Reaching for the 2020 Goal

The need for better information and sound management to minimize chemical risks

The volume of chemicals manufactured and used continues to grow, with a shift in production from highly industrialized countries towards developing countries and countries with economies in transition. Increased international co-operation is needed to eliminate or reduce the use of toxic chemicals, to promote the development and adoption of safer alternatives, and to build capacity for regulation and management at every stage of the lifecycle of chemicals. It is also important that existing national laws and international agreements for sound chemicals management be fully implemented. Public availability of adequate information about chemicals – including their multi-faceted impacts on health and the environment – is essential to support these efforts. Yet we are lagging further behind with testing chemicals before they become available on the market, while too little is known about many of those already in commerce. To meet the internationally agreed goal to produce and use chemicals in ways that minimize significant adverse impacts on human health and the environment by 2020, we urgently need to increase our knowledge of chemicals.

Chemicals and their risks

Among their many other benefits, chemicals can help boost agricultural production, make water safe to drink and treat disease. However, they may also present risks to human health and the environment at every stage of their lifecycle, from production and use to storage, transport and disposal.

Annual sales of products of the chemical industry doubled between 2000 and 2009, with the share manufactured in highly industrialized countries falling from 77 to 63 per cent and the share manufactured in the BRIICS countries (Brazil, Russia, India, Indonesia, China and South Africa) increasing from 13 per cent to 28 per cent (Sigman et al. 2012). Chemical production is expected to continue to grow in all parts of the world (Sigman et al. 2012, UNEP 2012a) **(Figure 1).** As production of bulk chemicals shifts away from highly industrialized countries, there are concerns that the risks of chemicals for human health and the environment will be increased due to lack of regulatory experience in some countries, as well as insufficient infrastructure and resources to address these risks.

A small bottle of mercury used in artisanal and small-scale gold mining. Mercury is of global concern because of its persistence in the environment, its ability to accumulate, and adverse impacts on people and ecosystems. *Credit: Kevin Telmer*

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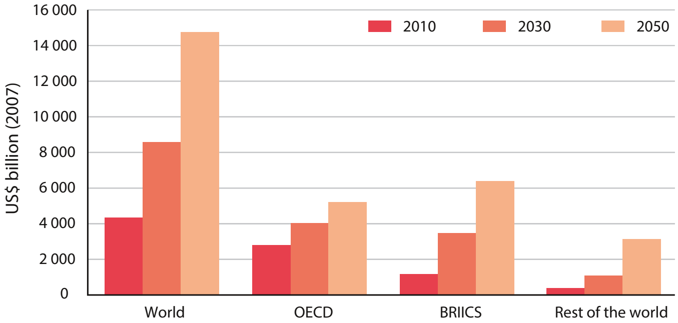


Figure 1: Current and projected chemical production (in sales) for the world, OECD members, BRIICS and other countries in the world, 2010-2050.
Source: Adapted from Sigman et al. (2012)

Chemicals can be grouped into several (sometimes overlapping) main categories, including industrial chemicals, pesticides and biocides, pharmaceuticals, and chemicals used in consumer products.

Industrial chemicals include a very wide range of substances used in chemical processes and products (such as dyes, solvents and plastics) as well as thousands of everyday chemicals. They are manufactured, stored, transported and used worldwide as gases, liquids, suspensions, or in solid state and may pose a great variety of risks (Dhaniram et al. 2012).

Pesticides and biocides are used to kill, repel or control pests, influence the life processes of organisms and destroy or prevent their growth, and preserve plant products. They can be man-made chemicals or, like rotenone, be derived from nature. The properties of these chemicals' formulations, the amounts applied, application methods and environmental conditions determine their behaviour and fate in the environment. For example, pesticides can move in the air through volatilization and vapour drift and have adverse effects on humans and other non-target organisms, damaging ecosystems and reducing biodiversity (Davie-Martin et al. 2012, Reimer and Prokopy 2012).

Pharmaceuticals are generally used in the diagnosis and treatment of disease in people and animals. This category is very important in terms of its health benefits and global economic value.

Chemicals in consumer products including those commonly used in households often have known or suspected risks for human health and the environment (Massey et al. 2008, UNEP/SAICM 2011, UNEP 2012a). They mainly belong to the large category of industrial chemicals, or are in cosmetics and other personal care products. Chemicals are used in almost all manufactured articles to enhance appearance or performance. Impurities or by-products derived from the manufacturing process may also be present.

Most types of chemicals eventually end up as waste. Chemicals produced during manufacturing and other activities may be disposed of on land, incinerated, or treated by physical or chemical means. Other chemicals end up as waste in discarded products. The harmful health and environmental effects of some chemicals in products have been discovered after the products were already in wide use. Examples include brominated flame retardants, some plastic additives, and perfluorinated compounds. Some chemicals used in products can interfere with hormonal systems and have adverse impacts on human and wildlife, including foetal development (UNEP/SAICM 2011, UNEP 2012a).

Young children are especially vulnerable to some chemicals in consumer products. Exposures that might have little effect in an adult can produce irreversible damage in a foetus, infant or child. *Credit: Grish*

Some hazardous chemicals, including pharmaceuticals and those in personal care products, are released directly to the environment, intentionally or unintentionally (Kierkegaard et al. 2012, Parolini et al. 2012). The presence of such contaminants in drinking water is a source of growing global concern (Piel et al. 2012, Radović et al. 2012). Also of growing concern internationally is electrical and electronic waste (e-waste), due to its rapidly increasing volume and the serious risks for human health and the environment presented by the many different chemicals it contains **(Box 1)**.

When products are used or discarded, the chemicals they contain are released to the environment **(Box 2)**. The ways chemicals enter the human body include inhalation, absorption through the skin and ingestion **(Figure 2)**. Many human health effects are causally associated with environmental exposures to certain

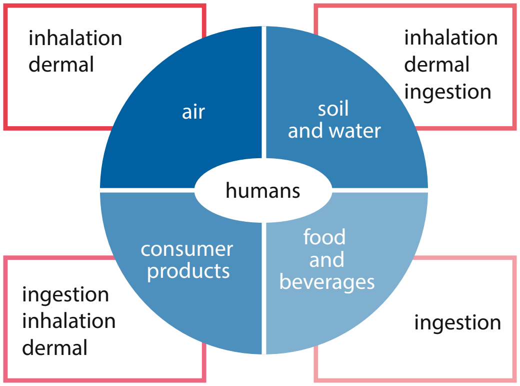


Figure 2: Possible exposure media and ways people come into contact with chemicals. Releases to air, soil and water may occur at any point in a chemical's lifecycle. *Source: Adapted from WHO (2010)*

Box 1: How can e-waste processing be made less dangerous?

E-waste contains valuable and scarce materials that can be reclaimed and recycled, but also hazardous substances that need special handling (Tsydenova and Bengtsson 2011). Dangerous practices such as open burning and acid baths are common in informal e-waste processing (Chan and Wong 2012, Sthiannopkao and Wong 2012). Workers, their communities and the environment are exposed to hazardous chemicals through air and water pollution and contaminated soil (Asante et al. 2012). Larger facilities, with appropriate technology, may meet higher health and safety standards through improved emission control, but there are health and safety risks even at such facilities (Nimpuno and Scruggs 2011).

E-waste processing can be highly profitable. Revenues from global e-waste recovery could reach US$14.6 billion by 2014 (Wolfe and Baddeley 2012). In principle, reuse and recycling can contribute to sustainable development by extending the lifetime of equipment, product parts and material. However, a large share of the e-waste exported from industrialized to developing countries, mainly in West Africa and Asia, is misrepresented as reusable equipment or donations instead of hazardous waste.

Protection of workers largely depends on understanding the chemicals present in production. Electronics stakeholders at different stages of the lifecycle of products need information on the chemicals in these products. Best practices for electric and electronic products include ways to decrease or eliminate use of hazardous chemicals; business standards and practices for tracking, handling and disclosing hazardous chemicals at the manufacturing, use and end-of-life stages; provision of information on potential safer alternatives; and green purchasing initiatives (IISD 2012, Lundgren 2012).

E-waste processing area in Taizhou, China. The volume of e-waste in the world is increasing rapidly, with current production at around 40 million tonnes per year. *Credit: Jiangjie Fu*

chemicals and chemical mixtures, including cancer, respiratory disorders such as asthma, neuropsychiatric and developmental disorders, birth defects, and endocrine diseases and diabetes (Prüss-Ustün et al. 2011, UNEP 2012a) **(Table 1)**.

Susceptibility to chemicals varies from person to person (Forestiero et al. 2012). In addition to genetic diversity, important differences in vulnerability are related to sex, nutrition and stages of life. The developing foetus, infants and children are especially susceptible to toxic chemicals (Landrigan and Goldman 2011). Their rapidly developing organs are immature and, compared to adults, children drink and eat more and breathe more air per unit body weight. People's vulnerability to hazardous chemicals may also vary according to their social roles and gender (UNDP 2011). Workers are particularly at risk, with migrant workers, those in the informal sector, and child labourers bearing a disproportionate burden. Vulnerable groups including children, women, workers, the elderly and the poor can be irrevocably damaged by hazardous chemicals, such as certain metals **(Box 3)** or brominated flame retardants and bisphenol A (BPA), a compound whose hormone-like properties have raised concerns about its suitability in consumer products and food containers (Rudel et al. 2011, Trasande et al. 2011, Channa et al. 2012).

In assessing the risks of the adverse health and environmental impacts of chemicals, the questions that need to be answered include: What are the dangers of these chemicals? How many, and how much, of these chemicals are released to the environment? And who or what (people or the environment) is being exposed? Knowledge of the environmental fate of chemicals, and pathways to human and environmental exposure, includes: releases to the environment; transport; distribution among different environmental compartments (air, water, soil, sediments, biota); transformation; and degradation. Depending on the chemicals' physicochemical properties, associated with persistence, they can be metabolized to other chemicals, bioaccumulated, and biomagnified through the food web.

Table 1: Some major health impacts associated with environmental exposures to chemicals and other environmental stressors. *Source: Adapted from EEA (2005)*

Health impact	Associations with some environmental exposures
Infectious diseases	Water, air and food contamination Climate change-related changes in the lifecycle of pathogens
Cancer	Air pollution Some pesticides Asbestos Natural toxins (aflatoxins) Polycyclic aromatic hydrocarbons Some metals, e.g. arsenic, cadmium, chromium Benzene Dioxins
Cardiovascular diseases	Air pollution Carbon monoxide Lead
Respiratory diseases, including asthma	Sulphur dioxide Nitrogen dioxide Inhalable particles Ground-level ozone Fungal spores Dust mites Pollen
Skin diseases	UV radiation Some metals, e.g. nickel Pentachlorophenol Dioxins
Reproductive dysfunctions	Polychlorinated biphenyls (PCBs) DDT Cadmium Phthalates and other endocrine disruptors Pharmaceuticals
Developmental (foetal and childhood) disorders	Lead Mercury Cadmium Some pesticides Endocrine disruptors
Nervous system disorders	Lead PCBs Methylmercury Manganese Some solvents Organophosphates
Immune response	Some pesticides

Mercury, for example, is transformed by aquatic micro-organisms into methylmercury and bioaccumulates in fish, sometimes reaching tens of thousands of times the concentration originally present in water **(Figure 3)**.

Persistent Organic Pollutants (POPs), controlled under the Stockholm Convention, are a group of chemicals that are particularly persistent and bioaccumulative. They can cause severe damage, including through cancer, eggshell thinning and disruption of organisms' endocrine systems (Fredslund and Bonefeld-Jørgensen 2012). POPs can travel long distances, far from where they were produced and used, thus creating transboundary challenges to their regulation.

Recent findings suggest that cycling of chemicals between environmental compartments is increasingly influenced by the effects of climate change (UNEP-AMAP 2011, Kallenborn et al. 2012). For example, higher temperatures will increase secondary emissions of POPs to the air by shifting partitioning of the POPs between air and soil, and between air and water. Releases from environmental reservoirs such as soil, water and ice will also increase due to increasing temperatures. The impact of temperature on emissions of semi-volatile POPs is probably the most important effect of climate change on the environmental cycling of POPs (UNEP-AMAP 2011).

International chemicals governance

Sound management of chemicals requires co-operation among countries, including sharing of information and experience, adoption of common chemicals control policies, and strengthening capacity. Chemicals are currently addressed in 18 multilateral environmental agreements (MEAs). The Stockholm Convention on POPs, for example, regulates some of the chemicals that present the greatest risks to humans and wildlife. Other MEAs whose purpose is to reduce exposure to hazardous chemicals include the Basel Convention, the Rotterdam Convention, and the Montreal Protocol on Substances that Deplete the Ozone Layer. A new legally binding treaty on mercury (Minamata Treaty) has just been agreed.

Some of these agreements are chemicals based (Montreal, Stockholm, Minamata) while others are lifecycle stage based (Basel, Rotterdam). The Stockholm, Basel and Rotterdam Conventions **(Box 4)** increasingly work together as a chemicals and waste "cluster", enhancing their effectiveness at national, regional and global levels (UNDESA et al. 2011).

Box 2: Chemicals in the environment

Some chemicals, like pesticides, were developed to kill insects, rodents, weeds or other organisms. As the environment is an open system, they may also have adverse impacts on non-target organisms, including bees and insect-eaters (Gil et al. 2012, Tu et al. 2013). After chemicals are released to the environment, they can be transported through air, water and soil. Transport by wind and water currents has led to widespread distribution and transfer of significant amounts of persistent chemicals as far as the Arctic and Antarctic (Scheringer 2009). Persistent chemicals can bioaccumulate and biomagnify through the food web, leading to higher levels of exposure in predator species (Ondarza et al. 2012).

Once chemicals are in the environment, it can be extremely difficult to control or remove them. Persistent, bioaccumulative and toxic (PBT) chemicals have particularly long-term effects on ecosystems that go beyond individual organisms. Endocrine disruptors, for example, can affect organisms' reproduction and have a direct impact on population growth (Blazer et al. 2012).

A large share of man-made chemicals eventually reaches the aquatic environment. Water bodies receive pollutants from diffuse sources such as agricultural runoff, as well as point sources such as sewage treatment plant effluent, and so are contaminated with complex, ill-defined mixtures of chemicals. In some cases, pollution with endocrine-disrupting substances has had dramatic effects on aquatic organisms, such as occurrence of intersex in fish (Sumpter and Jobling 2013). Tributyltin is implicated in the masculinization of female molluscs and fish (McGinnis and Crivello 2011) and oestrogens are thought to be the major cause of feminization in male fish (Baynes et al. 2012, Zhao and Hu 2012). Some effects of chemicals on ecosystems may still be undiscovered. It is not certain which chemicals pose the greatest risks to aquatic organisms, or what factors make some aquatic ecosystems more susceptible than others, for example to bioaccumulation (Sumpter 2009).

A wide range of uncertainties make environmental protection a challenge. In the case of multiple stressors, chemicals may be a factor affecting the resilience of ecosystems by weakening species' immune systems and making them more prone to, for example, fungal disease, competition from alien species, or changes in the environment. Sound data and information on the potential hazards of chemicals, including their properties and behaviour in the environment, need to be available and accessible in order to assess and manage their risks.

Tributyltin compounds are covered by the Rotterdam Convention, and the use of tributyltin as an antifouling agent on ships is banned by the International Maritime Organization (IMO). However, such measures require time to come into effect and to produce results. Moreover, measures are often taken on a chemical-by-chemical basis, responding to emerging scientific evidence. Chemicals management is therefore not keeping pace with the introduction of chemicals in the environment.

Mink frog with extra limb discovered in Minnesota, United States. Such deformities found in amphibians at various North American locations are possibly associated with the presence of certain chemicals in the environment. *Credit: USGS*

Pesticide spraying in a rice field, Karawang region, Indonesia. Most people in the world who apply pesticides do not use necessary protection.
Credit: Beawiharta/Reuters

Box 3: Health and environmental hazards of metals

A number of metals pose significant threats to human health and the environment. Some are necessary in small quantities for good health, but can cause acute or chronic toxicity in larger amounts (Phoon et al. 2012). Other metals, such as lead and mercury, cause significant damage even in small quantities. Aquatic organisms show a host of sub-lethal effects at increased metal levels, including changes in tissues, suppression of growth, poor swimming performance, reduced enzyme activity, behavioural changes, and changes in reproduction.

Sources of metal pollution include surface runoff from mining, fossil fuel combustion, domestic wastewater, solid waste incineration, use in products such as fuel and paint, and many industrial activities. Urban stormwater runoff often contains lead and other metals from roadways. Leaded fuel has been phased out in almost all countries. However, ongoing sale of leaded paint in many developing countries remains a serious concern (Weinberg and Clark 2012). Gold ore processing has led to a large number of cases of lead poisoning. In 2010 in Zamfara State, Nigeria, for example, 400 children died due to exposure to lead in gold ore, with 2 000 other children under treatment (Lo et al. 2012).

Mercury, whose emissions will be controlled under the new Minamata Treaty, presents a major health risk worldwide. It is released to the atmosphere from industrial activities such as metal and cement production, manufacture of vinyl chloride monomer, municipal waste incineration, fossil fuel combustion and mining. Some 10-15 million miners around the world are exposed to mercury (UNEP 2013). Mercury is used in a variety of products, including some computer monitors, some batteries, automobile switches, thermostats, medical devices and compact fluorescent light bulbs. When these products are disposed of or broken, the mercury can be released into the environment. Total mercury emissions were estimated at 1 960 tonnes in 2010 (UNEP 2013).

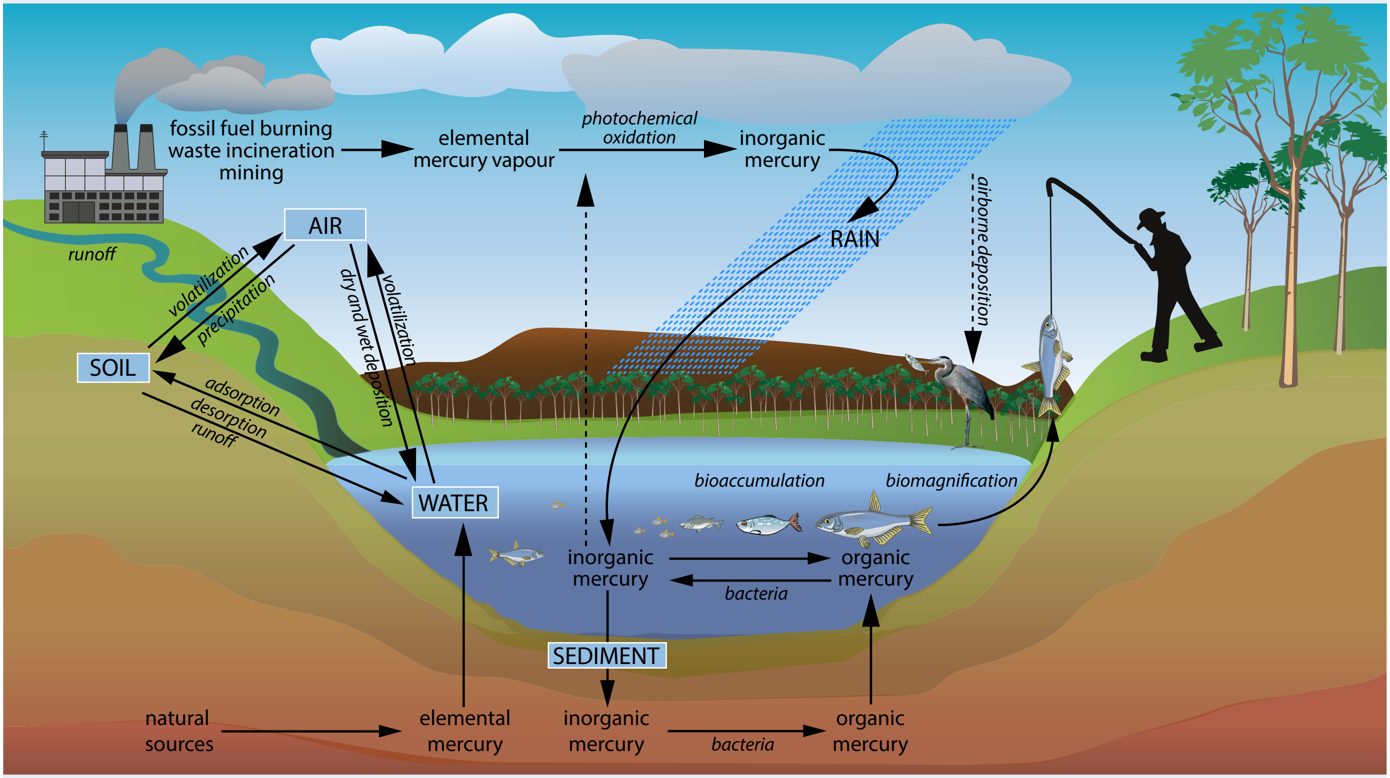


Figure 3: Mercury contamination affects people along several environmental pathways. Highly toxic methylmercury is formed in wet soil, sediments and water, where it bioaccumulates and biomagnifies. Fish consumption is a main route of human exposure. Infants, children and women of child-bearing age are particularly vulnerable to adverse health effects, which include permanent damage to the nervous system. Mercury can be transferred from mothers to unborn children.

Box 4: The Stockholm, Basel and Rotterdam Conventions

The **Stockholm Convention** on the protection of human health and the environment from Persistent Organic Pollutants (POPs) came into force in 2004. It restricts and ultimately aims to eliminate the production and use of listed chemicals. This Convention also promotes the use of both chemical and non-chemical alternatives to POPs. Twelve chemical compounds – "the dirty dozen" – were on the Convention's original list of POPs. They included pesticides such as the insecticide DDT, although its use to fight malaria is still allowed, as are unintended releases to the environment of listed chemicals such as the combustion products dioxins and furans. To date, ten more POPs have been added to this list and others are under review.

The **Basel Convention** on the Control of Transboundary Movements of Hazardous Wastes and their Disposal aims to protect human health and the environment, with strict controls, against the adverse effects which may result from the generation and management of hazardous waste and other wastes. It was adopted in 1989 in response to the discovery in the previous decade of the extent of imported toxic wastes in Africa and other parts of the developing world and came into force in 1992.

The **Rotterdam Convention** on the Prior Informed Consent Procedure for certain hazardous Chemicals and Pesticides in international trade entered into force in 2004. It promotes shared responsibility and co-operative efforts among Parties in the international trade of certain hazardous chemicals, in order to protect human health and the environment from potential harm and contribute to the environmentally sound use of these chemicals by facilitating information exchange about their characteristics, providing for a national decision-making process on their import and export, and disseminating these decisions to Parties.

To make optimal decisions on how to protect human health and the environment, governments, industry and the public need more information than is often available to them. This includes information on the amount and types of chemicals used in products, the way chemicals are released from production processes and products throughout their lifecycles, and data on the physicochemical properties, degradability and toxicity of chemicals. For the vast majority of chemicals, this information has either not been generated or is not accessible by the public. A considerable amount of the information is not publicly available, as it is considered to be sensitive information and the intellectual property of the developers of chemicals or their clients (Abelkop et al. 2012).

While the chemical industry continues to expand, only a small percentage of chemicals on the market have been adequately evaluated for their potential health and environmental effects (Judson et al. 2009, UNEP 2012a). Currently, experimental data on degradation half-lives, bioaccumulation potential and toxicity are publicly available for only a small fraction (less than 5 per cent) of industrial chemicals (Schaafsma et al. 2009, Strempel et al. 2012) **(Figure 4)**.

Lack of information is a serious obstacle to the assessment and management of chemical risks. During the 1992 UN Conference on Environment and Development countries identified "lack of sufficient scientific information for the assessment of risks entailed by the use of a great number of chemicals" as a major problem, especially in developing countries (UNCED 1992). Some hazardous substances incorporated in products present little risk during use, but much greater risks during production and waste management. The current situation could be improved through a combination of actions: disclosure of at least some parts of the information on chemicals use and properties that is currently confidential; substance-flow analyses for chemicals in a variety of products, covering all lifecycle properties, degradation half-lives, and toxicity; and compilation of the information generated in databases such that this information is publicly available in a systematic way.

Some progress has been made towards better information provision at the international level and a number of datasets are publicly available. Of particular importance is the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), first published in 2003 and updated every two years (UN 2011). GHS addresses the classification of chemicals by types of hazard and proposes harmonized hazard communication elements, including labels and safety data sheets. It aims to ensure that information on physical hazards and toxicity of chemicals will be available to enhance protection of health and the environment during handling, transport and use. The GHS also provides a basis for harmonization of rules and regulations on chemicals at national, regional and worldwide levels. However, it does not include the establishment of a publically accessible database for safety data sheets, nor does it address the need for information about chemicals in products.

At the 2002 World Summit on Sustainable Development in Johannesburg, countries agreed that by the year 2020 "chemicals

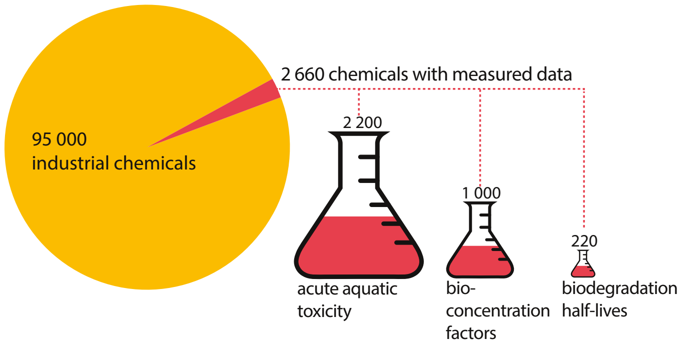


Figure 4: Out of a set of 95 000 industrial chemicals, very few had data on acute aquatic toxicity, the extent to which they build up in the environment (bioconcentration factors), or how long it takes them to break down (biodegradation half-lives). *Source: Adapted from Strempel et al. 2012*

should be produced and used in ways that minimize significant adverse impacts on human health and the environment". So far, progress towards reaching this goal has been limited (UNEP 2012a, b). Lack of adequate information on chemicals, mainly as a result of failure to require generation of the relevant information and disclose it, remains a major problem. The United Nations Conference on Sustainable Development (Rio+20) in 2012 reaffirmed the 2020 goal. It recognized that growing global production and use of chemicals and their prevalence in the environment call for increased international co-operation. It also expressed concern about the lack of capacity for sound chemicals management, particularly in least developed countries (UN 2012).

To achieve the 2020 goal, the Strategic Approach to International Chemicals Management (SAICM) has been developed as a policy framework whose overall purpose is strengthening sound management of chemicals throughout their lifecycle. In 2012, the third International Conference on Chemicals Management (ICCM3) reviewed progress and considered further actions on emerging policy issues including chemicals in products, removal of lead in paints, hazardous substances in electrical and electronic products, and nanotechnology and manufactured nanomaterials. It also considered perfluorinated chemicals and agreed to co-operative actions on endocrine disrupters. Transparency and sharing of data and information will be essential to make real progress in these areas (IISD 2012).

Ongoing and emerging challenges

The number of man-made chemicals in the environment is increasing. Since 1999, the presence of chemicals in the blood and urine of a sample of the population of the United States has been monitored. In 2009, 212 chemicals were reported, including 75 not previously measured (CDC 2009). Findings from the study indicated widespread exposure to some industrial chemicals; 90 to 100 per cent of samples assessed had detectable levels of substances including perchlorate, mercury, BPA, acrylamide, multiple perfluorinated chemicals, and the flame retardant polybrominated diphenyl ether-47. Recently, measurements for 66 of the chemicals were updated and an additional 34 chemicals were found to be present (CDC 2012). These data provide a good indication of the increased presence of chemicals in the environment. They show that despite widespread efforts to improve the knowledge on chemical risks and ways to manage them, we only partially understand the fate and impacts of chemicals in the environment. Because similarly comprehensive biomonitoring programmes are not being carried out in developing countries, these data are an important source of information on the extent to which chemicals may be present in the human body. Such data also point to what could be expected to happen in developing countries as manufacturing and use of chemicals in these countries intensifies.

Simulated nicotinoid pesticide exposure of a free-ranging forager honey bee labelled with a radio-frequency identification tag. *Credit: © INRA/C. Maitre*

Mixtures

People and ecosystems are exposed to mixtures of tens or hundreds of chemicals from a wide range of sources. Some chemicals are more harmful in combination with other chemicals than they are individually, even when the levels of individual chemicals are considered safe. Due to practical limits on measuring ecotoxicological effects, it is difficult to study interactions between more than two or three chemicals. Mixture effects have therefore become a major challenge for scientists and policy makers (EU 2012, Sarigiannis and Hansen 2012).

Empirical evidence provided by human toxicology and ecotoxicology has repeatedly demonstrated mixture effects. It strongly supports the need to take these combined effects into consideration in estimating acceptable human and environmental exposures. New approaches to toxicological testing, such as examining chemical interactions with a focus on the molecular and cellular level, are expected to provide a deeper understanding of toxicity and its health impacts (NIEHS 2011, Kavlock et al. 2012, Rider et al. 2012).

Low-dose exposures

An increasing body of scientific evidence indicates that many chemicals have biological effects at doses previously considered negligible (Vandenberg et al. 2012). For most chemicals, acute effects were originally noted at high doses. It is increasingly evident that more subtle deleterious effects can occur due to longer-term exposure to relatively low doses of chemicals, individually or in mixtures (Birnbaum 2012). The risks created by exposure to a low dose of an individual chemical from multiple pathways are referred to as "aggregate" risks. Cumulative risk assessment (studying risks created by aggregate exposure to multiple pollutants) is a developing approach to addressing low-dose exposures (Meek et al. 2011, Alexeeff et al. 2012).

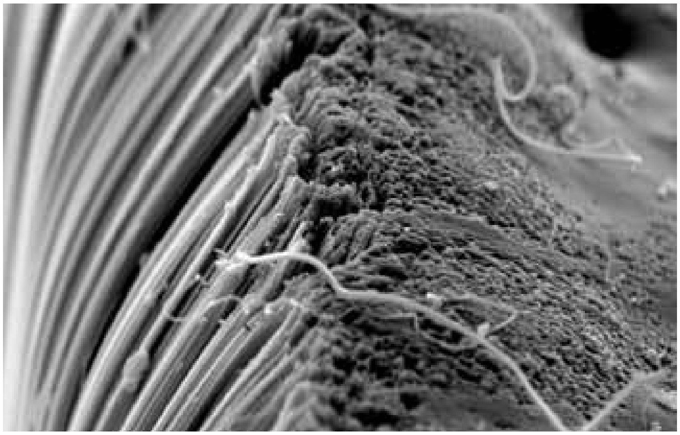
New concerns have recently been raised about the impact of pesticides on non-target organisms including insects, especially bees, and amphibians (Brühl et al. 2013). Studies suggest that low doses of neonicotinoids, a group of neurotoxic chemicals widely used in many countries as insecticides, could have sub-lethal effects on honey bees (Henry et al. 2012) and bumble bees (Whitehorn et al. 2012) with serious consequences for wild populations of these crucially important pollinators and therefore for agriculture and the environment (UNEP 2010, Rozen 2012). It has also been suggested that detailed investigation of the effect of neonicotinoids on mammalian brain function, especially brain development, is needed to protect human health, especially that of children (Kimura-Kuroda et al. 2012).

Replacing hazardous chemicals by similar ones

When efforts are made to eliminate a highly hazardous chemical in products, manufacturers frequently substitute another hazardous chemical in its place (DiGangi et al. 2010, Covaci et al. 2011). Often, these replacements create relatively unstudied health and environmental concerns that may differ little from those of the chemicals they replace. A "lock-in" problem exists when one chemical from a group of structurally similar chemicals is removed from the market and replaced by other chemicals from the same group, so that no true replacement takes place (Strempel et al. 2012). For example, polybrominated diphenyl ethers (PBDEs) are replaced by other brominated flame retardants, polychlorinated biphenyls (PCBs) replaced by short-chain chlorinated paraffins, and less-studied and unregulated halogenated solvents adopted in place of ones that have been extensively studied (OSHA 1999, Stockholm Convention 2012).

Nanotechnology

Nanosizing materials can give them different inherent chemical and physical properties. This challenges existing hazard identification approaches, which assume that the intrinsic property of a chemical can be discovered through studies of the bulk material. For example, from a chemical perspective carbon nanotubes are simply carbon, but in their nanotube form they present significant new hazards because of their shape and size (Maynard et al. 2011). Studies have shown evident toxicity of some nanoparticles to living organisms and ecosystems (Love et al. 2012). However, lack of available data and the inadequacy of current experimental protocols and risk assessment procedures make comprehensive risk assessments difficult to perform (Gajewicz et al. 2012, EEA 2013).



Scanning electronic microscope image of carbon nanotubes, which may present new risks due to their shape and extremely small size. *Credit: Anastasios John Hart, University of Michigan, United States*

New opportunities for testing and assessment

Since the 1960s, the steep rise in production of man-made chemicals has coincided with the development of increasingly sensitive analytical equipment and growing concerns about health and environmental effects, starting in 1962 when Rachel Carson's book *Silent Spring* was published (Ohandja et al. 2012). Today we know much more about chemicals, including their toxicity, pathways and environmental fate, than a few decades ago. With new technology, increasingly small amounts of chemicals can be detected in the environment. This allows earlier detection and better risk management. However, advances in technology also show our knowledge is far from complete, as additional contamination issues emerge with advancing analytical methods.

Monitoring chemicals in the human body and in the environment can help identify and track human and environmental exposure to chemicals and hence the results of chemical management. Particularly useful in early detection of adverse impacts in people and organisms, before overt damage has occurred, is the use of biological markers of exposure, effect and susceptibility. Monitoring in ecological systems is useful to determine how chemicals migrate in the environment, accumulate in animals and plants, and settle in sediments and soils. The importance of continuous, long-term measurement series for future generations cannot be overestimated. The Experimental Lakes Area (ELA) in Canada is a unique example of a "field laboratory" where long-term, ecosystem scale monitoring and experimentation have been carried out since 1968 (Blanchfield et al. 2009).

Models help to estimate exposure throughout an area of impact, and to determine where to place monitors optimally to assess whether chemical releases exceed allowable levels. Contaminant fate models are often used to predict levels of chemicals in air or water resulting from expected or unwanted chemical releases. These models are effective tools in various contexts, from plant siting and emergency response planning to chemical exposure assessment, but they need to be validated using actual measurements (MacLeod et al. 2010).

Advances in computational methods applied to toxicology promise to increase predictability while minimizing the need for costly or time-consuming animal assays (tests exposing organisms to, for example, naturally contaminated water, discharged effluents or sediment samples). Knowledge of quantitative structure-activity relationships (QSARs) can often, but not always, predict toxicity (OECD 2012). New assays based upon advances in molecular biology permit a fuller understanding of the effects of chemical perturbations in biological systems (Kavlock et al. 2012) **(Box 5)**.


Aquatic biomonitors use fish and their breathing patterns to detect the presence of potentially toxic substances in water. *Credit: United States Army Center for Environmental Health Research*

Identifying chemical sources, and using models and assessments to understand their impact, is important to underpin the work of international Conventions and Protocols. Improved measurement and analytical techniques allow chemicals to be identified and quantified more rapidly and accurately than in the past. They also reduce the costs of implementing and carrying out measurements. Assessments provide the basis for understanding the relative contributions of different sources and ranking actions that address the most important environmental releases.

Box 5: Predictive toxicology

Predictive toxicology aims at understanding the relation between the structure of a chemical and its effects, and at detecting the potential for risks before the chemical is produced or released. It includes tests for chemical and physical characteristics, such as flammability, and tests that point to the likelihood that the chemical produces mutations, reproductive or developmental effects, or readily enters the food chain. A new programme combines the insights of molecular toxicology with high throughput technology derived from the pharmaceutical industry to improve the prediction of the toxicity of large numbers of chemicals (Martin 2012). Validation of this new approach is in progress (Kavlock et al. 2012). If successful, this programme will provide better tools for the chemical industry and for regulators to disclose unwanted consequences of new or existing chemicals.

The costs of inaction

The production, use, storage, transport and disposal of chemicals and products containing chemicals result in a variety of external costs that are generally not (or not fully) borne by the companies that carry out these activities (UNEP 2012a). Examples include: maintenance of emergency response infrastructure; clean-up of contaminated sites; emergency and long-term care for individuals harmed by chemical exposures; home or institutional care and special education services for people with developmental problems; loss of value of contaminated real estate; loss of fishing, hunting, and farming opportunities; loss of safe water supplies; and water treatment and purification to remove chemical contaminants.

Costs associated with the risks of chemicals are difficult to assess. Nevertheless, the findings of studies that have estimated health and environmental costs support the urgency of risk minimization (Prüss-Ustün et al. 2011, Hutchings et al. 2012, UNEP 2012a). Chokshi and Farley (2012) reported that the cost-benefit ratio of environmental intervention in disease prevention is three times higher than clinical and non-clinical person-directed measures. They also noted the paucity of studies on the cost-effectiveness of environmental interventions.

Trasande and Liu (2011) found that the costs of lead poisoning, prenatal methylmercury exposure, childhood cancer, asthma, intellectual disability, autism and attention deficit disorder in the United States were US$ 76.6 billion in 2008. They estimated that pre-market testing of new chemicals, toxicity testing of chemicals already in use, reduction of lead-based paint hazards, and curbing mercury emissions from coal-fired power plants could prevent further increases in such costs. Another study estimates that preventing exposure to the neurotoxin methylmercury in children would yield an economic benefit of €8 000 to 9 000 million (about US$11-12 000 million) per year in the European Union (Bellanger et al. 2013). Mercury exposure in humans affects brain development, resulting in a lower IQ and, consequently, lower earning potential. The long-term cost to society can be calculated as lifetime earning loss per person.

Depending on the country, some costs may be covered directly by those responsible for them. For example, chemical manufacturers are sometimes taxed to provide funds for the clean-up of contaminated sites (US EPA 2012). In many countries employers provide funds for worker compensation. However, most costs associated with the risks of chemicals are not paid by industry. Therefore, these costs may not be taken into account when companies make decisions about which chemicals to produce and use, and how to manage them. One way to remedy the inefficiencies that result from excluding health and environmental costs is to implement cost internalization mechanisms using certain economic instruments, including fiscal measures or other economic incentives **(Box 6)**.

Box 6: Use of economic instruments

Economic instruments can be used to internalize the costs of chemical management and create financial incentives to improve chemical safety. If these instruments are well conceived, they may also generate public revenues and provide resources needed to fund agency programmes. For instance, in Sweden the costs of the Swedish Chemicals Agency (KemI) are largely borne by the pesticide and other chemical industries through chemical fees. These cover the costs of activities such as inspections and assessments of applications for approval of pesticides (KemI 1998). In 2010, about 57 per cent of KemI's costs were covered by these fees (about 29 per cent from pesticide fees and approximately 28 per cent from general chemical fees). These fees are calculated based on the number of chemical products and the volumes of these products. Firms are required to report to the Swedish Products Register.

In the United States, the Massachusetts Toxics Use Reduction Act (TURA) requires facilities that use more than a specified amount of a toxic chemical to pay an annual fee, which is used to fund chemicals management activities including enforcement, training, research and technical assistance (Massey 2011). California levies a fee on the sale of perchloroethylene (PCE), a garment care solvent, to provide grants and training to help garment cleaners make the transition to safer processes (California Air Resources Board 2012).

Gabon charges a 10 per cent tax on exported waste that it receives, while China charges a fee on industrial pollution that exceeds a base level and invests a portion of that revenue in pollution abatement programmes.

Towards better chemical risk management

Many different types of instruments exist worldwide to reduce chemical risks. Some are anticipatory and aim to avoid the production or sale of chemicals known to be harmful. Others are more concerned with the introduction of changes during the lifecycle of chemicals to protect people and the environment. Chemical disasters have led to the development of preventive approaches and response measures. In addition, specific regulations have been developed concerning toxic chemicals in consumer products. Examples are EU regulations on chemicals in cosmetics and the EU Toy Safety Directives.

Since 2007, the European Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) regulation has aimed to improve protection of human health and the environment and make the use of chemicals safer through better and earlier identification of their intrinsic properties **(Box 7)**. Under REACH, companies that place chemicals on the market are responsible for providing reliable, comprehensive information on the health and environmental hazards of these chemicals. REACH also calls for substitution of the most dangerous chemicals.

Some countries are making information about chemicals and chemical releases more easily available to interested parties and to the public than in the past. For example, the European Chemicals Agency is building a publicly accessible database with information about chemicals. Pollutant Release and Transfer Registers (PRTRs) are another important source of information. PRTRs are national inventories providing data to the public on releases and transfers of potentially dangerous chemicals and other pollutants. Some jurisdictions require companies to report on their use of certain chemicals. In the United States, the states of Massachusetts and New Jersey require annual reporting of toxic chemical use in manufacturing and other industrial facilities (Massey 2011). This approach increases the information available to government agencies and the public, ensures that company managers know what chemicals are being used in large quantities in their facilities, and facilitates identification of potential occupational and other hazards.

Box 7: The European REACH system

The European Registration, Evaluation, Authorisation and Restriction of Chemical Substances (REACH) system regulates industrial chemicals. It does not cover pesticides, biocides or pharmaceuticals, as these are dealt with under other European regulations. Under REACH, businesses that place chemicals on the market in the EU above 1 tonne per year must provide adequate documentation on properties, uses, and safe ways of handling them. Although REACH is still in its early stages and its implementation is challenged by data quality issues (Gilbert 2011), this general approach may serve as a useful model in other parts of the world. Registration of chemicals under REACH takes place between 2010 and 2018. To date, 140 000 chemicals have been pre-registered and full registrations have been completed for some 5 000. A recent assessment by the German Federal Environment Agency and the Federation of German Consumer Organizations found that REACH has had a positive impact during its first five years, but that there are also important areas for improvement. For example, concern was expressed that data submitted by industry did not always fulfil the requirements of the regulation (Flasbarth 2012). These findings highlight the importance of capacity building for adequate implementation and enforcement of requirements.

Measures to strengthen sound chemicals management range from improved government capacity for chemical regulation to increased support for businesses in selecting safer alternatives in product design. A key element is use of an anticipatory approach, whereby chemical risks are identified and prevented up front rather than addressed after damage has occurred (UNEP 2012c). Evolving approaches to protect people and the environment against the unwanted effects of chemicals occur at different levels:

- Prevention of production and use of harmful chemicals through multilateral environmental agreements (MEAs).
- Capacity building to support development of regulatory and other chemicals management infrastructure in developing countries and countries with economies in transition.
- Development of guidelines and systems to ensure transparency about chemical use in industry and in consumer products.
- (Re)design of products and processes in ways that minimize the use and generation of harmful substances, through approaches such as green chemistry, alternatives assessment, and toxics use reduction.
- Process engineering, aiming to prevent releases of chemicals during manufacture, distribution, use and waste treatment.
- Use of monitoring systems to detect chemicals released to environmental media.
- Identification of the health and environmental effects of chemicals through evaluating biological markers of exposure and effects in ecosystems and humans.

The way forward to minimize risks

Sound management of chemicals urgently needs strengthening to avert ongoing damage to human health and the environment and reach the 2020 goal. Reducing the production and use of toxic substances, promoting the development and adoption of safer alternatives, improving information flow and transparency, building capacity for improved chemicals governance, and reducing illegal international traffic in chemicals are key elements of sound chemicals management – with important roles for government, industry, researchers, and civil society organizations **(Box 8)**.

One of the most critical elements of sound chemical management is ensuring that chemicals are tested for their health and environmental effects prior to being placed on the market and incorporated into products. Thus far, chemicals governance activities have largely been reactive. With current trends in mind, a strengthened and more proactive governance approach is required based on science, best practices and lessons learned. Methods used to predict and detect the adverse effects of chemicals are critical to support sound chemicals management. They provide tools for generating essential data and information that can facilitate science-based decision-making.

To minimize the risks of chemicals, more attention should be paid to the earliest stages in their lifecycle, when chemicals are developed and synthesized before they find their way to the market – and when modern tools can be used to test and estimate *a priori* the properties, fate and impact of new chemicals. The value of results and measurements from research organizations, universities, government agencies and industry around the world would increase if they were collected and accessible in a formalized, open-access database. In particular, more effort is needed to obtain data and information on the impacts of chemical mixtures, low-dose exposures, nanomaterials and the impact, migration and transformation of chemicals in natural systems.

To minimize risks from exposure to chemicals and prevent unwanted chemicals entering the environment, more formalized monitoring, labelling and communication are needed. A broadened REACH system covering the full range of chemicals in commerce could be a model for a global system, to be accompanied by capacity-building programmes.

Information on safe use of chemicals (particularly pesticides, certain metals, and chemicals in e-waste) should be easily accessible and disseminated more thoroughly to related occupational groups, especially in developing countries. Safety and hazard preparedness training programmes are also required. Production and transboundary transfers of all chemicals need to be preceded by the compilation and submission of a dossier, by the producer or importer, containing the required data. To make this possible, procedures need to be implemented at the national level, taking into account the international framework for chemicals governance and building on existing procedures and regulations to improve chemicals risk management.

The presence of hazardous chemicals is not always obvious. Pesticides remaining on the human body after spraying can be made visible under special light. *Credit: Richard Fenske*

The outlook for chemicals governance, however, goes beyond technical and regulatory approaches. It begins by asking if there is a need for hazardous chemicals in the first place. In some cases, safer, non-chemical alternatives and approaches are available that are both proven and effective. Examples include integrated pest management, adoption of non-chemical substitutes for POPs, water-based processes for industrial cleaning, and adoption of safer substitutes for toxic flame retardants. Support for the assessment of such alternatives and approaches, and for prioritizing research and development in these areas, will be part of the way forward to better manage chemical risks.

To keep pace with rapid developments and new challenges, chemicals governance needs to benefit from the latest science and speed up testing and registration of chemicals. It also needs to be recognized that impacts occur "from cradle to grave", that production is frequently not located in one place, that both chemical products and environmental residues may be widely distributed, and that impacts vary due to the differing vulnerability of both human populations and ecosystems.

Box 8: Roles of stakeholders in minimizing chemical risks

Governments: Establish clear and consistent guidelines requiring disclosure of information about the hazards and uses of chemicals, estimate the costs of inaction against the risks from chemicals, and build capacity to strengthen sound chemicals management.

Industry: Disclose information about the hazards and uses of chemicals, and consider alternatives when developing chemicals to reduce chemical risks.

Scientists: Compile existing information in publicly accessible databases, and provide coherent interpretations in existing knowledge, identifying inconsistencies and gaps.

Civil society organizations: Gather and organize chemical information, promote the adoption of relevant regulations, help build capacity, and monitor implementation of policy measures.

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