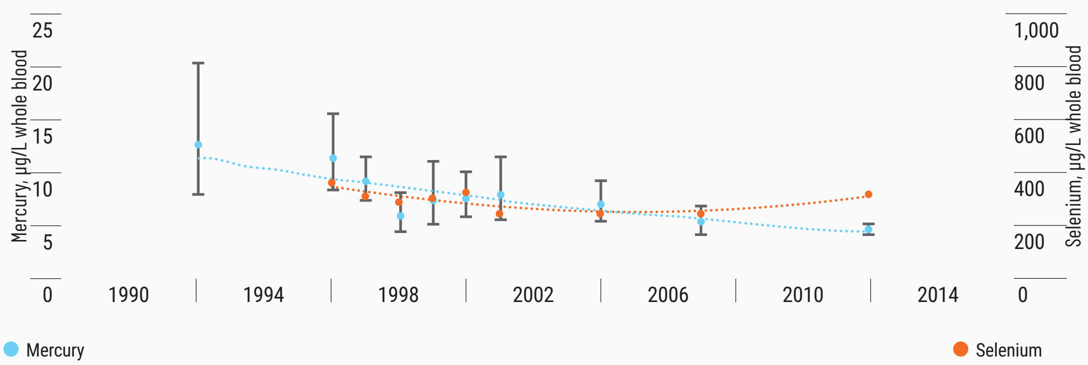


Figure 6.16 Mercury concentrations in cord blood from birth cohort studies by country (µg/L), 2003-2016 (adapted from UNEP and AMAP 2018, p. 69)

Concentrations of bisphenol A are decreasing, while concentrations of bisphenol S could be increasing

A recent literature review (Huang *et al.* 2018) found bisphenol A (BPA) concentrations in human urine in child and adult populations in Oceania, Asia, Europe and North America. However, it also found that restrictions on BPA use resulted in decreases in intake. In another study (Mendonca *et al.* 2014), BPA concentrations were found in 93 per cent of urine samples of infants without known exposure to it and in 75 per cent of their mothers' breast milk samples. Analyzing concentrations of four bisphenols in samples of adults in the United States taken over 14 years, a study (Ye *et al.* 2015) found BPA concentrations to be declining and concentrations of bisphenol S to be increasing, which could reflect trends in the use of the two substances. Measurable concentrations of bisphenol S in human urine are frequently reported (Wu *et al.* 2018).

6.5 Data availability, collection and analysis

Global monitoring is improving, but substantive data gaps in environmental surveillance persist

Data on chemical concentrations vary significantly across regions, media and chemicals. Far more data are available from higher-income countries than from lower- and middle-income ones. There are more data from the northern than the southern hemisphere, and more human monitoring data from OECD than non-OECD countries. Nevertheless, substantial data gaps remain. Of the roughly 100,000 chemicals for which there is at least limited toxicity information in the US EPA's AcTOR database, there is exposure information for less than one-fifth. Readily accessible data on concentrations in exposure-related media are only available for a much smaller fraction (Egeghy 2012).

There is ongoing, though limited, global monitoring of various chemicals, including mercury, POPS and lead. There is far less monitoring of other chemicals. Efforts undertaken in the context of the Stockholm Convention's Global Monitoring Plan, as well as the Global Mercury Assessment, are important contributions to continuously improving global trends in concentrations of POPs and mercury, respectively. Most environmental monitoring provides data on concentrations at specific moments in time, while longitudinal data covering several points in time are much rarer. Insightful studies have been completed using monitoring data before and after a government regulation has been put in place, attempting to demonstrate an effect. More and better focused research of this kind is needed.

Biomonitoring has made more information available on human exposures, although still more is needed

There has been an increase in human biomonitoring programmes. However, most surveys are limited to a small set of POPs and long-term trend data are primarily confined to monitoring studies conducted in developed countries. Global comparability of biomonitoring studies remains hampered by differences in data collection and reporting procedures. Both ongoing and newer programmes have expanded the list of chemical contaminants being measured beyond POPs to include other pesticides, bisphenol A, triclosan and phthalates, among others. However, most national programmes focus on surveillance of adults. There is a need for more studies on the elderly, adolescents, children and newborns, and/or perinatal experience among mothers (i.e. soon before or after giving birth). The United States National Health and Nutrition Examination Survey (NHANES), the Canadian Health Monitoring System (CHMS) and the Human Biomonitoring for Europe (HBM4EU) are important building blocks. The HBM4EU is a new joint effort of 28 countries to coordinate and advance human biomonitoring in Europe, and to provide better evidence of the actual exposure of citizens to chemicals and the possible health effects (HBM4EU 2018).

Standardization of data collection and testing protocols would aid the pooling of data and identification of trends

While there are many studies of chemical concentrations in environmental media and human fluids, these studies are difficult to aggregate in order to identify trends. Comparability of studies is often limited because samples are taken differently, chemical identities are not fixed, study methods vary, and data are reported in varied units of analysis. There are very few global assessments. Review studies that try to assemble regional and global trend information, based on individual studies, are often limited by differing data measurement and analytical methods. Recent monitoring standardization efforts, such as the Stockholm Global Monitoring Programme and the Consortium to Perform Human Biomonitoring on a European Scale (COPHES), are making global assessments more possible and reliable. Greater efforts to coordinate and harmonize national and regional data to facilitate global assessments are needed.

7/ Environmental, health and social effects of chemicals

Chapter Highlights

Chemical pollution is a major cause of human disease and premature deaths; the burden of disease from selected chemicals was estimated at 1.6 million lives and 44.8 million disability-adjusted life years (DALYs) in 2016.

Potential adverse health effects of chemical exposures include acute poisonings, cancers, reproductive and neurodevelopmental disorders, and disruption of the endocrine system.

Workers are often subject to disproportionally high exposures to hazardous chemicals. In 2015 it is estimated that almost 1 million workers died as a result of exposure to hazardous substances.

Foetuses, infants, children, pregnant women, the elderly and the poor are among the most vulnerable to the adverse effects of chemicals and waste.

Plastic litter has been linked to marine organism mortality and may also affect terrestrial animals.

Chemical pollution threatens ecosystem functions by adversely affecting pollinators, contributing to ocean dead zones, accelerating antimicrobial resistance, and increasing pressure on coral reefs.

The previous chapters in Part I addressed the increasing production and use of chemicals, releases to the environment, and concentrations. This chapter presents data and knowledge on the impacts of chemicals and waste on both human health and the environment. It is structured according to environmental effects, effects on biota and biodiversity, and human health effects. Attention is also given to social effects, including on vulnerable populations, men and women, and the poor. Prevailing data gaps, and challenges and opportunities in regard to acquiring pertinent knowledge, are briefly discussed.

7.1 Environmental effects

Heavy metals and pesticides have left a legacy of contaminated soils

Soils worldwide have been damaged by mining, agriculture and industrial wastes that contain heavy metals, including lead, cadmium, chromium, mercury and copper. Heavy metals damage soil quality and reduce the number of the microorganisms that are critical to soil fertility. The sources of some of this damage dates back more than a century. For example, soils have been contaminated by lead arsenate (historically used as an insecticide in fruit orchards in Europe, North America and elsewhere), arsenic compounds (used extensively to control cattle ticks and pests on bananas in Latin America and other parts of the world) and DDT (Schooley *et al.* 2008).

There are ongoing activities across the world to inventory and remediate contaminated waste sites. The Toxic Sites Identification Program, a project of the Global Alliance on Health and Pollution (GAHP), has reviewed more than 3,000 hazardous waste sites and estimated that as many as 200 million people may be directly affected by such sites (GAHP 2013). The European Commission (EC) has estimated that there are over 3 million sites in Europe where past activities have polluted soils. Some 250,000 of these are in need of urgent remediation (Science Communication Unit, University of the West of England 2013). The United States Environmental Protection Agency lists 1,317 "Superfund" sites for clean-up. These sites present current or future threats to human health or the environment because hazardous wastes have been abandoned, accidentally spilled, or illegally dumped there (US EPA 2018).

Even as these efforts are under way, new contaminated sites are being created as a result of irresponsible waste management practices. Improper disposal of waste electrical and electronic products (including televisions, computers and mobile phones) pollutes surface and groundwaters and contaminates soils, particularly at dumping or landfill sites in low-income countries (Wäger *et al.* 2012). The accidental collapse of mining dams and landfills (e.g. in Spain in 1998, Romania in 2000 and Brazil in 2015) often leaves large areas contaminated with heavy metals (Grimalt, Ferrer and Macpherson 1999; UNEP and United Nations Office for the Coordination of Humanitarian Affairs 2000; Hatje *et al.* 2017). If pesticides are misused or overused, they can poison agricultural soil, reduce its resilience, and interfere with natural nutrient cycles. Stockpiles of banned pesticides kept in poorly maintained facilities across Sub-Saharan Africa, for example, have left a legacy of polluted soils (Blankespoor *et al.* 2009). Legacy soil pollution threatens local communities and food supplies, biodiversity and fragile ecosystems.

Dead zones are expanding in marine and freshwater ecosystems worldwide

Many physical, chemical and biological factors combine to create "dead zones" (or hypoxia),

© UNEP/Usman Tariq, artisanal and small-scale gold mining site where oxygen levels cannot support life, in the open ocean, coastal waters and large lakes. Organic and nutrient enrichment related to sewage/industrial discharges and land run-off have led to increases in hypoxic zones in both marine and freshwater ecosystems in the last 50 years. Increasing nutrient loads can stimulate overgrowth of surface algae, which sink and decompose. The decomposition process depletes the supply of oxygen available to support organisms. While the largest marine dead zone appears to be in the northern Gulf of Mexico (United States Geological Survey 2018), dead zones also exist in the Baltic Sea, the Black Sea, and off the coast of Oregon, in Lake Eire and in Chesapeake Bay in North America (Díaz and Rosenberg 2011; Altieri *et al.* 2017; Breitburg *et al.* 2018; McCarty 2018).

Significant damage to the atmospheric ozone layer has been halted

According to the 2018 Scientific Assessment of Ozone Depletion (World Meteorological Organization 2018), "as a result of the Montreal Protocol much more severe ozone depletion has been avoided. [...] Northern Hemisphere mid-latitude total column ozone is expected to return to 1980 abundances in the 2030s, and Southern Hemisphere mid-latitude ozone to return around mid-century. The Antarctic ozone hole is expected to gradually close, with springtime total column ozone returning to 1980 values in the 2060s. [...] The Kigali Amendment is projected to reduce future global average warming in 2100 due to hydrofluorocarbons (HFCs) from a baseline of 0.3-0.5°C to less than 0.1°C." As a result of ozone protection efforts, by 2030 up to 2 million cases of skin cancer may be prevented globally each year (van Dijk *et al.* 2013). It is estimated that at least 100 million cases of skin cancer and many million cases of cataracts will be avoided by the end of this century as a result of implementation of the Protocol (UNEP 2015). In the United States, among people born between 1890 and 2100, there could be, according to the US Environmental Protection Agency, 280 million cases of skin cancer avoided; approximately 1.6 million deaths from skin cancer prevented; and more than 45 million cases of cataract also prevented (US EPA 2015).

7.2 Effects on biota and biodiversity

Hazardous chemicals adversely affect wildlife in various ways

In wildlife, high or prolonged exposure to certain chemicals leads to reproductive, immunological and neurological damage or even death. Many surfactants and heavy metals are toxic to aquatic organisms. Dioxins and PCBs adversely affect reproduction in turtles and some birds, correlating with smaller and more fragile eggs. PCB exposure has been implicated in the suppression of immune systems in seals and other marine mammals, contributing to mass die-offs in Europe in the late 1980s. Studies of sea turtles have found high levels of other perfluorinated compounds, which weaken the immune system and result in greater vulnerability to opportunistic infections (Swackhamer *et al.* 2009; Israel 2013). A 2018 study indicates that the drug diclofenac continues to adversely affect the health of the vulture population in India more than a decade after it was banned (Nambirajan *et al.* 2018).

Some endocrine-disrupting pharmaceuticals have been found to have adverse effects on wildlife (such as feminizing of male fish, preventing reproduction, or triggering population collapse) at very low concentrations (Kidd *et al.* 2007; Osachoff *et al.* 2014). A recent review of studies of chemical contaminants in marine ecosystems found that a wide range of chemicals had the general effect of reducing productivity and increasing respiration levels in wildlife (Johnston *et al.* 2015).

A Europe-wide study provides strong evidence that chemicals threaten the ecological integrity, and consequently the biodiversity, of almost half the continent's water bodies. This study, which tested for some 223 chemicals across 4,000 monitoring sites, found that organic chemicals were likely to have acute lethal effects on sensitive fish, invertebrates or algae species at 14 per cent of sites and chronic long-term effects at 42 per cent (Malaj *et al.* 2014). Some studies have also suggested that chemical pollution adds to existing pressures on the world's coral reef ecosystems (Box 7.1).

Box 7.1 **Coral reefs are under threat from chemical pollution**

Oxybenzone, a chemical widely used in sunscreens, has been found to have damaging effects on coral planulae. According to a study undertaken in the United States, in Hawaii and in the US Virgin Islands (Downs *et al.* 2016), oxybenzone was shown to be a genotoxicant to corals and a skeletal endocrine disruptor. In Hawaii in 2018, the state legislature moved to prohibit lotions containing oxybenzone and octinoxate (State of Hawaii 2018). Danovaro *et al.* (2008) found that several chemicals in sunscreens – even at very low concentrations – cause rapid and complete coral bleaching, adversely affecting the biodiversity and functioning of reef ecosystems. Herbicides have also been reported to reduce the reproductive output of reef-building corals (Cantin, Negri and Willis 2007).

By affecting insects and pollinators, pesticides may be jeopardizing ecosystem services

The continuous application of pesticides can deplete insect and microorganism populations, generating pesticide-resistant pests and adversely affecting predator-prey relationships. A recent study (Hallmann *et al.* 2017) found that the population of flying insects in protected areas in Germany had declined by more than 75 per cent during the previous 27 years. Loss of insect diversity and abundance could have cascading effects on food webs and jeopardize ecosystem services. A review by Chagnon *et al.* (2015) found that insecticides have significant adverse effects on ecosystem services such as decomposition, nutrient cycling, soil respiration and invertebrate populations. Adverse effects were noted among earthworms, which fulfil functions that are imporant for soil fertility, and pollinators.

Neonicotinoids, which are among the world's most widely used insecticides, can affect the sperm count of male honey bees and reduce the number of queen bees; they may also play a role in recent declines in bumblebee colonies. Adverse effects on pollinators, in turn, have direct effects on agricultural yields and food supplies (Moffat *et al.* 2015; Straub *et al.* 2016).

Plastic litter has been linked to marine organism mortality and may also affect terrestrial animals

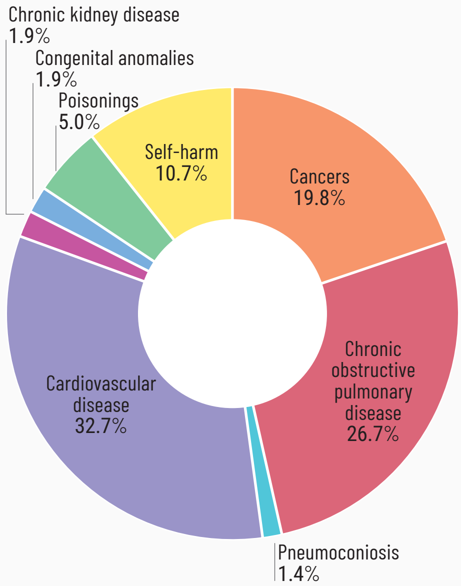
In the past decade, increasing public concern has arisen over the potential effects of marine litter on marine ecosystems. A report by UBA (Essel *et al.* 2015) notes that plastic litter in the oceans has adverse effects on 663 species, with more than half of them ingesting or becoming entangled in plastic debris. Fish and seabirds easily mistake microplastics floating at or below the ocean surface for food. Laboratory studies have confirmed that a variety of marine organisms, including zooplankton, have the capacity to ingest microplastics (Setälä, Fleming-Lehtinen and Lehtiniemi 2012; Cole *et al.* 2013). Moreover, plastic debris in seawater tends to adsorb POPs such as PCBs, DDT and PAHs which, if ingested, exhibit a wide range of adverse chronic effects in marine organism (Rios *et al.* 2010).

Microplastics also affect the health of terrestrial animals. Among other reasons, this may be due to the leaching out of hazardous chemicals (e.g. phthalates and bisphenol A) from plastic particles, which can harm vertebrates as well as invertebrates (de Souza *et al.* 2018). There is also evidence suggesting that microplastics adversely affect, for example, earthworms, which in turn may affect the soil condition (de Souza *et al.* 2018). Given a relative lack of scientific studies on this topic, calls have been made to further investigate the effects of microplastics on soil organisms (Norwegian Institute for Water Research 2018; Rillig and Bonkowski 2018).

Releases of antimicrobials, heavy metals and disinfectants contribute to antimicrobial resistance

The WHO has identified the spread of antimicrobial resistance (AMR) as one of the 10 most important threats to global health in 2019 (WHO 2019). A review of the scientific literature concluded that the large majority of scientific publications found evidence of a link between antibiotic use in animals and AMR in humans (Review on AMR 2016). The environmental dimension of AMR was identified as an issue of emerging concern in a 2017 report by UNEP. Strong evidence indicates that releases of antimicrobial compounds to the environment, combined with direct contact between natural bacterial communities and discharged resistant bacteria, are driving bacterial evolution and the emergence of more resistant strains (Singer *et al.* 2016; UNEP 2017a). Moreover, evidence is emerging that biocides (such as triclosan) and heavy metals (including cadmium, copper, zinc and mercury) contribute to the spread of AMR because they increase the selection for antibiotic resistance genes among bacteria (Wales and Davies 2015; Singer *et al.* 2016; UNEP 2017a). The generation of microplastic wastes may be fuelling

Figure 7.1 Deaths (total: 1.6 million) attributed to selected chemicals (per cent), 2016 (adapted from WHO 2018a, p. 2)



the spread of AMR, as plastic pollution facilitates increased gene exchange among bacteria (Arias-Andres *et al.* 2018; Imran, Das and Naik 2019).

7.3 Human health effects

The burden of disease from chemicals is high

In 2018, the WHO estimated the disease burden preventable through sound management and reduction of chemicals in the environment at around 1.6 million lives and around 45 million disability-adjusted life years (DALYs) in 2016 (Figure 7.1). This corresponds to 2.7 per cent of total global deaths and 1.7 per cent of the total burden of disease worldwide for that year (WHO 2018a). These figures are likely to be underestimates, given that they are based only on exposures to chemicals for which reliable global data exist (including lead causing intellectual disability, occupational carcinogens such as asbestos and benzene, and pesticides involved in self-inflicted injuries). As shown in Figure 7.1, cardiovascular disease caused the largest share of deaths attributed to these chemicals, followed by chronic obstructive pulmonary disease and cancers.

The *Lancet* Commission on Pollution and Health (Landrigan *et al.* 2017) identified chemical pollution as a significant "and almost certainly underestimated" contributor to the global burden of disease, highlighting the gaps in data and knowledge on many chemicals in use. According to the Global Burden of Disease (GBD) Study (GBD Risk Factors Collaborators 2016), casualties from occupational exposure to carcinogens amount to 0.5 million, and those from soils contaminated by heavy metals and other chemicals to another 0.5 million.

Lead is a priority pollutant for human health

According to data compiled by the Institute for Health Metrics and Evaluation (IHME) at the University of Washington (IHME 2019) in the Context of the Global Burden of Disease Study, in 2017 lead exposure accounted for more than 1 million deaths and the loss of around 24.4 million DALYs, with the highest burden in low- and middle-income countries. According to the WHO (2016), addressing lead exposure alone would prevent 9.8 per cent of intellectual disability, 4 per cent of ischaemic heart disease and 4.6 per cent of stroke.

The preventable burden of disease from chemicals involved in unintentional acute poisonings was estimated at 78,000 deaths in 2016

For chemicals in acute poisonings, the disease burden preventable through sound management and reduction of chemicals in the environment was estimated at approximately 269,000 deaths and 15.4 million DALYs in 2016 (WHO 2018a). This includes the following sub-categories: pesticides involved in self-inflicted injuries were estimated to account for around 156,000 deaths and 7.4 million DALYs; chemicals involved in unintentional acute poisonings (methanol, diethylene glycol, kerosene, pesticides, etc.) were estimated at around 78,000 deaths and around 4.6 million DALYs; and chemicals involved in congenital anomalies were estimated to account for approximately 30,000 deaths and 3.2 million DALYs. These figures are based only on exposures to chemicals for which reliable global data exist. The World Health Statistics 2018 (WHO 2018b) found that "although the number of deaths from unintentional poisonings has steadily declined since 2000, mortality rates continue to be relatively high in low-income countries".

Exposure to known chemical carcinogens increases the likelihood of cancer

Cancer is the second leading cause of death globally. It was responsible for 8.8 million deaths in 2015. The most common causes of cancer death are cancers of the lung (1.69 million deaths), liver (788,000 deaths) and colon (774,000 deaths). Approximately 70 per cent of deaths from cancer occur in low- and middle-income countries (WHO 2018c). In 2012, 57 per cent of new cancer cases, 65 per cent of cancer deaths and 48 per cent of five-year prevalent cancer cases were in developing countries (IARC 2012). The WHO has estimated that around 19 per cent of all cancers are attributable to environmental factors. This estimate includes indoor and outdoor ambient air pollution, second-hand smoke, asbestos, dioxins and other pollutants found in industrial emissions, constituents found

Table 7.1 Total number of agents and POPs classified by the IARC Monographs per group (Volumes 1-123) (IARC 2018)

Group	Description/ classification	Number of agents	POPs
Group 1	Carcinogenic to humans	120	polychlorinated biphenyls; 2,3,7,8-tetrachlorodibenzo-p-dioxin; 2,3,4,7,8-pentachlorodibenzofuran; lindane; pentachlorophenol
Group 2A	Probably carcinogenic to humans	81	DDT; polybrominated biphenyls
Group 2B	Possibly carcinogenic to humans	299	chlordane; chlordecone; heptachlor; hexachlorobenzene; α- and β-hexachlorocyclohexanes; toxaphene (polychlorinated camphenes); mirex; polychlorinated paraffins (of average carbon chain length C12 and average degree of chlorination approximately 60 per cent)
Group 3	Not classifiable as to its carcinogenicity to humans	502	Aldrin; dieldrin; endrin; hexachlorobutadiene; polychlorinated dibenzofurans (other than 2,3,5,7,8-PnCDF); polychlorinated dibenzodioxins (other than 2,3,7,8-TCDD)
Group 4	Probably not carcinogenic to humans	1	none

in food and drinking water such as pesticide residues, arsenic or aflatoxins, and ionizing and non-ionizing radiation (WHO 2011; Prüss-Ustün *et al.* 2016).

The International Agency for Research on Cancer (IARC), a specialized agency under the WHO, provides evidence on the carcinogenicity of agents (including chemicals, mixtures, occupational exposures) to humans or animals. Agents classified by the IARC Monographs are divided into four groups. Table 7.1 provides an overview of the more than 1,000 chemicals and other agents classified by the IARC to date, including classification of POPs regulated under the Stockholm Convention (not all have been evaluated to date, e.g. PFOS, HBCD). Five POPs are classified in Group 1. Of the proposed POPs (Secretariat of the Stockholm Convention 2017; Secretariat of the Stockholm Convention 2018), PFOA is classified as Group 2B and dicofol as Group 3.

A 2011 WHO report provided global statistics for two chemicals, asbestos and lead, which were classified as a carcinogen and a probable carcinogen, respectively. It estimated that asbestos exposures resulted in 107,000 deaths worldwide per year (Prüss-Ustün *et al.* 2011). Although social and genetic factors play critical roles in breast cancer causation, the role of some chemicals such as PCBs and ethylene oxide is well-recognized (Prüss-Ustün *et al.* 2016). Roughly 14 per cent of lung cancers are attributable to ambient air pollution and 17 per cent to household air pollution (Prüss-Ustün *et al.* 2016). Pesticide exposure of pregnant women has been found to increase the risk of childhood leukaemia in their children. Additional evidence supports a link between naturally occurring arsenic above a certain threshold in drinking water and the risk of bladder cancer (Turner, Wigle and Krewski 2010; IARC 2018).

Laboratory studies show chemicals can cause disruption of endocrine systems and hormonal disorders

An increasing number of epidemiological studies show that environmental exposures to endocrine-disrupting chemicals (EDCs) (Box 7.2) are associated with human diseases and disabilities (Vandenberg *et al.* 2012; Di Renzo *et al.* 2015). Studies show that chemically induced hormonal effects can appear at exposures at extremely low dosages, although the science on this is not settled. Endocrine-disrupting chemicals include some pesticides, flame retardants, and components of fuels, plastics and plasticizers. A recent report by UNEP (2017b) lists several phenols, certain phthalates, bisphenol F and S, and four parabens, among others, as EDCs or potential EDCs. Recent studies address whether EDCs may be contributing to the increase in the

incidence of metabolic diseases such as type 2 diabetes and obesity (Heindel *et al.* 2015)

A 2012 review (Bergman *et al.* 2013) of the state of the science on endocrine-disrupting chemicals noted that many endocrine-related diseases and disorders are on the rise (e.g. low semen quality among many young men, genital malformations, adverse pregnancy outcomes, neurobehavioural disorders, cancers, obesity and type 2 diabetes). While genetic factors alone cannot account for the increased incidence of such diseases, a variety of factors can be involved, including (but not limited to) exposure to chemicals. While hundreds of chemicals are known or suspected EDCs, only a small share have been sufficiently investigated to identify overt endocrine effects in intact organisms. Significant uncertainties and knowledge gaps remain in the understanding of EDCs and their effects. However, this review noted that exposure of humans and wildlife to EDCs is widespread and that some associations

Box 7.2 Endocrine-disrupting chemicals

Endocrine-disrupting chemicals (EDCs) are chemicals that can alter functions of the endocrine system and consequently cause adverse health effects. The endocrine system consists of many interacting tissues that communicate with one another and the rest of the body by means of hormones. This system is responsible for controlling many processes in the body, from gamete formation to conception and early developmental processes such as organ formation, and most tissue and organ functions throughout adulthood. EDCs interfere in some way with hormone action and, in doing so, alter endocrine function and lead to adverse effects on the health of humans and wildlife. Some observed health effects associated with EDCs include, but are not limited to, cancer as well as reproductive, developmental, immunological and neurological disorders (UNEP 2017b).

with adverse effects have become apparent. Examples include high exposure to dioxins and PCBs as risk factors in breast cancer, and risks of prostate cancer related to occupational exposure to pesticides. The review also found that wildlife populations have been affected by EDCs, particularly due to some POPs, banning which has allowed some populations to recover.

Exposure to some hazardous chemicals can harm reproductive capacities

Exposure to certain hazardous chemicals has been shown to effect sexual functioning and fertility in both women and men, as well as developmental disorders in the foetus and offspring. Preconception and prenatal exposure to toxic chemicals is a critical issue for both women and men of childbearing age. While adverse effects on reproductive outcomes can arise from a range of sources, some pharmaceuticals (e.g. thalidomide and diethylstilbestrol [DES], both now phrased out) are well-recognized hazards to reproduction.

Lead has long been known to be harmful to pregnancy. Maternal lead exposure, even at low levels, may be associated with reduced foetal growth, lower birth weight, pre-term birth and spontaneous abortion (US NTP 2012; Health Canada 2013). Other substances, such as alkyl phenols, alkyl phenol ethoxylates, polyethoxylates, bisphenols and various pesticides, have been associated in laboratory studies with a range of adverse reproductive health effects including sperm count decline, hypospadias and cryptorchidism in offspring, and cancer of the breast and testes (Rim 2017). A study of sperm count and sperm quality among a general sample of men in the United States found a significant association between adverse outcomes and the heightened urinary presence of several metabolites of phthalate esters, recognized as potential endocrine disruptors (Bloom *et al.* 2015).

Pesticides such as dibromochloropropane (DBCP) are associated with sterility (Thrupp 1991) and DDT exposures have been linked to pre-term birth (Longnecker *et al.* 2001), which has prompted regulatory action in many countries and at the global level. Phthalates such as dibutyl phthalate and DEHP are associated with reduced sperm count and motility (Wang *et al.* 2015). A recent cohort study conducted as a part of the Canadian Maternal-Infant Research on Environmental Chemicals found exposure to PFOA and PFHxS may reduce fecundability (Vélez, Arbuckle and Fraser 2015a). Exposure to triclosan has been associated with low fertility in epidemiologic studies (Vélez, Arbuckle and Fraser 2015b). Some research suggests that exposure to some nanomaterials may adversely affect reproductive systems (Vasyukova, Gusev and Tkachev 2015).

Neurological health is affected by exposure to hazardous chemicals

The most common neurodegenerative ailments among the elderly include Alzheimer's, Huntington's and Parkinson's diseases and various neurodevelopmental disorders including learning disabilities, sensory deficits, developmental delays and cerebral palsy. While genetics and other factors play important roles in determining these outcomes, some common industrial chemicals (including lead, methylmercury, PCBs, arsenic and toluene) have been identified as potential causes of neurodevelopmental disorders and subclinical brain dysfunction. Exposure to these chemicals during early foetal development causes brain injury at doses much lower than those affecting adult brain functions (Grandjean and Landrigan 2006).

Lead exerts toxic effects in all parts of the nervous system. There is no known safe blood lead concentration. Even blood lead concentrations as low as 5 µg/decilitre, once thought to be a "safe level", may be associated with decreased intelligence, behavioural difficulties, and learning problems in children (WHO 2018d). Lead poisoning causes life-threatening encephalopathy (disruption of brain function), particularly in young children. There is a large literature on the neurodevelopmental toxicity of lead in children (Lidsky and Schneider 2003; Bellinger 2004; Needleman 2004; US NTP 2012; Lanphear

2015). The effects include reduced cognition and behaviour scores, changes in attention (including attention deficit hyperactivity disorder [ADHD]), impaired visual-motor and reasoning skills, and impaired social behaviour and reading ability. The brain is particularly vulnerable to lead exposure during early childhood. It interferes with synaptogenesis, the trimming of synaptic connections, and myelination during the early years of childhood growth (Lanphear 2015).

Neurobehavioural problems such as autism, ADHD and dyslexia affect about 10-15 per cent of children born in industrialized countries. The United States Centers for Disease Control and Prevention (US CDC) reported that one in 68 children in the United States had an autism spectrum disorder. Scientific evidence indicates that the incidence of both autism and ADHD in industrialized countries is increasing (US CDC 2014). While there is some evidence that chemical exposure is a contributing cause, the science is not conclusive. More conclusive is the effect of mercury and PCBs with respect to cognitive deficits. Research shows that there are critical windows of vulnerability during embryonic and foetal and infant development; during these periods exposures to chemicals such as some persistent organic pollutants (POPs), pesticides and lead are likely to cause learning disabilities, hyperactivity and other cognitive deficiencies (Rice and Barone 2000; Lanphear 2015). A 2016 study (Arbuckle *et al.* 2016) found concentrations of lead, and to a lesser extent bisphenol A and phthalates, in children's urine to be significantly associated with adverse behavioural indicators. Continued research has revealed an increasing number of chemicals with potentially adverse neurological effects (Grandjean and Landrigan 2014) (Table 7.2), including some phthalates (Arbuckle *et al.* 2016) and bisphenol A (Braun *et al.* 2017).

Fragranced products and some chemicals contribute to multiple chemical sensitivity

Multiple chemical sensitivity (MCS) refers to a chronic disease in which low levels of chemicals invoke a multiplicity of unrelated symptoms. This disease has increasingly been recognized in several countries since the 2000s (Carman 2017). Chemicals associated with MCS include those found in cleaning products, pesticides, air fresheners and cosmetics. Steinemann (2016; 2018a; 2018b) reported strong evidence that some fragranced consumer products (as an important source of indoor air pollution) are also an important contributor to MCS and can cause adverse health effects such as respiratory problems, headaches and skin problems. A literature review found that sufficiently strong evidence in MCS diagnosis was currently lacking and called for further longitudinal epidemiological studies (Rossi and Pitidis 2018).

Table 7.2 Chemicals identified by Grandjean and Ladrigan (2014, p. 333) as being toxic to the human nervous system, 2006 and 2013

Groups of chemicals	Number identified in 2006	Number identified in 2013	Number identified since 2006
Metals and inorganic compounds	25	2	hydrogen phosphide
Organic solvents	39 (including ethanol)	40	ethyl chloride
Pesticides	92	101	Acetamiprid, amitraz, avermectin, emamectin, fipronil (Termidor), glyphosate, hexaconazole, imidacloprid, tetramethylenedisolfotetramine
Other organic compounds	46	47	1-3-butadiene
Total	**202**	**214**	**12 new substances**

Some of the substances listed above continue to be the subject of scientific debate regarding their toxicity to the human nervous system.

7.4 Social effects

The benefits and risks of manufactured chemicals and chemical production are not equally shared across the world (Landrigan *et al.* 2017). Workers in developing economies are often exposed to heavy risks from hazardous workplace chemicals used in product manufacture, while consumers in high-consumption economies enjoy the benefits of inexpensive products. The suffering of the poor from polluted air and water often outweighs the benefits they gain from cheap products and foods. Women and children, particularly among the poor, are frequently exposed to disproportionate risks and lack the social or political means to protect themselves.

7.4.1 Vulnerable populations

Workers typically have higher exposures to hazardous chemicals than do other community members

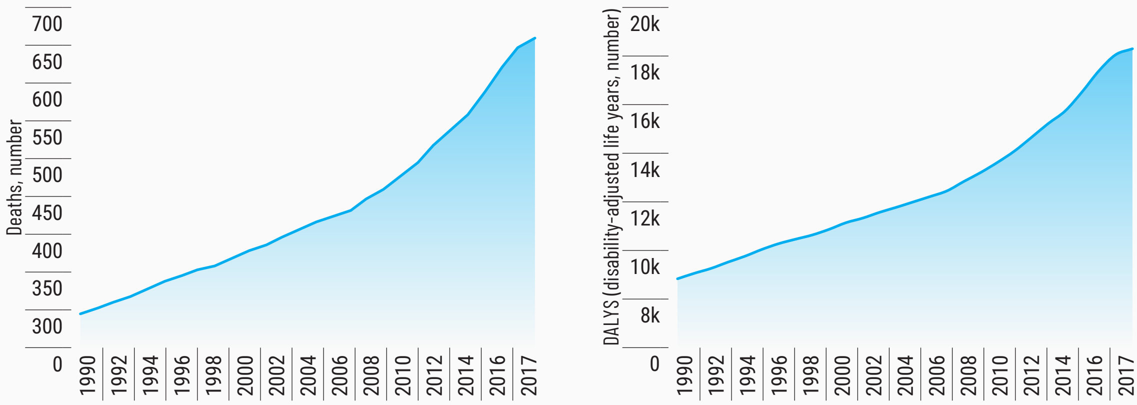
Specific conditions of work put workers at high levels of risk from chemical exposures, particularly those working in SMEs in developing countries and economies in transition, working in the informal economy, subject to shift work or working as migrant labourers. These workers are often subject to less regulated working conditions, have a higher risk of suffering health impairments, and have less access to health services (Santana and Rubeiro 2011; SAICM Secretariat 2016).

Where hazardous chemicals are used in industrial workplaces, the air can be contaminated with dusts and volatile chemicals released from materials, products and processes. Workers, who may spend eight or more hours there, may come into contact with significant amounts of these chemicals. There is no reliable way to determine the number of chemicals in workplaces around the world, or how many workers are exposed to these chemicals. Virtually every type of workplace in every sector uses chemicals, which means a wide range of workers are potentially exposed (ILO 2013a).

Workers are exposed to hazardous chemicals throughout the supply chain, from extraction, to manufacturing, to recycling and disposal. Of particular concern is the exposure of workers in chemical-intensive industries where the use of manufactured chemicals is rapidly expanding (including electronics, textiles, construction and agriculture), as well as services such as cleaning, maintenance, hairdressing, manicure and pedicure. Moreover, workers in lower-income countries are particularly at risk from exposure during informal recycling activities (Landrigan *et al.* 2017). For example, a study in Zimbabwe found significant adverse effects on workers from the management of hazardous

© UNITAR/Andrea Cararo, worker at a wastewater treatment plant in Ulaanbaatar, Mongolia

Figure 7.2 **Deaths and DALYs from occupational exposure to cadmium, 1990-2017 (adapted from IHME 2019)**



Global, both sexes, all ages, all causes, risk: occupational exposure to cadmium

waste (including paint, cleaning products and pesticides) in informal enterprises (Jerie 2016).

In 2015 almost 1 million workers died from exposure to hazardous substances, including dusts, vapours and fumes (an increase of more than 90,000 workers compared to 2011), based on estimates released by the ILO (Hämäläinen, Takala and Kiat 2017). Statistics from the Global Burden of Disease Database quantify the global effects of occupational exposure to cadmium in 2017 at more than 18,000 DALYs and around 659 deaths in 2017 and show a steady increase in both metrics (IHME 2019) (Figure 7.2). Among other diseases, cadmium has been associated with cardiovascular disease and cancer (Adams, Passarelli and Newcomb 2012; Tellez-Plaza *et al.* 2013).

Endocrine-disrupting and carcinogenic chemicals put workers at risk

Worldwide, the highest exposures to carcinogens in terms of concentrations take place in workplaces. A 2016 WHO report estimated that 2-8 per cent of all cancers arose from occupational chemical exposures (WHO 2016). An extensive study of cancer in Great Britain found that 8,010 (5.3 per cent of all cancers) total cancer deaths in that country were attributable to occupation in 2004; out of the 339,156 cancer registrations in 2004, 13,598 were estimated to be attributable to occupational exposures while asbestos exposure accounted for 4,216 (Rushton *et al.* 2012). More specifically, the WHO estimated that 6 per cent of deaths from cancers of the lung, bronchus and trachea were attributable to chemicals found in the workplace. Occupational exposures to arsenic, asbestos, beryllium, cadmium, chromium, diesel exhaust, nickel and silica were estimated to cause 111,000 deaths (and 1,011,000 DALYs) from lung cancer in 2004 (Prüss-Ustün *et al.* 2011).

A series of studies from the United States and Asia published in the 1990s and 2000s reported increased risks of adverse reproductive outcomes among microelectronics workers, including spontaneous abortions, menstrual aberrations, infertility, birth defects and cancer in offspring. Despite increased corporate and government attention to the hazards of lead, nickel, arsenic and chlorinated solvents used in the industry, recent studies suggest that higher rates of spontaneous abortions and menstrual aberrations continue among electronics workers in the Republic of Korea (Kim, Kim and Lim 2015).

Many chemical-related facility injuries and fatalities occur each year

While the chemical industry has implemented several programmes to prevent accidents at chemical manufacturing facilities, accidents at refineries, downstream manufacturing plants and other locations are reported to injure or kill hundreds of workers each year (Mihailidou, Antoniadis and Assael 2012; International Association of Oil and Gas Producers 2017; Zhao *et al.* 2018; OECD 2019). The best known example of a major chemical accident is the exposure of more than half a million people, including thousands fatally, to around 42,000 kg of methyl isocyanate and other gases released from a Union Carbide pesticide plant in Bhopal, India in 1984 (Broughton 2005). The EU tracks chemical accidents through its Major Accident Reporting (eMARS) System (EC 2018). A review of chemical accidents reported in the news media between October 2016 and September 2017 (Wood 2017) indicates that chemical accidents and near misses continue to occur frequently in OECD countries, but that fatality rates are lower than those in non-OECD countries. According to this study, OECD countries accounted for nearly two-thirds of events (421 out of 668), but barely one-third of deaths (201 out of 579).

Occupational exposure to hazardous chemicals results in a wide range of chronic diseases

Diseases associated with exposures to hazardous substances are estimated to kill about 438,000 workers annually (ILO 2005). Common diseases associated with hazardous chemical exposures include asthma, asbestosis, byssinosis, silicosis, mesothelioma, bauxite fibrosis, contact dermatitis, berylliosis and chronic obstructive pulmonary disease. For example, working in building cleaning services that use commercial cleaners has been associated with new-onset asthma (Zock, Vizcaya and Le Moual 2010). Workers exposed to high levels of carcinogens are particularly vulnerable. Asbestos exposure alone claims over 100,000 lives every year, and this figure is rising (Prüss-Ustün *et al.* 2016).

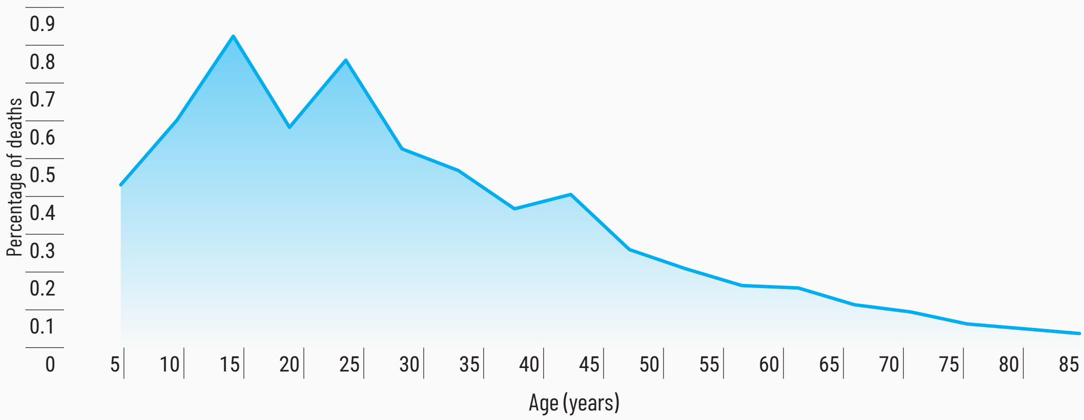
Agricultural workers may be exposed to high levels of pesticides while working in fields, or in local communities or camps where they live. Exposures in fields occur as a result of direct pesticide applications, pesticide drift from areal applications, and residues on plants or in soils. Protective clothing, training and regulatory enforcement are often lacking in both developed and developing countries.

Miners are also highly exposed to hazardous chemicals, particularly in developing countries. In many parts of the world minerals are extracted by artisanal and small-scale mining (ASGM). The large majority of the miners are very poor, exploiting marginal deposits in harsh and often dangerous conditions – and with considerable impact on the environment. Small-scale mining is thought to involve 13 million people directly and affect the livelihoods of a further 80-100 million (International Institute for Environment and Development 2002). Research in Ghana among ASGM communities found that more than 50 per cent of miners and 25 per cent of non-miners surveyed exhibited serious mercury toxicity and up to 7 per cent had neurological problems (Amankwah and Ofori-Sarpong 2014).

Foetuses, infants and children are more susceptible to the risks of chemical exposure than adults

Children's health and development are compromised by exposures to a wide array of hazardous chemicals. Children are particularly sensitive to these exposures because of their higher body surface to weight ratio, differences in metabolism, ongoing organ growth and development, and lack of understanding and caution. Learning disorders, hyperactivity and attention deficits in children are associated with exposures of foetuses or infants to hazardous chemicals, including lead, mercury, manganese, dioxin and PCBs. During foetal development the brain is particularly vulnerable to some toxins, such as methylmercury and PCBs. Methylmercury affects the proliferation and migration of neurons; methylmercury and PCBs both affect synaptogenesis. Even small amounts of mercury in the diets of pregnant women have been associated with language, attention and memory impairment in their offspring (Bose-O'Reilly *et al.* 2010). The health of children and young adults is particularly affected by unintentional poisonings (Figure 7.3).

Figure 7.3 **Percentage of deaths attributed to unintentional poisonings by selected chemicals by age, 2016 (adapted from WHO 2018a, p. 2)**



Children in developing countries are at particularly high risk

Significant reductions in childhood blood lead levels have been documented in industrialized countries that have phased out leaded gasoline and lead in paints – although the WHO has estimated that 99 per cent of children with high blood lead levels live in developing countries where lead in gasoline and paint is still prevalent (WHO 2009). Children living in the vicinity of waste sites are particularly at risk. A study assessing 200 hazardous waste sites in 31 countries found close to 780,000 children to be at risk of diminished intelligence from exposure to lead (Chatham-Stephens *et al.* 2014).

The ILO has estimated the number of working children aged five to 14 to be 168 million worldwide, of which 60 per cent are engaged in agriculture. Some 85 million child labourers have been reported to be in hazardous work such as farming, construction, textiles, mining, tanning, ship breaking and fishing, including many who are exposed to toxic chemicals. Although in absolute terms middle-income countries are

host to the largest numbers of child labourers, the highest incidence of children working in hazardous occupations is in Sub-Saharan Africa (ILO 2011; ILO 2013b).

The elderly are particularly susceptible to the risks of hazardous chemicals

Chemical exposures can aggravate compromised organs and increase vulnerability to opportunistic disease in the elderly. The ability of the body to respond to the physiological challenge presented by hazardous chemicals is dependent in part upon the health of the organ systems that eliminate those substances from the body (Risher *et al.* 2010). Older people are susceptible to the effects of mercury because of declining organ functions, and to air and water pollution because of impaired DNA repair mechanisms. Low-level exposure to lead may increase their risk of high blood pressure and the incidence of cognitive impairments and psychiatric symptoms (anxiety and depression) (Payton *et al.* 1998). Exposures to lead and PCBs have been linked to dementia, while Parkinson's disease has been linked to exposures to the manufactured heroin 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP), the pesticide rotenone and the metal manganese (Stein *et al.* 2008). Links between Parkinson's and Alzheimer's diseases and various solvents and pesticides are suspected, although the evidence is not conclusive (Allen and Levy 2013).

7.4.2 Gender

Different factors determine chemical exposure for men and women

Social and cultural norms, family traditions and, in some countries, laws and regulations differentiate how men and women are exposed to hazardous chemicals. The differences include the kinds of chemicals encountered, as well as the concentrations and frequency of exposures. In addition, men and women differ in their physiological susceptibility to the effects of exposure to hazardous chemicals. Women are especially vulnerable to some chemicals during pregnancy and lactation, while the higher volume of fatty tissue in women's bodies makes them more vulnerable to fat soluble chemicals such as the halogenated hydrocarbons (UNDP 2011; SAICM Secretariat 2016; (WECF 2016). Men may be particularly at risk, for example, due to potential adverse effects on sperm quality (Rim 2017; Bloom *et al.* 2015).

Gender differences in workplace exposure

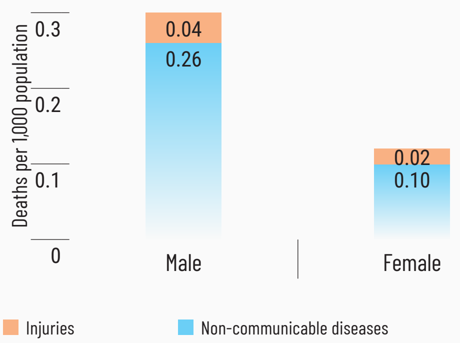
Often men are more likely than women to be engaged in physically dangerous occupations with high chemical exposures. In occupations such as fishing, mining, tanning, stone cutting, construction, boat disassembly and equipment handling, for example, men are more likely to be exposed to acids, solvents, heavy metals, asbestos, fuels and explosives; they are also more likely to be exposed at greater concentrations than women. Women make up most of the assembly line workers among supply chain vendors in emerging economies, particularly in electronics, toys and textiles, where they may be exposed to solvents, mastics, metals in paints and coatings, dyes, and textile finishing chemicals. In agricultural work women make up 43 per cent of the workforce (FAO 2011). While men are more likely to be directly exposed to pesticides during application, women and children are more likely to be indirectly exposed during planting, maintenance work and harvesting (Arbuckle and Ritter 2005; UNDP 2007; Pesticide Action Network Asia and the Pacific 2017). Pesticide exposure can affect women's fertility, reproductive health, menstruation patterns and risk of endometriosis (García 2003). In men occupational pesticide exposure can be associated with adverse effects on sperm quality (Martenies and Perry 2013; Miranda-Contreras *et al.* 2015; Cremonese *et al.* 2017).

Gender differences in domestic exposure

Use of certain product types varies significantly by gender. This difference is often associated with conventional family roles and occupations. Where women work in homemaking, teaching, health care, elder care and child care, they are more likely to be exposed to soaps, detergents, food preservatives, cooking oils, solvents, insecticides, and pesticides used in vector control. Because women and girls usually assume responsibility for cleaning and household management, they are more likely than men to be exposed to toxic chemicals found in cleaning agents and sanitizers (UNDP 2011). According to the WHO (2018a), the disease burden preventable through sound management and reduction of chemicals in the environment is significantly higher for men (Figure 7.4), mainly due to their higher occupational exposure in certain sectors.

Women are significantly greater users of cosmetics and personal care products, many of which are directly applied on the skin (UNEP 2016; WECF 2016). They include skin lightening products, which often contain hazardous substances such as mercury. In some cultures women are likely to use large amounts of cosmetics, particularly perfumes, skin creams, nail varnishes, deodorants and hair treatments. One report has suggested that British women may put an average of 515 chemicals on their bodies every day (Rice 2009). Cosmetics and personal care products are among the most chemical-intensive products on the commercial market. Some 5,000 chemical ingredients are used in the personal care industry. Many products contain parabens, phthalates, propylene glycol, 1,4-dioxane, triclosan, diethanolamine, benzaldehyde and various other biocides, some of which are linked to allergies, asthma, endocrine disruption, reproductive damage and cancer (Ostojić 2016; SAICM Secretariat 2016). Women of colour have been shown to be particularly at risk (Zota and Shamasunder 2017).

Figure 7.4 **Deaths attributed to selected chemicals, by gender, 2016 (adapted from WHO 2018a, p. 2)**



7.4.3 Poverty, social stratification and cultural aspects

Chemical pollution disproportionally affects the poor

The poor in both higher- and lower-income economies are at a higher risk of disease and deaths caused by chemical pollution (GAHP 2013). Nearly 92 per cent of pollution-related deaths occur in low- and middle-income countries. Disease caused by pollution is most prevalent among minorities and marginalized populations (Landrigan *et al.* 2017). Such disadvantaged groups, which are disproportionally affected by the cumulative impacts of pollution and poverty, often lack the financial, social and political capacities to avoid such exposure, particularly in lower-income countries. In cities minority and disadvantaged people often reside in neighbourhoods near industrial areas, production facilities, waste dumpsites, waste treatment facilities, or polluted water or land; in rural areas the poor often reside near mining operations, agricultural fields sprayed with pesticides, livestock feeding lots, abandoned chemical stockpiles, waste disposal sites or polluted water sources (Goldman and Tran 2002; GAHP 2013; Collins, Munoz and JaJa 2016; Starbuck and White 2016).

A number of studies have found low-income individuals to have significantly higher exposures to diabetogenic EDCs (Ruiz *et al.* 2018). A study of the health effects of toxic waste sites in India, Indonesia and the Philippines concluded that the burden of disease from living near hazardous waste sites (measured in DALYs) is comparable to that from outdoor air pollution or malaria (Chatham-Stephens *et al.* 2013). In the United States living near industrial facilities has been associated with non-Hodgkin lymphoma (de Roos *et al.* 2010). Poor and disadvantaged people also often experience significant adverse chemical exposures at work. Where poor people find work either in industry, agriculture or the informal sector, they are more likely than higher-wage workers to work in dangerous, unregulated settings where exposures to hazardous chemicals are high (Rockefeller Foundation 2013).

The housing of poorer people puts them at greater risk from hazardous chemicals

Low-income housing in industrialized countries may contain asbestos, lead and formaldehyde and be heavily sprayed with pesticides. Building materials in developing countries may be cheaply made or recycled, with little concern for possible chemical risks. Studies have shown that indoor air quality in low-income housing is often more hazardous than that in middle-income housing, as it has higher levels of contaminants such as lead, PAHs, allergens and pesticides (Rauh, Landrigan and Claudio 2008).

Contamination through food can be higher as a result of poverty or traditional diets

In high-consumption countries where high-quality and organic foods are available to high wage earners, the food available to low-income people with limited means is high in preservatives and stabilizers and marketed in single-use plastic packaging that may contain phthalates, heavy metals and other additives (Rather *et al.* 2017). In developing countries the traditional meats, fish and vegetables available to the poor may be contaminated with pesticides and the residues of industrial pollution. Indigenous people reliant on traditional diets of fish and marine mammals may be among the most highly exposed to persistent, bioacumulative and toxic chemicals (PBTs) (Undeman *et al.* 2018). For example, studies in Canada showed that First Nations people consuming large amounts of fish (Marushka *et al.* 2017) and Inuit consuming marine mammals (Hu, Laird and Chan 2017) could have an elevated intake of PCBs, dichlorodiphenyldichloroethylene, and methyl mercury. In the United States a study of the Yupik people of St. Lawrence Island (Alaska) found PCBs in their blood at levels six to nine times higher than in that of the general population in the lower 48 contiguous states (Carpenter and Miller 2011).

7.5 Challenges and opportunities related to information about chemicals' effects

Examining trends in the environmental, health and social effects of manufactured chemicals worldwide is limited by the availability and quality of information; the capacity of science to characterize chemical mixtures and synergistic effects; and the research still needed to link chemical exposure with environmental, health and social outcomes.

Effects information is still lacking for thousands of chemicals, although work is progressing

In the past 50 years corporations, governments and university research labs have documented the health and environmental effects of hundreds of manufactured chemicals. The OECD High Production Chemicals Programme and, in the EU, REACH registration dossiers have more systematically expanded this information, and some high production chemicals and substances such as lead, mercury, asbestos and PCBs are well-studied. However, a comprehensive inventory of the health and environmental effects of thousands of other chemicals is still lacking. There is a large volume of research on chemical effects that result in cancer and chronic obstructive pulmonary disease. However, chemical effects on reproductive, endocrine, immunological and neurological systems are less well-explored. There is substantial information on chemical effects on some plants and aquatic and terrestrial organisms that are conducive to laboratory study, but much less field-based research on chemical exposure effects.

There are many studies on occupational exposures, and much research on chemical effects on adult men. Only recently has more research appeared on the effects of chemical exposure on women and children. Little research has been conducted on such effects on the elderly, the poor, communities, or larger marine and terrestrial animals. The social effects of chemical exposures on communities, and the disparities of effects among subsets of the population, are little recognized or studied.

Despite progress, significant challenges remain in understanding mixture effects and long-term, low-dose exposures

Important progress is being made in developing approaches and methods to assess mixture toxicity, and several reviews and guidance documents reflecting the state of science are available (OECD 2011; Meek *et al.* 2011; WHO 2017; US ATSDR 2018). Although the development of research methods for studying the multiple exposures and complex interactions of mixtures is advancing, methodological challenges remain in understanding cumulative exposure to various chemicals and related potential health and environmental effects and research in this area is continuing to help ensure a high level of protection (Kortenkamp, Backhaus and Faust 2009). Often humans and ecosystems are exposed to a heterogeneous set of compounds or products, some of which may have combinational or synergistic effects. Complex interactions can occur with mixtures of chemicals, such that the toxicological effects experienced as a result of such exposures may differ significantly from the laboratory-studies on the effects of the individual chemicals (EC 2011). For example, a study of the effects of five common pesticides mixed together, as opposed to individually, demonstrated an effect greater than a simple additive effect on the brain enzymes of steelhead salmon (Laetz *et al.* 2009). Understanding the effects of long-term and low-dose exposures to mixtures of chemicals, particularly among young children, is also limited. These topics are discussed in more detail in Part III.

Causal relationships between exposures and effects are often difficult to establish

Diseases are multifactorial. They are often the result of both genetic and environmental factors. Establishing causal relationships is difficult due to various intrinsic factors that can hinder clinical and epidemiological studies, as well as a lack of consensus on appropriate study designs and research methodologies. Epidemiological studies often require long time periods, large populations, or both. Clinical studies provide results that may be difficult to extrapolate to existing conditions. Where controversies arise, multiple studies may generate contradictory results and lead to long delays in taking risk management decisions since the science has not been settled. In some instances, the best that can be achieved is plausible associations based on mathematical modelling; statistical associations; combinations of laboratory, experimental and field studies; or various forms of expert judgment (Adams 2003).

8/ The economic benefits of action and the costs of inaction

Chapter Highlights

Various studies have estimated the economic benefits of action taken to reduce or avoid exposure to dangerous chemicals, and the costs of inaction under the current policy framework.

Robust economic analysis is challenging and is associated with uncertainties; refinement of methodologies is ongoing and further studies are needed.

There is evidence that chemical exposure places an economic burden on health care systems, and that it reduces the productivity and capability of the workforce and the well-being (or utility) of wider populations through reduced disposable incomes and increased suffering.

The costs associated with exposure to harmful chemicals are estimated to be in the range of several per centage points of global GDP; likewise, the economic benefits of action from preventing chemical exposure are significant.

A study of the economic and social effects of using harmful chemicals could help to raise awareness of the global scale of chemicals and catalyse further action.

Large numbers of chemicals are manufactured, distributed, and incorporated into mixtures, articles and products globally. They provide a wide range of essential functions, generating substantial economic value and social benefits. These benefits arise at the point of sale (and along various supply chains) from the functionality that chemicals impart in products, the efficiency they support in manufacturing, and the process and product innovations they enable. Throughout a product's life cycle, however, exposure to harmful chemicals can cause damage to human health and well-being, biodiversity, and terrestrial and aquatic wildlife. This chapter supplements the analysis provided in the previous chapters. It discusses economic aspects of the valuation of costs and benefits associated with chemicals, and examines the differences between private benefits (or costs) and social benefits (or costs); economists refer to social benefits/costs as "externalities". The available economic analysis – which is limited to a comparatively small number of substance-disease pairings and countries – is reviewed.

8.1 Externalities associated with chemicals across the value chain

In economic terminology, an externality may be referred to as a cost or benefit that affects a party which has not chosen to incur that cost or benefit. External costs may arise, for example, from the impaired functioning of ecosystem services, biodiversity loss, or harm to wildlife. Quantitatively relating the impact of chemical pollution (or of human consumption patterns) to ecosystems damage, biodiversity loss or harm to particular species remains challenging (Marques *et al.* 2017; Wilting *et al.* 2017; Chaplin-Kramer and Green n.d.). More economic analysis exists

of the external costs to human health that are attributable to chemical pollution.

Concerning chemicals and waste management, knowledge is emerging about the economic benefits of reduced exposure to harmful chemicals (the "benefits of action") along with analysis of the economic costs identified with exposure to these chemicals (the "costs of inaction"). Examples of the costs of inaction are the direct costs of health care and the indirect costs arising from time off work or impaired capability (Nordic Council of Ministers 2015). For business the costs of inaction could include provision of occupational health care, or litigation and reputational damage.

Box 8.1 **Externalities: the differences between market prices and social costs (Helbling 2017)**

Consumption, production and investment decisions often have effects on people who are not directly involved in these decisions: that is, they are external to specific transactions. These effects can be positive or negative. So-called "technical externalities" – where external effects impact the consumption and production opportunities of others, but the market price of the product in question does not reflect these external costs – are the most common.

Environmental pollution, from harmful chemicals or any other source, is a classic example of a negative externality. Polluters make decisions based on the marginal costs incurred by them and marginal benefits accruing to them through production. However, they seldom consider the external (or indirect) costs that society incurs as a result of the production of a good. The indirect costs are not borne by the polluter or passed on to the consumer. They are not taken into account in market prices or in economic transactions. The social costs of production are therefore greater than the private costs.

Negative externalities may be accompanied by positive externalities. Positive externalities could include investment in research and development (R&D), perhaps by the same polluter, resulting in functional benefits facilitated by chemical use in new products. These new products may support weight savings and longer product lifetimes – resulting in, for example, wider social benefits beyond the private cost.

The main problem with externalities is that market outcomes may not be efficient, leading to overproduction of goods with negative externalities and underproduction of those with positive ones. Externalities present significant policy problems when indirect costs (or benefits) are not internalized by individuals, households and companies in their economic transactions.

Environmental costs are distributed within and between countries. While significant methodological challenges, data gaps and uncertainties continue to exist, it is clear that the economic costs of exposure to harmful chemicals are not only globally significant but are currently underestimated (Landrigan *et al.* 2018). Since the publication of UNEPs report *Costs of Inaction on the Sound Management of Chemicals* (UNEP 2013), new economic analysis has emerged that has further raised awareness and sparked debate. Known risks are evolving and new ones are emerging. Much of the economic evidence available focuses on Europe and the United States, while disproportionate health and environmental burdens are being experienced in low- and middle-income countries (LMICs) (Attina and Trasande 2013; UNEP 2013; Trasande *et al.* 2016a; Landrigan *et al.* 2018).

Scope of the review and analysis

The review and analysis in this chapter explore the current state of knowledge along two dimensions:

- *The economic benefits of action (BoA) or reduced or avoided damage to human health and/or the environment from reduced/avoided exposure to dangerous chemicals*. These economic benefits include estimated benefits arising from, for example, the number of lives saved or cases of cancer avoided. Estimates are typically ex-post (they "look back"), using information on effects from regulatory (or voluntary) actions already taken. However, they seek to guide, refine and improve future actions.

- *The economic costs of inaction (CoI) or damage to human health and/or the environment that are estimated to be occurring at present – or can reasonably be expected to occur in the future – under the current policy framework*. These costs point to the need for new or amended actions, either regulatory or voluntary or a combination of the two.

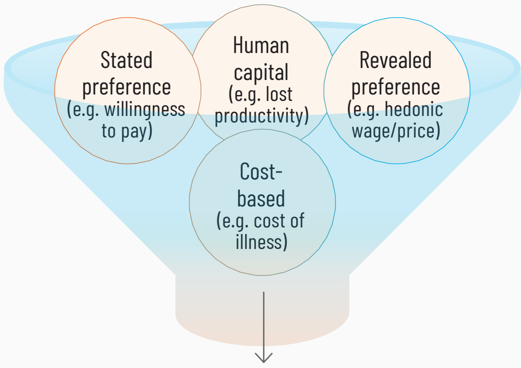
The entire literature is not covered in this chapter. Only published and/or peer-reviewed literature is referred to. No new estimates of economic value and effects have been generated for the purposes of this report. While any economic assessment of specific policy action should consider overall net effects, neither the wider economic effects related to innovation, nor the costs of regulatory implementation and compliance, are considered in detail. In addition, economic assessment is ongoing in public agencies in various jurisdictions around the world and in academia. In the case of the former it would not be possible to cover the large technical literature, although specific examples are noted. Much published academic work focuses on a relatively small number of substance-effect parings and is confined to studies in Europe and North America.

Any understanding of the economic burden of disease attributed to chemicals is limited by the scientific data. The strength or otherwise of evidence on causality between individual substances and health effects is an ongoing debate that continues to evolve as new associations are discovered (Harremoes *et al.* 2001). The focus of this chapter is on economic methods, and the results obtained in trying to chart these complex relationships, rather than on reviewing the epidemiological evidence.

8.2 How have economists identified costs and benefits?

Economic assessments of the BoA and CoI seek to reflect complex relationships. Robust economic analysis requires several earlier analytical stages, which are themselves subject to uncertainty and limited by the extent of epidemiological and biomonitoring data. Although significant effects on ecosystem services, biodiversity and wildlife have been identified, most *economic* analysis currently relates to the effects of chemical exposure on human health. Here the key methodological steps include: establishing

Figure 8.1 Identifying the economic costs of inaction and the benefits of action



an epidemiological relationship (dose-response function) between chemical exposure and a specific health outcome; evaluating the role of chemical exposure in this outcome, alongside other factors; and considering the latency of the disease and incorporating data on exposure within and across populations. While the CoI may be determined using data on current exposure, BoA analysis requires longitudinal (before and after) exposure data to identify attributable effects of an intervention. Only then can judgements be made concerning the number of attributable cases and their monetary and economic effects.

Common approaches to identify the economic costs of inaction and the benefits of action are summarized below. One of these approaches is typically used when assessing the costs of inaction and benefits of action for any single chemical (Figure 8.1). One approach involves estimating the costs of ongoing exposure (or the avoided costs from avoided exposure). Both involve directly observing the costs of specific health treatments. This is referred to as the *cost of illness or avoided cost* approach. It is a *cost-based* approach reflecting market-traded goods (i.e. labour, wages and drugs/treatments). However, this approach excludes effects on those not in the labour force, especially the young and the old, and does not capture suffering experienced by the individual. Another approach involves estimating the value of lost earnings from reduced/lost economic productivity due to disease, suffering or impaired capability. This is referred to as the *human capital* approach. Again, it relates to market-traded goods (i.e. labour and wages) but involves important assumptions about labour market participation, future earnings and discounting.

Directly or indirectly available market information may also *reveal individual preferences*. Examples are observing the wage differentials between risky and non-risky jobs, or differences in housing costs in different environments. Sometimes, to reduce the risk of death or suffering, individuals or firms incur voluntary expenditures ("avertive" expenditures) such as those on safety equipment or occupational health testing and analysis. Again, this reflects the purchase and use of market-traded goods (i.e. equipment and expertise). The *stated preference* technique relies on asking people questions through carefully designed surveys to elicit their willingness to pay for certain interventions that would improve their health. Examples include the contingent valuation method (which involves asking questions on their willingness to pay) and conjoint analysis (which elicits preferences from particular combinations of attributes and alternatives). This technique does not involve the purchase of market-traded goods, but reflects *individual valuation*.

Commonly used output indicators for health are based on mortality (premature death), morbidity (disease) and health life years. These are expressed as disability adjusted life years (DALYs) and quality adjusted life years (QALYs), while further indicators such as value of a life year (VOLY) or years of life lost (YOLL) are used in identifying health-related costs (World Bank 1993; Prüss-Ustün *et al.* 2016; GBD 2016 DALYs and HALE Collaborators 2017). The value of statistical life (VSL) is estimated using either the revealed preference or the stated preference estimates. (OECD [2010] presents a meta-analysis of value of statistical life [VSL] estimates obtained in various countries, using stated preference methods.) However, methodological developments are far from static (Box 8.2).

Box 8.2 Current methodological developments: SACAME

Coordinated by the OECD and funded by the European Commission, the Socio-economic Analysis of Chemicals by Allowing a better quantification and monetization of Morbidity and Environmental impacts (SACAME) project aims to support improved socio-economic analysis through better quantification and monetization of effects. In the longer term, the project's objective is to develop harmonized OECD methodologies for estimating the economic costs and benefits of managing chemicals, in support of implementation of the Strategic Approach to International Chemicals Management (SAICM) (OECD 2018).

To date, several project papers have been published exploring economic analysis in the context of several different chemicals/chemical groups, including phthalates (Holland 2018), formaldehyde (Hunt and Dale 2018a) and the solvent methyl-2-pyrrolidone (NMP) (Hunt and Dale 2018b). The papers also explore thematic methodological issues, such as the challenges of using benefit transfer methods (Navrud 2017), approaches for the assessment of perfluoroctanoic acid (PFOA) and persistent bioaccumulative and toxic (PBT) substances more generally (Gabbert 2018), and how chemical risk assessments can better support economic analysis in decision making (Chiu 2017). Several studies note variations in existing valuation studies, extensive data gaps, and the need for multidisciplinary expertise. Some also call for new primary evidence, particularly from Asia.

8.3 What the data tell us: interpreting the findings

Monetary valuation is an important aspect of this chapter, and of the field of policy analysis more generally. The section above noted whether methods are market-based or non-market-based approaches. In interpreting the studies that follow, while a comparison of the aggregate values identified with gross domestic product (GDP) is useful in dealing with market-based approaches, the same comparison may be insufficient and potentially misleading when economic analysis uses approaches that are not market-based (Box 8.3).

8.4 The benefits of action taken in the last 50 years are globally significant

Global treaties have "locked in' major economic benefits, to accrue over this century

All countries are Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, which entered into force in 1989 (with several later amendments). Moreover, all countries are also Parties to the London (1990), Copenhagen (1992), Montreal (1997) and Beijing (1999) amendments. As at 30 October 2018, 58 Parties had ratified the Kigali amendment (2016) which will enter into force on 1 January 2019. As the loss of stratospheric ozone is avoided and the ozone layer recovers, several studies have sought to quantify the long-term effects of this multilateral environmental agreement (MEA). Much of the analysis concerns the United States, where the cumulative benefits of avoided cancers and cataracts have been estimated at up to US dollars 4 trillion (1990-2065). In Europe the associated benefits have been estimated at some euros 7 trillion (1990-2100), or around euros 300 billion per year (Amec Foster Wheeler *et al.* 2017; US EPA 2015).

The Minamata Convention on Mercury came into force much more recently, in August 2017, although national and international activities to monitor and reduce mercury exposure have existed for a number of years (UNEP 2016; US EPA 2018; UNEP n.d.). Implementation of this MEA, which addresses specific human activities that contribute to widespread mercury pollution, will help reduce global mercury pollution in the coming decades. Bellanger *et al.* (2013) estimated the monetary value of neurotoxicity prevention through methylmercury (MeHg) control in Europe: prenatal exposure was

Box 8.3 Utility, economic value and economic cost

Utility is a measure of satisfaction/dissatisfaction that individuals obtain by consuming a certain good or service. For example, each individual draws satisfaction from the enjoyment of good health, leisure or another consumer good. Conversely, dissatisfaction arises from poor heath, excessive work or exposure to pollution. The additional satisfaction/dissatisfaction resulting from the consumption of additional units of each good is referred to as the marginal utility or marginal disutility.

Economic value is the amount of money each individual spends, or is willing to spend, to obtain the utility from a certain good. Again, if the good results in disutility, the individual may pay to avoid that good or accept some compensation to continue suffering from this disutility. This economic value is a measure of the maximum amount of money the individual is willing to pay/able to pay to derive utility from the good.

Economic value and market price, however, need not be the same. The value of the good is the opportunity cost of obtaining that good, i.e. the amount the individual gives up to obtain it. The value of leisure, for example, is the potential wage income sacrificed to obtain it. Economic value can be provided by market price where markets are competitive and markets exist for the good.

Certain goods may not only have use values, but also non-use, existence or intrinsic values. In such cases the value and price cannot be the same. Human life, for example, has intrinsic value beyond any market price or effect; the lives of the older people and others not in the labour market are clearly not less valuable. In these cases, economists rely on various non-market valuation techniques to estimate the value of life. Therefore, costs refer to the economic costs or the opportunity costs of consuming a good (or bad). The cost of pollution is the opportunity cost of healthy life, or what the individual sacrifices to pay for his or her ill health.

associated with the loss of 600,000 IQ points per year, corresponding to a total economic benefit from removing methylmercury of around euros 9 billion per year, while the global benefits of neurotoxicity prevention were estimated at upwards of around US dollars 20 billion per year. The authors pointed out, however, that "the validity of such calculations is limited by the lack of exposure assessments" (Bellanger *et al.* 2013).

The benefits of action based on chemical legislation are valued at least in "the high tens of billions' per year

Future policy actions can be informed by and benefit from evaluation of policy actions taken in the past. Since the 1960s, regulatory and voluntary actions combined have substantially reduced the aggregate costs associated with exposure to a range of harmful chemicals. It has been conservatively estimated that the benefits of these actions are in the "high tens of billions" of euros per year in the EU alone. These estimates were derived largely from effects on human health (including in the areas of cancer, neurodevelopmental effects and reproductive health), based on a series of case studies where sufficient data existed. As methods to aggregate monetary values improve and more data become available, the known value of such benefits of action is likely to increase, perhaps significantly (Amec Foster Wheeler *et al.* 2017). However, analyses have not yet captured the possible effects of new/increased and/or multiple exposures, or of so-called "regrettable substitutions". Similarly, the economic costs and benefits of a selection of restrictions under the EU's REACH Regulation have been evaluated (ECHA 2016; ECHA 2017).The economic costs of restrictions under REACH (data are not available for all cases reviewed) have amounted to euros 290 million per year. The monetary benefits, although these could only be identified in a relatively small number of cases, have been in the order of some euros 700 million per year.

In the United States a retrospective evaluation of the benefits and costs of emission controls, imposed by the Clean Air Act and associated regulations between 1970 and 1990, assessed the effects of sulphur dioxide, nitrogen oxides, particulate matter, volatile organic compounds, lead, ground level and stratospheric ozone, and ambient air quality (US EPA 1997). Only some of these emissions are included in typical assessments of "chemical" pollution. Health conditions and effects assessed in the evaluation included premature mortality, lost IQ points, hypertension and coronary heart diseases; hospital admissions; and respiratory related ailments, asthma attacks and restricted activity days. Total monetized benefits, realized between 1970 and 1990, were estimated at just over US dollars 20 trillion (central estimate). This compared to direct costs of approximately US dollars 0.5 trillion (US EPA 1997).

In January 2018 the Canadian Government published proposals for further controls to eliminate asbestos. Using break-even analysis, the impact assessment explored the number of avoided cases of lung cancer or mesothelioma required to meet the expected costs (Government of Canada 2018).

Environmental improvements are clear, but it is more difficult to attribute monetary values

In Europe the environmental benefits of action on chemicals, both regulatory and voluntary, since the 1960s have also been assessed. Among the benefits identified are reductions in chemicals found in water used for domestic, agricultural and industrial purposes; evidence of recoveries in some fish populations and in their reproductive capacity; avoided damage to biodiversity and ecosystem services; increased protection of recreational activities/aesthetic value; and avoided damage to bird and insect life as well as contamination of land and soil, consistent with regulatory action (Amec Foster Wheeler *et al.* 2017). Attributing environmental benefits (e.g. for biodiversity conservation, or protection of ecosystem services and wildlife) to specific actions, or identifying and aggregating quantitative and monetary effects and the extent of data gaps, are challenging. Economic estimates are possible in fewer cases, and those available are more uncertain. As in the case of analyses of health effects, available studies are limited in terms of chemical substance and location. There is a risk that environmental effects will be overlooked in policy analysis and that early warnings will be missed.

8.5 Despite progress, the global costs of inaction are substantial

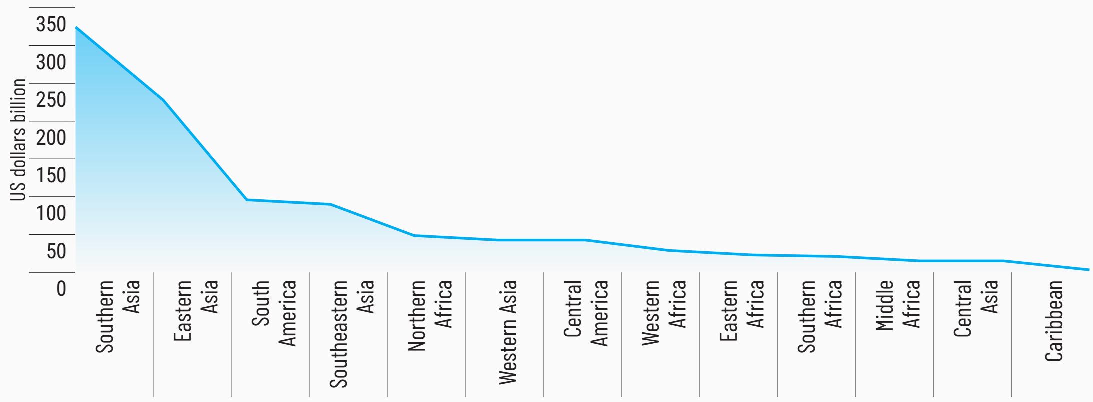
The market and non-market costs of inaction could be as high as 10 per cent of global GDP

A global assessment of the disease health burden from environmental exposure to chemicals was published in Grandjean and Bellanger (2017). This study attempts to reflect a broader set of known chemical effect relationships (including subclinical effects) than those included in previous global burden of disease studies. The study indicates that calculations based on disability adjusted life year (DALY) are likely to understate effects, which may actually contribute costs exceeding 10 per cent of global GDP. Costs associated with neurotoxicants, air pollution and endocrine-disrupting chemicals (EDCs) were examined. It is important to note that the effects reported were based on both market effects (productivity effects or health costs) and non-market effects (willingness to pay valuation). This should be borne in mind when comparing results with respect to GDP. Future refinement of the estimates might usefully involve separating these effects.

The costs of inaction are disproportionate in low- and middle-income countries

Although sparse, research has increasingly sought to establish the costs of inaction in LMICs (Landrigan *et al.* 2018). In the context of the Minamata Convention, Trasande *et al.* (2016a) evaluated the impact of mercury exposure as being between US dollars 77 million and 130 million at 15 sites in LMICs, using data on mercury levels in hair and effects on IQ, lost productivity and DALYs. This study built on earlier ones that looked at the economic effects of childhood lead exposure on lifetime productivity and earnings in LMICs more generally. These

Figure 8.2 Lost lifetime earning potential for each cohort of children under five from childhood lead exposure in 2011 (US dollars billion) (adapted from Attina and Trasande 2013)



studies suggest the greatest burdens may now be borne in these countries, with total losses of up to around US dollars 1 trillion (some 1 per cent of global GDP), comprising US dollars 135 billion in Africa (4 per cent of GDP), US dollars 700 billion in Asia (some 2 per cent of GDP) and US dollars 140 billion in Latin America and the Caribbean (2 per cent of GDP) (Attina and Trasande 2013) (Figure 8.2).

The public health costs from endocrine-disrupting chemicals are globally significant

Several recent studies have focused on costs from EDCs. They assess costs only from European exposure and from EDCs on which the authors consider that sufficient epidemiological studies exist. Several studies have used a weight of evidence characterization approach, adapted from that used by the Intergovernmental Panel

on Climate Change (IPCC). While the strength of evidence and probability of causation have differed and caused some debate, the effects assessed include IQ loss, autism, attention deficit hyperactivity disorder (ADHD), endometriosis, fibroids, childhood obesity, adult obesity, adult diabetes, cryptorchidism, male infertility, and mortality associated with reduced testosterone (Trasande *et al.* 2016b).

Although the key conclusions are not without uncertainties and data gaps, and have stimulated debate, they illustrate significant economic costs. They suggest that the costs of inaction are in the order of hundreds of billions of euros per year in Europe alone. Neurobehavioral deficits (IQ loss, ADHD and autism) represent around euros 150 billion per year (Bellanger *et al.* 2015), male reproductive disorders and diseases euros 15 billion per year (Hauser *et al.* 2015), female reproductive disorders euros 1.5 billion per year (Hunt *et al.* 2016) and obesity and diabetes in the order of euros 18 billion per year (Legler *et al.* 2015). Few studies have evaluated the cost burden of all the effects above. The suggested costs, after accounting for probability of causation, are in the hundreds of billions of euros: euros 157 billion (Trasande *et al.* 2015), which was later updated to euros 163 billion per year, over 1 per cent of the EU's GDP (Trasande *et al.* 2016b), or higher still (Rijk *et al.* 2016).

Additional studies have aimed to estimate costs for the United States and China. A 2016 study estimated the disease costs from EDCs in the United States at US dollars 340 billion (Attina *et al.* 2016). For China, a 2019 study (Cao *et al.*2019) estimated the total disease cost from exposure to EDCs at approximately Chinese Yuan 429 billion, equivalent to more than 1 per cent of national GDP. This overall estimate for EDCs was based on an estimate on the disease cost for male infertility, adult obesity and diabetes from exposure of the Chinese population to phthalates, which was estimated at more than Chinese Yuan 57 billion in health care costs in one year.

Low-level exposure, even to well-studied and well-regulated chemicals, is an ongoing problem

Exposure to some chemicals has decreased substantially. Of these chemicals, the most extensively studied are heavy metals, particularly lead. However, exposure to lead in ceramics, batteries, paints, water pipes and waste continues to occur (Attina and Trasande 2013; Amec Foster Wheeler *et al.* 2017; Amec Foster Wheeler, Trinomics and Technopolis 2017). Low-level lead exposure in the United States has been associated with some 435,000 deaths per year from cardiovascular and ischemic heart disease. That figure is about 10 times higher than previously estimated, reflecting new evidence that associates cardiovascular disease with concentrations of lead once considered safe (Lanphear *et al.* 2018). Costs from IQ deficits and hospitalization associated with low birth weight babies, attributed to perfluorooctanoic acid (PFOA) levels in mothers, was estimated at some US dollars 350 million in 2013-2014, down from around US dollars 3 billion in 2003-2004 (Malits *et al.* 2018).

Evidence on liabilities, compensation and reputational damage is limited, but the costs are significant

Limited evidence exists on the costs incurred by specific companies. A small number of high-profile incidents/accidents have involved fines of several million to several hundred million US dollars. Analysis of decision-making in these cases suggests that greater public disclosure of information might have reduced risks (Makino 2016; Shapira and Zingales 2017).

Historical liabilities can be responsible for ongoing financial costs. A good example is the compensation payable to individuals exposed to asbestos. In this case compensation pay-outs (as well as damage to human health) have continued long after extensive regulatory actions. This may reflect several factors, including: continued exposure to "historical" asbestos which is "locked" in older buildings; the long latency period between exposure and the onset of disease; and people living longer through treatment, hence requiring prolonged care. The Institute and Faculty of Actuaries has estimated total costs arising from all past, present and future asbestos claims in the United States at up to US dollars 275 billion, with costs of several billion US dollars each in France, Germany, Italy, the Netherlands and the United Kingdom (The Actuary 2002).

8.6 How effective are the methods used, and what are remaining challenges and data gaps?

Challenges reflect multiple causal factors, the geographic scale and the latency of disease

Existing techniques have limitations. They cannot fully capture the costs incurred in terms of reduced quality of life, pain and suffering. Assessing the costs of illness requires accurate information on medical costs, but data are often missing on length of suffering, absence from work and hospital admission days, particularly in LMICs. Estimates are sensitive to the technology used and its efficiency and efficacy, which can vary between and within countries along with health care systems. Estimating the economic value of lost productivity requires making assumptions about labour force participation, future productivity growth and wages, and the marginal relationship between IQ and earnings. This approach also excludes effects on those not in the labour force, as well as wider effects on households. Better models are needed to establish linkages between cause and effect with greater certainty, and to incorporate effects from multiple exposures. This problem is compounded by extensive data gaps. (See Amec Foster Wheeler *et al.* [2017] on the extent and quality of existing data required for economic assessment.)

Progress has been made, but challenges remain with respect to attribution and aggregation

Despite several new studies, quantifying physical impacts on human health so as to assign monetary values remains a challenge. The monetary values of impacts provide useful reference values for cost-benefit analysis, green accounting, and the assessment of the impact of regulations. However, there is a lack of data for quantifying (and assigning monetary values to) the physical impacts of chemical releases. This applies, in particular, to impacts on ecosystems and biodiversity, which is a major gap, recognizing initiatives such as TEEB (The Economics of Ecosystems and Biodiversity) to lay foundations and look at further methods (TEEB n.d.). Better information is required on the full spectrum of potentially problematic chemicals beyond a relatively small, well-studied group, many of which are already the subject of regulation. (See Sørensen *et al.* 2017 for a review of the valuation literature.) Further research is also needed in order to distinguish and attribute disease end points to specific chemicals, or groups thereof, from more general lifestyle or non-chemical environmental factors. As methods improve, however, the known benefits of action and costs of inaction are likely to increase, perhaps significantly.

8.7 Lessons learned and potential actions

Economic analysis helps to set out the underlying trade-offs inherent in the use of harmful chemicals. Much progress has been made: there is mounting, improving and more detailed analysis showing that ongoing chemical exposure places substantial economic burdens on health care systems, as well as undermining the productivity and capability of the workforce. These burdens are considerable at national and global levels, amounting to several per centage points of GDP.

"Pollution is very costly; it is responsible for productivity losses, health care costs and costs resulting from damages to ecosystems. But despite the great magnitude of these costs, they are largely invisible and often are not recognized as caused by pollution. The productivity losses of pollution-related diseases are buried in labour statistics. The health-related costs of pollution are hidden in hospital budgets. The result is that the full costs of pollution are not appreciated [and] are often not counted [...]".

- Landrigan et al. 2018

There is better analysis of economic damage, the spatial extent of such damage from local chemical use, the decision-making processes of business when addressing environmental externalities, and the distribution of burdens within populations and across countries (Landrigan *et al.* 2018).

Robust economic analysis is technically challenging. It requires several analytical inputs which are associated with uncertainties and debate (Bond and Dietrich 2017). These inputs include information on substance-disease pairings, specific dose-response relationship data, and information on exposure (across populations and over time) that are needed before judgements can be made about economic effects. While all economic analysis is subject to uncertainty and revision, significant data gaps and methodological challenges remain. Further analysis is required in order to verify effects and refine analytical methods. Drawing thematic conclusions from existing analysis becomes difficult due to differences in method, scoping and the time periods assessed, as well as differences in unit cost, valuation assumptions and approaches used. There is a need for more retrospective economic assessment, and for improved assessment of causal relationships, unintended consequences, and the effects of interactions among multiple chemicals and mixtures and among multiple regulations (Dudley 2017).

These considerations are offset by the relatively limited range of economic costs that it is currently possible to report. Overestimation may occur when extrapolating from uncertain cost data, and more work is needed on the verification of some effects. However, the economic costs of inaction (and the benefits of action) are likely to be understated for three reasons:

- While progress has been made, the economic analysis is drawn largely from a group of comparatively well-studied chemicals, several of which are regulated. A larger group consists of known or suspected pollutants whose effects are not quantified or to which a monetary value has not been attributed. A still larger group has not yet been studied.
- Even for the well-studied group of chemicals, current economic approaches do not currently permit the quantification of all known economic effects.
- Very little quantified/monetary analysis exists regarding effects on the environment (e.g. ecosystems, biodiversity, plant and animal life).

Substantial damage to human health and the environment has been reduced or avoided through extensive regulatory action. Global treaties have ensured that significant benefits are likely in the mid to long term. At a societal level, however, several health outcomes (e.g. incidence rates for several cancers) that are partly associated with chemical exposure (along with many other factors) appear to be worsening (Amec Foster Wheeler *et al.* 2017).

The available economic analysis is overly biased towards a small number of high-income countries. There is a disproportionate health burden in LMICs due to environmental exposure to chemicals, along with ongoing low-level exposure even to well-studied and well-regulated chemicals (Landrigan *et al.* 2018). Analysis also lacks national, subnational and social disaggregation. There is a pressing need for new research on a wider range of chemicals/groups, as well as on a wider range of end points and exposure routes. The need for new research and new exposure data, including concentrations of chemicals in humans (biomarker and biomonitoring data), is particularly urgent in LMICs. Consistent methods, consensus on unit values, and new empirical data on costs are required, building on the work of the European Chemicals Agency (ECHA n.d.), the OECD (2018) and other organizations and individuals.

The scale of the challenges posed by chemicals and waste are not matched by the attention paid to it by policymakers and the general public (Das and Horton 2018; Landrigan *et al.* 2018). A global study of the economic and social effects of using harmful chemicals, comparable to the Stern Review on the *Economics of Climate Change* (Stern 2007), does not exist. Such a study could raise awareness of the global scale of these effects and catalyse further action.

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Chapter 6

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