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REVIEW

Environmental chemistry in the twenty-first century

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Abstract Human society actually faces many environmental challenges such as environmental pollution, climate changes and loss of biodiversity. These issues induce major risks for ecosystems and are a serious threat for further life on Earth. Anthropogenic pressure may continue to exacerbate the present-day problems. Prevention and mitigation of environmental issues demands sound science and dedicated political support. For that, environmental chemistry is a central and multidisciplinary science that will provide new concepts and applied methods to solve actual environmental issues. Here, we outline the scope of environmental chemistry. The Anthropocene era and major chemical disasters are discussed. We present also the challenges of atmospheric chemistry, analytical chemistry, statistics and chemometrics, and education in environmental chemistry.

Keywords Chemistry · Ecology · Ecotoxicology · Environmental chemistry · Environmental science · Scientific discipline

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Introduction

Human society in the twenty-first century faces major environmental problems such as global climate change, pollution and extinction of plants and animals. These problems are interconnected and have stemmed from human population explosion, excessive use of natural resources, industrialization and urbanization. Consequences of these problems are threats to ecosystem and human health. As a central science, chemistry is essential to identify, understand and solve environmental challenges. Accordingly, environmental chemistry is becoming an increasingly important scientific discipline in the twenty-first century.

According to Baird and Cann (2012), "environmental chemistry deals with reactions, fates, movements and sources of chemicals in air, water and soil." It is a fast-emerging discipline, which aims at understanding the fate of pollutants in ecosystems (Lichtfouse et al. 2012). The major task of environmental chemists is to keep eye on the changes occurring in the natural environment because of its interactions with chemicals (Hussein 2014). Furthermore, chemists have to help others in understanding natural and man-influenced processes and to make them cooperate in reducing and adapting to any negative consequences (Shakhashiri and Bell 2014). This science often produces results having a clear and important message for us (Francesconi 2012).

The environmental impact of humans may be estimated by using the environmental impact model summarized in the following relation (Baird and Cann 2012; Miller and Spoolman 2010):

$$I = P \times A \times T$$

where I—environmental impact, P—population, A—affluence and T—technology.

In the above relation, the behavior of the variables *A* and *T* is not simple, i.e., not always (positive) linear. They do not necessarily cause a negative impact on the environment. The relation implies that environmental impact is a function of human population, affluence and technology. The role of affluence or resource consumption per person depends on consumer behavior and is different for developed and developing countries. The role of technology depends on the nature of the technology, i.e., whether its use leads to environmental protection or environmental degradation.

Another conceptual framework for environmental impact is the Drivers–Pressure–State–Impact–Response (DPSIR). Ecosystem-based management (EBM) should focus on ecosystem services, and including these services into holistic management approaches improves management (Kelble et al. 2013). Kelble et al. (2013) had proposed a conceptual model which merges the broadly applied DPSIR conceptual model with ecosystem services to yield a Driver, Pressure, State, Ecosystem service and Response (EBM-DPSER) conceptual model. While the DPSIR model informs ecosystem management to protect ecosystems from human impacts, the EBM-DPSER model aims to effectively inform ecosystem management for the benefit of humans. By highlighting ecosystem services, this model emphasizes the reliance of human society on ecosystems and the benefits to humans from ecosystems. Similarly, Yee et al. (2012) proposed an integrated DPSIR framework by incorporating environmental and human health into a single framework. Such a framework will be helpful in developing a research program that will help decision-makers to endorse such policies which promote sustainable and healthy communities. For different derivative schemes of the DPSIR-type conceptual framework, see recent review by Patrício et al. (2016).

Environmental chemistry is a relatively young science. Research on the impacts of chemicals on the environment and human health mainly started after the publication of Rachel Carson's influential book "Silent Spring" in 1962. The scope of environmental chemistry is growing as we progress in the twenty-first century. This science is more close to our daily lives as remarked by Jardim "environmental chemistry is perhaps the branch of chemistry that has more links to the daily life aspects than any other subject" (Jardim 1998). The earth–air–water system has been called by Liss and Raiswell as a "gigantic chemical factory" (Liss and Raiswell 1982). Changes in the composition and properties of this system will not be without consequences for the inhabitants of the planet Earth.

Environmental chemistry is a broad field of research. It covers a broad range of topics, from formation and destruction of zone in the stratosphere to concentrations of contaminants in different environmental segments. It also deals with sediments, ice and biota. It also considers different factors and processes in addition to contaminant concentrations. Some of these factors and processes are environmental factors, e.g., pH, temperature, availability of oxygen; degradation and transformation; bioavailability; transport and migration; distribution; bioaccumulation; and biomagnification. The toxicity of a particular environmental chemical in a particular environment depends not only on its total concentration but also on several other factors such as its speciation, bioavailability and presence or absence of its agonists and antagonists. The study of environmental chemistry requires background knowledge of many other scientific disciplines in addition to knowledge of chemistry. This review article comprehensively outlines the science of environmental chemistry. It will serve as a useful guidance for researchers in general and also as an educational resource for students at both undergraduate and graduate levels. First we begin with environmental chemistry sphere (Fig. 1) and then go to an introduction of the Anthropocene era.

The Anthropocene era

Now we are living in an era where humans have a substantial impact on the planet. We have changed the "Natural Capital", which includes natural resources and natural services. We have made excessive use of natural resources and therefore affected natural services. The current unsustainable use of nonrenewable resources especially of fossil fuels has affected our life-support system. Anthropogenic activities have resulted in many environmental problems such as air pollution, acid rain, stratospheric ozone loss, enhanced greenhouse effect, global warming and global climate changes, and disturbance of natural biogeochemical cycles. These problems have severe consequences for life on earth. These environmental problems have affected biodiversity, ecosystem and human health. Thus, humans have become a geophysical force and have a significant impact on the planet. So this human activity-dominated era where humans have become an important geophysical force on the planet is said to be a new era started after the loss of the Holocene.

The term "Anthropocene" was coined by the Nobel Laureate in Chemistry 1995, Crutzen (2002), where he initially proposed that the Anthropocene probably started in the latter part of the eighteenth century, when analyses of air locked in polar ice revealed the start of growing global concentrations of CO_2 and CH_4, the time being in coincidence with James Watt's invention of the steam engine in 1784. Anthropocene is the proposed name for the present geological epoch where humans are a geophysical force of planetary importance and which is heavily affected by human activities (Williams and Crutzen 2013). The Anthropocene signifies a new chapter in the history of both mankind and of the planet Earth and is geologically a

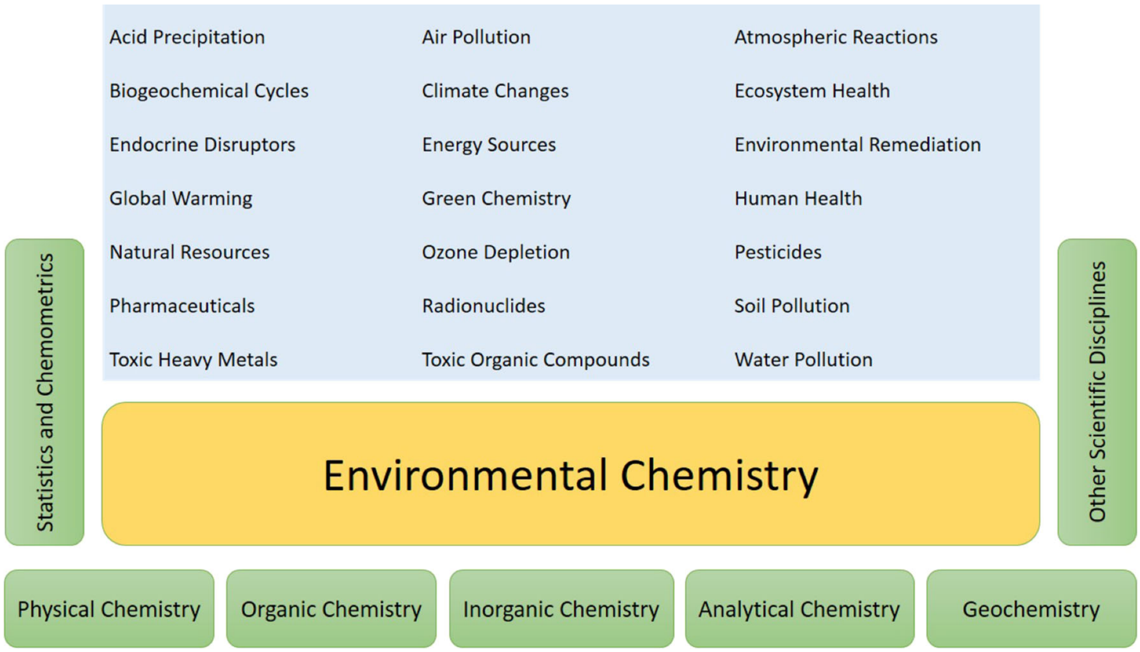


Fig. 1 Sphere of environmental chemistry. Some areas covered in environmental chemistry have been shown. Environmental chemistry stands on the four traditional areas of chemistry and on geochemistry; however, owing to its interdisciplinary nature, it also uses knowledge and information from many other scientific disciplines

remarkable episode in the history of the planet. It presents challenges for both science and the society (Zalasiewicz et al. 2010). Human influence on the planet Earth is likely to have important and long-term consequences (Zalasiewicz et al. 2011).

Environmental chemical disasters

Human society in the twentieth century has witnessed some major environmental chemical disasters. The following examples are noteworthy:

- Minamata disease
- Acid rain
- Antarctic ozone hole
- Bhopal gas tragedy
- Chernobyl accident
- Exxon Valdez oil spill
- Donana mining catastrophe

Table 1 summarizes these disasters.

Acid precipitation had become top environmental problem in Norway. Precipitation over much of southern Scandinavia contained large quantities of H^+, SO_4^{2-} and NO_3^-. The pH of many lakes was below 5.0, and SO_4^{2-} was the major anion instead of bicarbonate. The source of the pollutants was a continued increase in consumption of fossil fuels in the highly industrialized areas of Great Britain and Central Europe. Decline in fish populations was well documented. Fish were eliminated from lakes and rivers due to steady increases in acidity with resulting interference in reproduction and spawning (Wright et al. 1976).

These are not the only environmental chemical disasters happened on the planet; they are probably the worst of their kinds. For example, in addition to Minamata disease in Japan, an epidemic of methylmercury poisoning occurred in 1971–1972 in Iraq in farmers and their families when they were exposed to the compound by eating bread made from wheat seed treated with a methylmercury fungicide. A total of 6530 cases were admitted in hospitals, and 459 hospital deaths were attributed to the said poisoning. Similarly, poisoning incidents have occurred in Pakistan and Guatemala due to consumption of flour and wheat seed treated with methyl- and ethylmercury compounds (Bakir et al. 1973). Thus, we should practice our science more responsibly. The science of environmental chemistry is such a mirror, which shows us the dark faces of science, especially of (conventional) chemistry and forces the chemical industry to practice environment-friendly chemistry. This science cares for all the inhabitants of the planet.

The interdisciplinary nature of environmental chemistry

Environmental chemistry is truly interdisciplinary in nature. While basically a chemistry, it is at the crossroad of physics, chemistry, geology and biology (Fig. 2a). The

Table 1 Some major environmental chemical disasters of the twentieth century

S. no	Disaster	Chemical(s) involved	Place	Date	Environmental/ecological damage	Reference(s)
1	Minamata disease	Methyl mercury (MeHg)	Minamata Bay, Japan	The disease was first officially discovered in May 1956 in Minamata City	Development of Minamata disease in the fish-eating population. Of the 2252 officially recognized patients, 1043 died	Harada (1995)[a]
2	Acid rain	SO_2 and NO_x	Scandinavia	1960s	Decline in fish populations in lakes and rivers	Pyatt (1987), Wright et al. (1976)
3	Antarctic ozone hole	Chlorofluorocarbons (CFC)	Antarctica	Since early 1980s	–	Abbatt and Molina (1993), Rowland (1991, 2006), Solomon et al. (1986)
4	Bhopal gas tragedy[b]	Methyl isocyanate gas	Bhopal, India	Night of December 02-03, 1984	>2000 lives lost in first few days, and several thousand suffered from morbidity and permanent disabilities	Mittal (2016), Sriramachari (2004)
5	Chernobyl accident[c]	Radioactive material (80 petabecquerel [PBq] of ^{137}Cs, ^{90}Sr, ^{239}Pu and other radioactive isotopes) polluting 200,000 km^2 land in Europe	Chernobyl, Ukraine	April 26, 1986	Increased incidence of thyroid cancer/carcinoma in children and adolescents in Ukraine	Cardis et al. (2006), Møller and Mousseau (2006), Tronko et al. (1999)
6	Exxon Valdez oil spill	260,000 barrels of crude oil	Prince William Sound, Alaska	March 24, 1989	100,000–300,000 (according to Piatt et al.), 250,000 (according to Piatt and Ford) marine birds killed[d]	Piatt et al. (1990), Piatt and Ford (1996)
7	Donana mining catastrophe	~5 million m^3 of acid pyrite sludge rich in Zn, Pb, Cd and As	Spain	April 25, 1998	Massive fish, invertebrate and bird mortalities	Meharg et al. (1999)

[a] For an original account of Minamata disease, interested readers are referred to articles by McAlpine and Araki (1958, 1959)

[b] This was the worst chemical disaster in history. Methyl isocyanate (MIC) was used in the manufacturing of the carbamate pesticide carbaryl (Sevin) in Union Carbide factory in Bhopal, India. Detailed description of the disaster can be found in De Kumar (1989)

[c] Worst environmental nuclear disaster in history. For details, see Ginzburg and Reis (1991)

[d] The number has been shown as 36,000 between March and September 1989 by Maki (1991), the then senior science advisor to Exxon Company

interdisciplinary nature of environmental chemistry was highlighted at the time of launching the first issue of the journal "Environmental Chemistry Letters" published by Springer, wherein the Editors-in-Chief of the journal communicated in the first editorial of the journal that "Environmental Chemistry Letters will exclusively publish high-quality scientific articles, reporting novel findings at the research frontiers of geology, chemistry, physics and biology" (Lichtfouse et al. 2003). Similarly, Olivier Donard, a member of International Advisory Board of the journal "Environmental Chemistry" published by CSIRO Publishing, commented that "environmental chemistry is in fact a complex scientific discipline at the crossroad of physics, chemistry and biology, relying on advanced analytical chemistry dealing with ill-defined multi-phase systems." Kevin Francesconi, another member of the same board at the time (and currently Editor-in-Chief of *Environmental Chemistry*) commented that "environmental chemistry is one of the (few) public and friendly faces of chemistry." The above comments appeared in the first editorial of Environmental Chemistry (Green and Hecker 2004).

While the foundation for the interdisciplinary field of environmental chemistry is chemistry, i.e., physical, organic, inorganic and analytical chemistry (Lenoir and May 1997), it uses knowledge and information from many other scientific disciplines such as physics, geology, biology, atmospheric science, microbiology, ecology, toxicology, soil science, engineering (Fig. 2b). Geochemistry is also important in understanding environmental chemistry (Sverdrup 1996). Knowledge from physical chemistry and

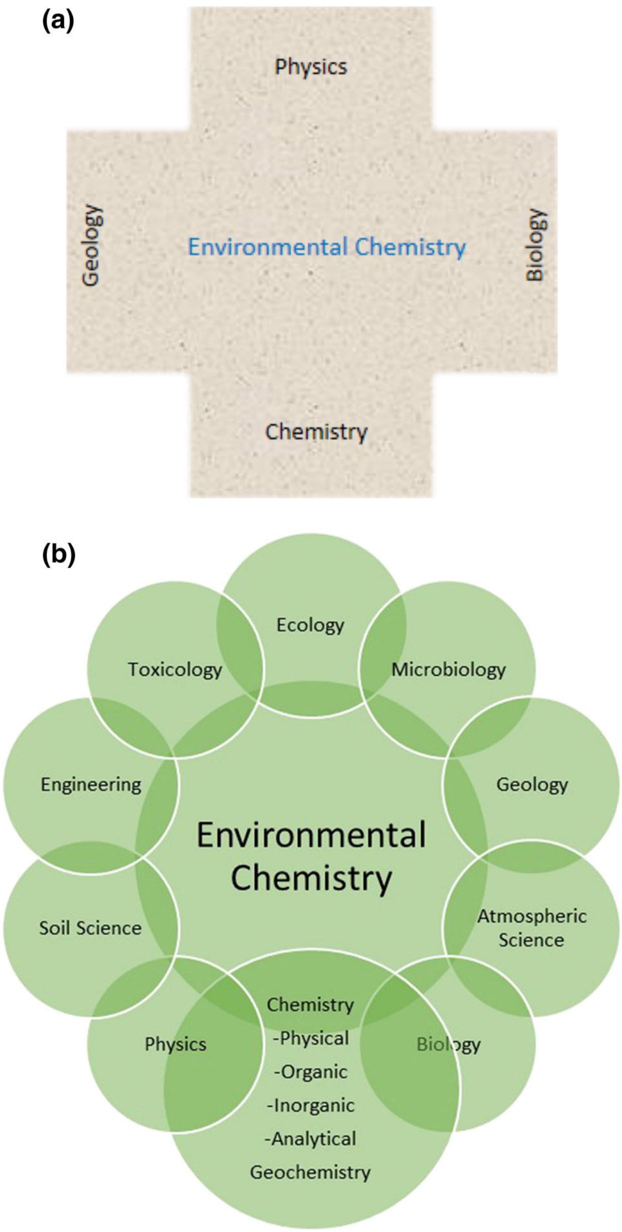


Fig. 2 Schematic showing the interdisciplinary nature of environmental chemistry: **a** environmental chemistry is at the crossroad of the natural sciences, i.e., physics, chemistry, geology and biology. **b** Environmental chemistry is associated with many other scientific disciplines

pharmacology was used to describe the partitioning of organic chemicals in biota; knowledge from inorganic chemistry was used to describe mineral dissolution and metals' speciation in aquatic environment (Sedlak 2016). Bioinorganic chemistry may help in understanding the biogeochemical cycling of elements (Ochiai 2010). Similarly, research on assessment of water and sediment quality is a multidisciplinary exercise, which involves chemists and biologists (Batley 2004). Studying the transport and fate of environmental contaminants requires skills from many sciences including geology, hydrogeology, atmospheric chemistry, organic chemistry, inorganic chemistry, agronomy, biology, health science and ecology (Suk et al. 1999).

Many new areas of research at the interface of environmental chemistry and other fields of chemistry are developing: for example, environmental physical chemistry (Waite et al. 2015; Wine 2010), environmental organic chemistry (Eisenreich and Simonich 2015), environmental bioinorganic chemistry (Ochiai 1974, 2010), environmental analytical chemistry (Brown 2009), environmental geochemistry (Cannon and Hopps 1968). The interactions among different chemistry fields will yield fruitful results. Christian G. Daughton had advised us to spend time at the edges. Daughton emphasized that "interesting chemistry happens at interfaces" (Daughton 2001). Daughton also advised us to communicate and collaborate with scientists in other fields. In fact, the knowledge of environmental chemistry is limited without the knowledge of the sister disciplines of ecotoxicology and ecology.

Environmental chemistry and ecotoxicology

Environmental chemistry and ecotoxicology have close ties and are therefore offered together in many institutions. Ecotoxicology deals with the study of the impact of environmental chemicals on organisms in their natural habitats, i.e., in the wild. This science integrates the disciplines of environmental chemistry, biochemistry, toxicology and ecology (Escher et al. 1997). It is clear that concentration data alone will not be sufficient to describe or predict contaminant effects on an ecosystem (Batley 2004). It is of central importance to assess the potential toxicological and ecological effects of environmental pollutants. Chemists are encouraged to participate in the solution of ecotoxicological problems (Stumm et al. 1983). For a full understanding of ecotoxicological effects, a close collaboration of environmental chemistry and biology is needed (Escher et al. 1997).

The ecotoxicological effects of contaminants may also be changed by changes in the environment. The phenomenon of global climate change is one of the biggest challenges in the twenty-first century. This may have an additional impact on effects of contaminants (Bebianno and Minier 2014).

Environmental chemistry and ecology

Environmental chemistry is also connected with ecology, the broadest discipline in biology. Environmental pollution has effects on organisms on molecular, cellular, tissue, organ, individual, population and community levels. An understanding of such effects and their consequences for ecosystem and human health requires an understanding of ecology. Accordingly, knowledge of ecology is necessary for a comprehensive understanding of environmental chemistry. Here, four striking examples are presented (Fig. 3):

- DDT and birds
- Diclofenac and vultures
- Heavy metals, e.g., Cd and amphibians
- Pesticides, e.g., imidacloprid and honey bees

DDT application had affected bird populations in the USA. Declines were recorded in the populations of peregrine falcons, bald and golden eagles, ospreys, kestrels and other predatory birds (Cox 1991). Diclofenac, a non-steroidal anti-inflammatory drug (NSAID), was proposed as responsible for the population decline of the Oriental white-backed vulture (*Gyps bengalensis*) in Pakistan (Oaks et al. 2004) as well as other scavenger birds of the genus *Gyps* on the Indian subcontinent. By 2004, populations of *G. bengalensis* were declined by more than 99% and those of long-billed vultures (*G. indicus*) by 97% in India since 1992 (Proffitt and Bagla 2004). Vultures were exposed to diclofenac through feeding on diclofenac-contaminated livestock carcasses. The birds died because of visceral gout resulting from kidney failure. Necroscopy studies of dead individuals revealed the presence of uric acid crystals in visceral organs. The declines stopped and populations partially recovered after the ban on the veterinary use of diclofenac in 2006 by the governments of India, Pakistan and Nepal with Bangladesh following the suit in 2010 (Balmford 2013). Residues of veterinary drugs such as diclofenac in animal carcasses are also a threat for vultures in Europe (Richards and Ogada 2015).

During a study in Central Europe, no amphibians were observed in majority of habitats heavily contaminated by mining for heavy metals (Adlassnig et al. 2013). Similarly, a negative correlation has been found between heavy metal pollution and populations of solitary wild bees. A steady decrease was observed in the number, diversity and abundance of such bees with increasing heavy metal concentration. At Olkusz (Poland), an increase was observed in the natural mortality of the solitary bee *Megachile ligniseca* with increase in heavy metal concentration in pollen (Moroń et al. 2012). Pesticides, e.g., imidacloprid (a neonicotinoid insecticide), are also hazardous to beneficial insects at very low doses (Maini et al. 2010). In honey bees, chronic intoxication by imidacloprid could cause immunodeficiency and diseases (Halm et al. 2006). Ingestion of trace residues of imidacloprid at concentration range of 1 ppb has been found to substantively decrease worker fecundity (number of offspring produced per unit of time) of bumble bees (*Bombus terrestris*) (Laycock et al. 2012). Neonicotinoid insecticides interfere with the foraging ability of bees (Blacquiere et al. 2012). Environmental pollution also affects soil microorganisms. Higher concentrations of heavy metals in soils decrease the population, diversity and activities of microbes (Abdu et al. 2016).

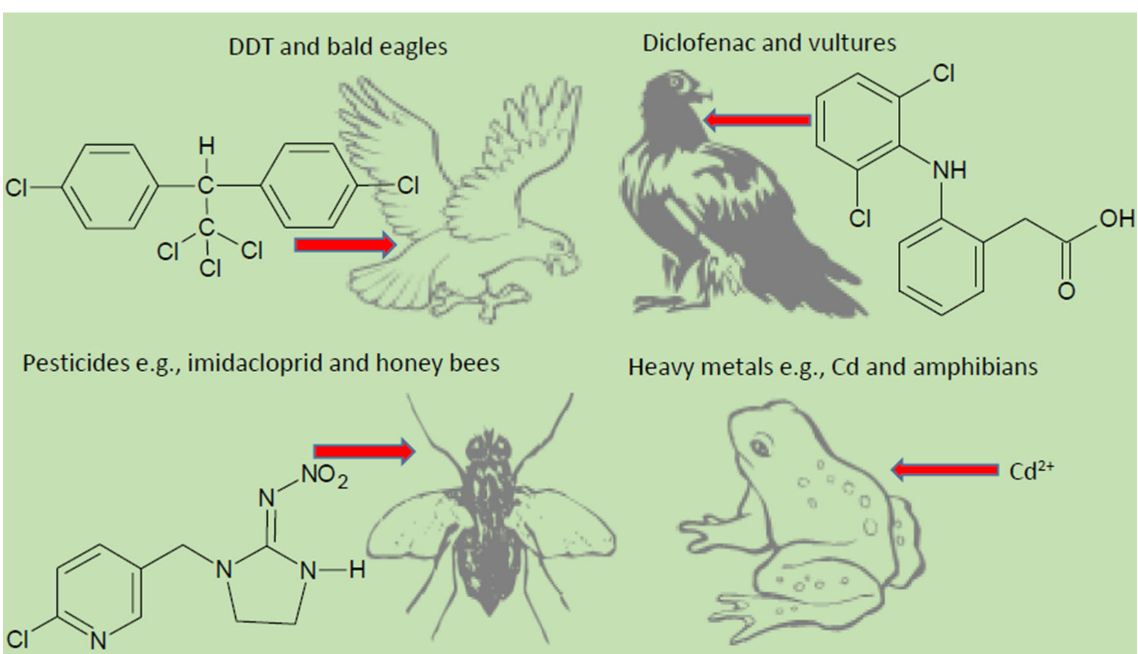


Fig. 3 Striking examples of the impact of environmental pollutants on wild populations of some animal species

In addition to organic and inorganic pollutants, acid precipitation also affects living organisms in aquatic and terrestrial ecosystems. For instance, declines in fish populations had occurred in Norway, Sweden, and some parts of eastern North America due to acidification in lakes and streams. The primary cause of population decline was reproductive failure resulting from the toxicity of acidic waters for eggs and juvenile fishes (Schofield 1976). Apart from causing mortality and population declines, environmental chemical pollution also induces changes in the behavior of animals and humans. Endocrine-disrupting chemicals (EDCs) change different behaviors such as sexual behavior, communication, dominance, aggression and cognition. Exposure to such chemicals also increases susceptibility to infectious diseases (Zala and Penn 2004). Now these chemicals are present in the global water cycle (Tijani et al. 2016). An update of the scientific knowledge on endocrine disruptors is presented in "State of the Science of Endocrine Disrupting Chemicals—2012" published by United Nations Environment Program (UNEP) and the World Health Organization (WHO) (UNEP and WHO 2013) [this report has been criticized by (Lamb et al. 2014)]. Similarly, pesticides can affect birds indirectly by decreasing their food supply (e.g., insects), by causing in them anorexia (loss of appetite accompanied by weight loss) or by making them more vulnerable to predation (Cox 1991).

Population declines of different species have severe consequences for human health and the environment. For example, declines in vultures' populations result in an increase in incidence of rabies, plague, etc. Declines in honey bees' populations lead to pollination problems. Declines in amphibians' populations will affect mosquito populations as amphibians and their tadpoles are predators of mosquito larvae. Furthermore, declines in wild populations of different species may have other severe consequences currently unknown. Apart from environmental pollution, climate change has also significant ecological consequences. Anthropogenic climate change is now recognized as one of the major currently unsolved challenges facing human society in the coming time (Ravishankara et al. 2015). Changes occurring as a result of climate change are intimately linked to human health (WHO 2003). While climate change is the most prominent aspect of present-day global change, other aspects such as damage or destruction of ecosystems also need solutions (Molles 2016). Disturbance to agriculture, forestry and fisheries will also have serious consequences for humans. Being central science, chemistry must play its role in understanding the life-threatening consequences of climate change and in moving to sustainable development.

Atmospheric chemistry

Atmospheric chemistry is an interesting but challenging science. Chemistry in the atmosphere has a significant impact on climate, human health and overall life on earth. The most important atmospheric challenges in the twentieth and twenty-first centuries included acid precipitation, stratospheric ozone loss, enhanced greenhouse effect and global warming and global climate changes. Research progress in responsibly handling these challenges is to some extent satisfactory and in some cases even outstanding (e.g., ban on ozone-depleting chemicals) but more is to be done and implemented. Mitigation of the acid precipitation problem as a result of substantial reductions in atmospheric emissions of SO_2 and the (slow) recovery of Antarctic ozone hole as a result of the phasing out of chlorofluorocarbons (CFCs) demonstrate that scientifically informed interventions matter. Most importantly, efforts should be done to reduce global emissions of CO_2 and other greenhouse gases in order to mitigate global warming and climate change.

The Nobel Prize in Chemistry 1995 was awarded jointly to Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland (Fig. 4) working in the field of atmospheric and environmental chemistry "for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone" (Nobel Media AB 2014). For a background of the prize, see article by Parthiban (1995). They studied the role of CFCs in depleting ozone in the stratosphere (Crutzen 1974, 1979; Crutzen et al. 1978; Molina and Rowland 1974; Rowland 1989; Rowland and Molina 1975). Their work is a very significant contribution in science and has a significant impact on the global science policy especially the Montreal Protocol of 1987 for phasing out the use of ozone-depleting environmentally destructive chemicals. Manahan (2000) has called the study of ozone-depleting CFCs as "the greatest success story of environmental chemistry" to the end of the twentieth century. These scientists are duly recognized for their significant contribution to science. Interested readers are referred to recent tributes to these scientists (Francesconi 2012, 2013; McNeill et al. 2015). A recently published book edited by Crutzen and Brauch (2016) is also interesting.

The conversion of SO_2 to sulfuric acid and NO_x to nitric acid has led to acid precipitation, resulting in damage to forests and fish death in some lakes in areas such as Scandinavia and the northeast of North America. Although the situation has improved due to significant reductions in SO_2 emissions, the acid rain problem is now getting worse in Asia (Crutzen and Steffen 2003). Atmospheric chemistry has an important impact on climate change and vice versa.

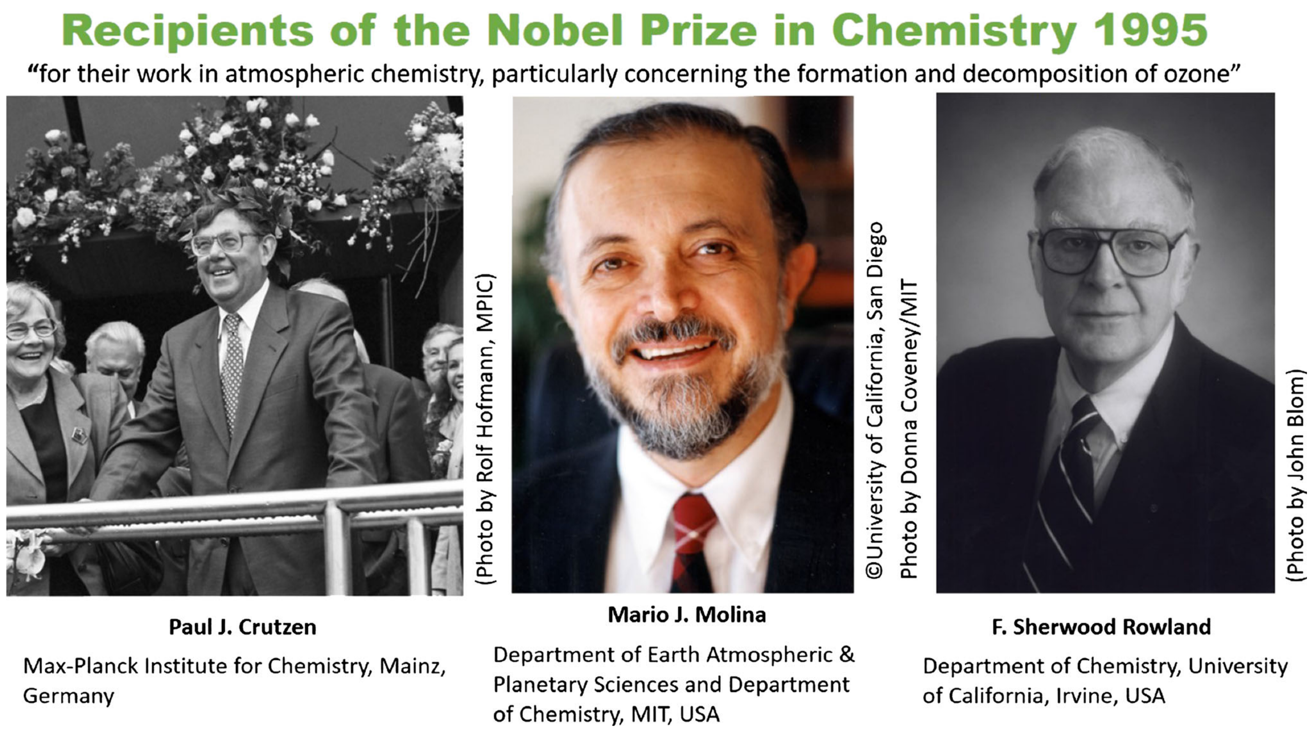


Fig. 4 Recipients of the Nobel Prize in Chemistry 1995. The photograph of Prof. Crutzen was taken during a reception at the Max-Planck Institute for Chemistry, Mainz, Germany, on October 18, 1995, after announcement of his Nobel Prize award. Photographs of Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland are used with permission from Max-Plank Institute for Chemistry, Mainz, Germany; University of California, San Diego, USA; and University of California, Irvine, USA, respectively

Climate change can change H_2O concentrations in the troposphere, further affecting chemistry impacts on climate (Wuebbles et al. 1989). Depending on the scenarios of energy use in the future and uncertainties in models, it is estimated that further emissions of CO_2 and other greenhouse gases will cause an increase of 1.4–5.8 °C in global average temperature during the twenty-first century, which will be accompanied by a rise of 9–88 cm in sea level (Crutzen and Steffen 2003).

Atmospheric chemistry is an important area of research, and much efforts are to be done to produce fruitful results in the best interest of life on Earth. Research on aerosols is among the current hot topics in atmospheric chemistry (Ravishankara et al. 2015). A rapidly expanding field in atmospheric chemistry is molecular identification of organic compounds in the atmosphere. To a great extent, understanding the processes, which involve organic compounds in the atmosphere, depends on sound identification of these compounds (Noziere et al. 2015). In order to stabilize Earth's climate in the Anthropocene, deliberate intervention into Earth's systems may be considered on a global scale (Anbar et al. 2016). Much is to be done to explore the fundamentals of photochemistry at interfaces and its atmospheric consequences (George et al. 2015). Another important research area is multiphase chemistry. "Multiphase chemistry deals with chemical reactions, transport processes, and transformations between gaseous, liquid, and solid matter" (Pöschl and Shiraiwa 2015). It plays an important role in the Earth system, climate and health (Pöschl and Shiraiwa 2015). The issues of greenhouse effect, global warming and rapid climate change present much more dark scientific, economic and political challenges (Rowland 2006). According to Manahan (2000), greenhouse effect (and consequent global warming and climate change) may be the greatest of all threats to the global environment.

Analytical chemistry, statistics and chemometrics

Environmental chemistry is a quantitative science (Hites 2001); therefore, analytical chemistry, statistics and chemometrics are necessary and important tools for this discipline. "Chemometrics is the branch of chemistry concerned with the analysis of chemical data and ensuring that experimental data contain maximum information" (Wold 1995). While a detailed discussion of this topic is beyond the scope of this article, the importance of these disciplines for environmental chemistry is comprehensively highlighted. Progress in analytical chemistry provides the foundation essential for modern environmental chemistry (Garrigues 2005). The development of combined gas chromatography–isotope ratio mass spectrometry (GC-IRMS) is a valuable advancement for determining stable isotopes, with applications in environmental studies (Philp 2007). With advancement in analytical chemistry, detection limits are improved and the use of chlorinated solvents for extraction of environmental pollutants from different matrices is minimized or even eliminated. An example of such an advancement is the use of solid-phase extraction (SPE) disks. Micro-sized disks have been used in the analysis of herbicides in water, where a small volume of eluent, as small as 50 µL, was used for elution of the compounds from the disk and no evaporation of solvent was required. Thus, as small as 10 mL sample volumes may be used, with 0.1 µg L^{-1} detection limits (Thurman and Snavely 2000). Another advancement in detection of environmental pollutants at low levels is the development of nano-capillary electrophoresis, also called microchip electrophoresis (Ali et al. 2016).

The study of complexation has major importance in environmental chemistry. Luminescence line-narrowing spectroscopy (LLNS) has been used for the study of the complexation of lanthanides to humic substances (HS), e.g., Eu(III) complexation with humic substances (Ariese et al. 2008). Computational spectroscopy is also coming forward to help in advancing environmental chemistry, see book chapter by Kubicki and Mueller (2010). An interesting point from this chapter is worth mentioning "as the biotic factors influencing environmental chemistry are increasingly recognized as being critically important, the ability to model a complex inorganic–organic–biotic system will be invaluable in understanding how nature works on a molecular level."

In environmental chemistry, we frequently encounter real field data from the environment, for which we need statistical treatment in order to draw meaningful and valid conclusions. Different statistical tests are applied in specific situations to explore the associations among different variables under study. Examples of such statistical analyses include principal factor analysis (PFA) (Adami et al. 1997), and multiple factor analysis (MFA) (Stanimirova et al. 2005). A background knowledge of statistics and use of statistical software (such as SPSS) is required to analyze and interpret environmental data. For details about the use of chemometrics in environmental chemistry, interested readers are referred to specific books on the subject, e.g., Chemometrics in Environmental Chemistry-Statistical Methods edited by Einax (1995b), Chemometrics in Environmental Chemistry-Applications edited by Einax (1995a) and Chemometrics in Environmental Analysis by Einax et al. (1997). In addition to analytical chemistry and chemometrics, the use of advanced software makes the job of an environmental chemist easier.

Ice cores, lake sediments and tree rings

Ice cores, lake sediments and tree rings can be used as information archives in environmental and climate studies. Lake and peat sediments capture pollutants from the atmosphere and thus indirectly record changes in their deposition over time (Norton et al. 2016). Ice cores from Svalbard have been used to study climate and pollution records. Such records have provided information about anthropogenic effect on Svalbard environment by showing elevated levels of non-sea-salt sulfate, nitrate, acidity, fly-ash and organic contaminants especially during the second half of the twentieth century (Isaksson et al. 2003). Assessment of Hg concentrations in sediments is one of the primary means for assessment of the trend of the contamination (Zhang et al. 2011). Guevara et al. (2010) had reported Hg records in sedimentary sequences in Nahuel Huapi National Park, Northern Patagonia, Argentina, to identify atmospheric sources of Hg during the past millennium. The investigation suggested volcanic events and forest fires as potential sources of the element. Sedimentary records of Hg stable isotopes can be a useful tracer in understanding sources, fate and history of Hg contamination in large aquatic ecosystems, for example the Great Lakes (Yin et al. 2016). Geochronological studies of aquatic sediment archives give information about the initial appearance of a contaminant and its afterward behavior and fate in the aquatic environment (Heim and Schwarzbauer 2013). A recent study that aimed at reconstructing pollution history in Sheyang River (China) from sedimentary records has revealed that anthropogenic activities have caused a significant anthropogenic enrichment of metals such as Cu, Ni, Pb, Cr and Zn in the river sediments. This study uncovered the history of anthropogenic metal inputs into the Sheyang River during the last century (Wu et al. 2016).

Dendrochemistry can also be used as a research tool in environmental chemistry. Dendrochemistry (a special application of dendroecology) deals with the relationship of wood chemistry to atmospheric, soil and internal biological processes, which affect uptake of elements and their incorporation into annual growth rings (McLaughlin et al. 2002). Trees can preserve the uptake record of a contaminant over time in their rings, and this dendrochemical archive can be used as a tool to know about the history of contaminant releases (Burken et al. 2011). Using Hg concentrations in poplar and willow tree cores, it has been demonstrated that use of dendrochemistry has potential value in recording historical Hg emissions from industrial activities in the past (Maillard et al. 2016). The use of dendrochemistry in environmental monitoring is seen as a promising tool (Watmough 1997). In addition to annual growth rings, tree bark has been suggested as a suitable passive atmospheric sampler in locating the sources of persistent organic pollutants (POPs). Tree bark is lipophilic in nature and therefore easily adsorbs and accumulates POPs from the atmosphere. Apart from indicating sources, tree bark analyses can also be used in long-term monitoring of remediation (Peverly et al. 2015).

Dendrochemistry can possibly help in the studies of acid deposition and tropospheric ozone as stressors on forests. Acid deposition has implications in cation mobility/mobilization, depletion of essential nutrients and solubility of phytotoxic metals such as Al^{3+}. Dendrochemistry can additionally help in evaluating the response of forest trees to increasing atmospheric CO_2 levels (Fig. 5).

Environmental chemistry, green chemistry and sustainable development

The effective solutions of an environmental problem require a deep understanding of the nature and dimensions of the problem. Such a deep understanding of an environmental problem is not possible without a good knowledge of chemistry and environmental chemistry. Merely suppressing the symptoms of an environmental problem with temporary solutions should not be the only rely-upon option. Schrader (1994) had explained the situation by using the analogy of a fever that accompanies infection: "a fever cannot be removed unless we fight the infection. We can treat the symptom with an aspirin but later it recurs unless the infection is excised."

Environmental chemistry with ecotoxicology will play a key role in sustainability research (Giger and Sulzberger 1997). The knowledge of environmental chemistry is essential for sustainable development. One important step toward sustainable development is the transition from conventional chemistry to green chemistry. Advancement in environmental chemistry provides the grounds for this transition. Environmental chemistry advocates the design of environment-friendly (green) molecules and discourages the synthesis of environmentally problematic molecules. One of the important agendas of green chemistry is catalysis instead of using bulk reagents. Catalysis will play a central role in making sustainable development in this century (Cusumano 1995). Scientists and particularly chemists should accept responsibility for the science they practice, see a recent article on ethics and chemistry by Koch (2016). Chemists should play a leading role in achieving a sustainable future.

Environmental chemistry education

Environmental chemistry is central to environmental sciences as chemistry is central to sciences. It is perhaps the most important environmental science and is becoming more important than ever before. The future generations may be facing more diverse and complex environmental challenges than the current generation does. The academia has to educate and train generations of scientists with progressively more environmental and economic challenges and less natural resources. Therefore, we must make environmental chemistry an integral part of our current and future chemistry curricula. It is now increasingly becoming a component of chemistry courses and curricula (Cooper et al. 2001).

It is a challenge to the academia to produce chemistry graduates according to the market forces. At the same time, it is increasingly important to produce chemists who are ecologically and environmentally literate. Pro-ecological education is especially important in the education of chemists and chemical engineers (Namiesnik 1999). Roberta Aram and Stanley Manahan (the latter author is a well-known environmental chemistry text book writer of the twentieth century) have remarked that "ecologically literate chemistry graduate is becoming a real goal among US colleges and universities" (Aram and Manahan 1995). According to Zoller (2005) "environmental literacy is imperative for all chemists" and for achieving this goal, an interdisciplinary and conceptual approach is required as the leading teaching strategy. Interdisciplinarity should be a central element in chemistry teaching, particularly in environmental chemistry (Zoller 2001). Problem-based learning (PBL), an approach of student-centered learning, has also been found as an effective methodology for learning environmental chemistry; it improves the ability of students to collaborate (Jansson et al. 2015).

Apart from being a science in its own place, environmental chemistry is also an effective means of teaching and learning chemistry by providing context to the chemistry content. Environmental context in chemistry makes the chemistry content more related to the students' everyday lives and thus more attractive for them. Adding environmental information to the chemistry curriculum can be a double-edge tool: enhancing learning of chemistry content and serving as a source of environmental knowledge (Mandler et al. 2012). Adding environmental context can also enhance students' perceptions about relevance of chemistry to real-life problems (Robelia et al. 2010). Thus, chemistry can be easily communicated to students by dissolving its contents in the solvent of environmental context. For example, the topic of "soil" can be used for introducing students to some important chemical concepts like ion exchange, surface chemistry, and structural inorganic chemistry (Tran et al. 2001). Environmental issues present a wonderful link of human concerns and interesting chemistry (Spiro and Stigliani 1998). Furthermore, an environmental perspective is of benefit for non-science students because they find a context for learning chemistry

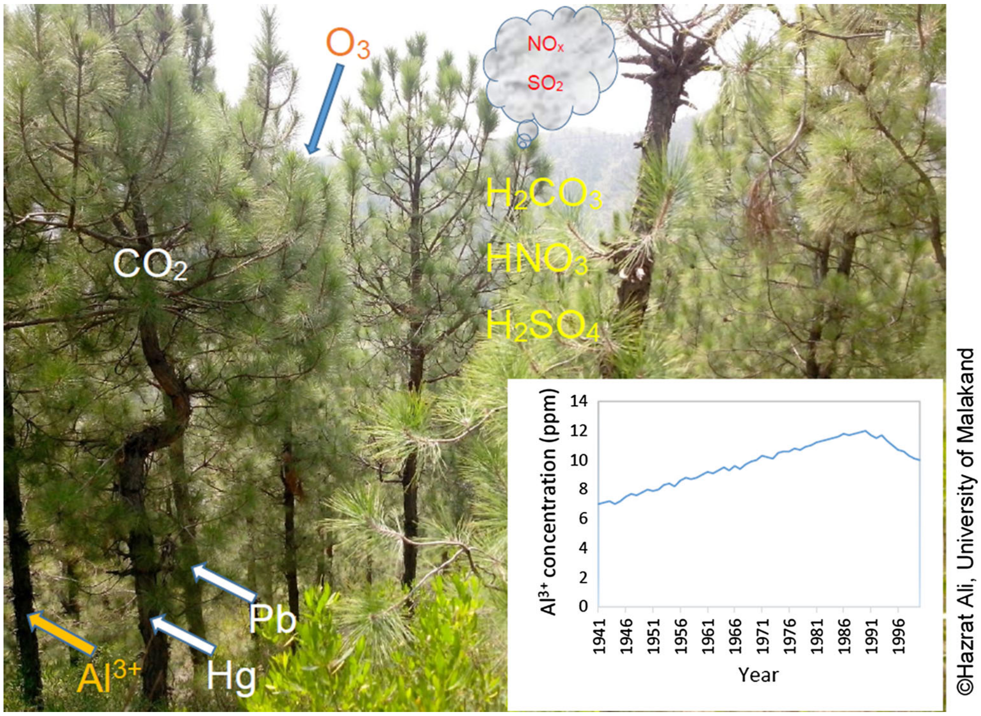


Fig. 5 Dendrochemistry can be used as a research tool in environmental chemistry. Historical record of industrial emissions of metals like Pb and Hg resulting from past industrial activities can be obtained from dendrochemical analysis of tree annual growth rings. Dendrochemistry can also be used possibly in studies investigating the effects of acid deposition, tropospheric ozone and increasing atmospheric CO_2 levels on forest trees. The insert graph is a hypothetical plot of Al^{3+} ion concentration in pine trees over a period of 60 years (1941–2000). This hypothetical plot is shown to depict the effect of acid rain on soil chemistry and thus on the concentration of the phytotoxic Al^{3+} ion in forest soils and its subsequent uptake, translocation and incorporation in annual rings of pine trees

in it (Swan and Spiro 1995). Here a noteworthy point is presented from a 1995 article of Swan and Spiro published in Journal of Chemical Education: "Scientific literacy alone cannot be the goal; we need both scientifically literate non-scientists and environmentally and rhetorically aware chemists, who together can harness language and science toward solving the environmental and technological problems that affect us all" (Swan and Spiro 1995). Non-chemists also need a background knowledge of environmental chemistry in order to make informed decisions that lead to environmental improvement (Aram and Manahan 1995).

Students should be made familiar with issues of depleting petroleum resources and environmental persistence of petroleum-based products. Activities with focus on biorenewable feedstocks should be demonstrated to students at their school and college level. A good example is that of Hudson et al. (2015), which can initiate discussions on topics such as environmental pollution, biodegradation, materials sourcing and comparison between petroleum-based and biomass-based feedstocks. A laboratory course recommended for M.S students in Environmental Chemistry and Ecotoxicology at Masaryk University, Czech Republic, consisted of experiments on partition coefficient (n-octanol–water), Henry's law constant, soil sorption, volatilization from soil, bioaccumulation, photochemical degradation and microbial degradation (Růžičková et al. 2006).

Environmental chemistry is also an integral part of environmental sciences curricula. Modern environmental science must be multidisciplinary (Jørgensen 1999). Alegria and Nei (2014) emphasized the need of a stronger component of environmental chemistry in environmental science curricula. They remark that "there is no modern environmental science without environmental chemistry and there is no environmental chemistry without chemistry." Lammel et al. (2014) had conducted a survey to check the availability of environmental chemistry in bachelor- and master-level environmental sciences programs in Europe. They have found that about 25% of the existing institutions offer environmental chemistry in their courses, which shows the clear establishment of environmental chemistry as a discipline. Apart from an integral part of chemistry and environmental science curricula, environmental chemistry should be a part of chemical engineering curricula.

At the 1st international Education in Environmental Chemistry (EEC) workshop,[1] a part of the essential message of the introductory keynote address of the Committee on Education in Environmental Chemistry (CEEC) Chairman (Uri Zoller) was that "environmental chemistry education is imperative in chemistry education at all levels" (Zoller 2002). The follow-up workshop, of the above-mentioned workshop, held in 2003 recommends that "a core course in environmental chemistry should be taught to science majors, non-majors and chemical and industrial engineers alike" (Zoller 2005).

Environmental chemistry literature

Research in environmental chemistry is communicated to the scientific community and the public through publications in journals of chemistry, environmental chemistry, environmental sciences and related disciplines. A short list (of 20) journals publishing environmental chemistry research is given in Table 2. Furthermore, a list of authoritative textbooks and a handbook of environmental chemistry is given in Table 3, one of the first major textbooks published in 2005 by Eric Lichtfouse, Jan Schwarzbauer and Didier Robert (Lichtfouse et al. 2005), who also founded the European Association of Chemistry and the Environment in 1999 (http://www.europeanace.com), and the journal Environmental Chemistry Letters in 2002 with a team of environmental chemists. The chapters of this book have been downloaded 132,664 times according to Bookmetrix, on December 1, 2016. The book series Environmental Chemistry for a Sustainable World further provides comprehensive chapters on topics such as nanotechnology, health risk, green materials, hydrogen production, CO_2 sequestration and biofuels (http://www.springer.com/series/11480).

Funding environmental chemistry research

Conducting fruitful research requires expertise and funding for instruments and chemicals, etc. Regarding funding for research in environmental chemistry, a statement from Baird and Cann (2012) is worth mentioning: "environmental chemistry is not just a topic of academic interest, but one that touches our life every day in very practical ways." According to a study survey in Germany, Austria and Switzerland by Schaeffer et al. (2009), a large number of academic researchers from these European countries, with focus on environmental chemistry, ecotoxicology and ecology of chemical pollutants in different environmental media, have shown their concerns about the decline in political and financial support for academic environmental research and education. The authors of this study propose the creation of specific units in national funding bodies for addressing basic and interdisciplinary research in the field of chemicals-related environmental sciences. The results of another online survey by this research group about financial support for research in environmental chemistry and ecotoxicology in Germany show that funding can be improved even in countries such as Germany (Hollert et al. 2011). In China, support and funding for environmental research is encouraging, which is reflected from the number of environmental chemistry research projects funded and funding amount from Division of Environmental Chemistry of the National Natural Science Foundation of China (NSFC) during the last three decades; for details, see Jiang et al. (2016).

The disciplinary position of environmental chemistry

Environmental chemistry has a unique position among the scientific disciplines because of its real interdisciplinary nature. It is actually at the crossroad of the basic natural sciences of physics, chemistry, geology and biology and has an input of knowledge from many other scientific disciplines. The actual domain of environmental chemistry is usually not much clear to people, even to a large proportion of chemists. This situation has created confusions about the placement of environmental chemists in academic institutions, chemical industries and other governmental organizations. Traditionally, in many universities, environmental chemistry has been developed in non-chemistry departments such as soil science or agriculture (for soil chemistry), oceanography (for chemical oceanography), meteorology (for atmospheric chemistry) and civil engineering or geology (for geochemistry or groundwater chemistry) (Buffle et al. 1995). Many, even good, chemistry departments at universities and other degree awarding institutions have no established environmental chemistry sections. As a result, actual and potential environmental chemists often either work as orphan scientists in chemistry departments or as refugee scientists in other academic departments such as geosciences, environmental sciences and biological sciences. However, the situation is changing and this chemical science will hopefully occupy its place in the chemistry circle. In 1994, W.H. Glaze communicated in an Environmental Science and Technology editorial that "now environmental

[1] This workshop was held on January 10–12, 2002, in Rome, Italy, and was sponsored and organized by the Committee on Education in Environmental Chemistry (CEEC) of the Federation of the European Chemical Societies (FECS) Division of Chemistry and the Environment (DCE).

Table 2 A list of 20 journals publishing environmental chemistry research

S. no	Journal name	Publisher	2015 Impact factor[a]
1	Atmospheric Chemistry and Physics	European Geosciences Union	5.114
2	Atmospheric Environment	Elsevier	3.459
3	Chemistry and Ecology	Taylor & Francis	1.281
4	Chemosphere	Elsevier	3.698
5	Environmental Chemistry	CSIRO Publishing	2.455
6	Environmental Chemistry Letters	Springer	2.918
7	Environmental Geochemistry and Health	Springer	2.079
8	Environmental Pollution	Elsevier	4.839
9	Environmental Research	Elsevier	3.088
10	Environmental Reviews	NRC Research Press	4.630
11	Environmental Science and Pollution Research	Springer	2.760
12	Environmental Science and Technology	American Chemical Society	5.393
13	Environmental Toxicology and Chemistry	Wiley	2.763
14	Environment International	Elsevier	5.929
15	Journal of Atmospheric Chemistry	Springer	1.550
16	Journal of Environmental Sciences	Elsevier	2.208
17	Journal of Hazardous Materials	Elsevier	4.836
18	Science of the Total Environment	Elsevier	3.976
19	Tellus Series B-Chemical and Physical Meteorology	Co-Action Publishing	2.402
20	Toxicological and Environmental Chemistry	Taylor & Francis	0.634

[a] Impact factors are based on Thomson Reuters Journal Citation Reports 2016

chemistry is ready to take its place in chemistry departments as a legitimate field of inquiry" (Glaze 1994). In 2014, twenty years after this statement, M. Filella at the Institute F.-A. Forel, University of Geneva, Switzerland, has described the situation very interestingly "many chemists working in the field of environmental chemistry will have experienced the feeling of being looked down on by other chemists doing 'real science.' The roots of this attitude may lie in a profound misunderstanding of what environmental chemistry is actually about, a misunderstanding fostered by the unusual position of environmental chemistry among scientific disciplines" (Filella 2014). Actually, an important job in environmental chemistry is to establish connections between molecular approaches of laboratory experiments and systems approach of multidisciplinary field studies (Wehrli and Schwarzenbach 1997).

Conclusion

This review article comprehensively outlines the science of environmental chemistry. Environmental chemistry is an important scientific discipline and is becoming increasingly important in the twenty-first century, the century of environmental responsibility. Release of chemicals into the environment has significant impact on wildlife and human health. The environmental stories of many chemicals have prompted us to design and promote more environment- and eco-friendly processes and products. We have to keep eye on the environmental impact of existing and emerging chemicals in order to avoid mistakes like those of DDT and diclofenac, which caused population declines of bald eagles in North America and *Gyps* vultures in the Indian subcontinent, respectively. Similarly, other contemporary environmental problems such as global climate changes, global warming, ozone depletion, acid deposition and changing biogeochemical cycles are issues, which have significant consequences for life on Earth. Atmospheric chemistry is an important area of research with important contributions to our understanding of the Earth system. A deep understanding of the atmospheric chemical processes will be helpful in knowing the impact of human activities on the atmosphere and climate. More dedicated research on multiphase processes will yield results which will help in mitigating climate change and protecting ecosystem and human health in the Anthropocene era. Environmental chemistry is an integral part of chemistry curricula at all levels and is an important part of other science and engineering curricula such as environmental sciences and chemical engineering. Production of environmentally and ecologically literate and socially responsible graduates should be one major aim of higher education.

Table 3 Authoritative textbooks on environmental chemistry

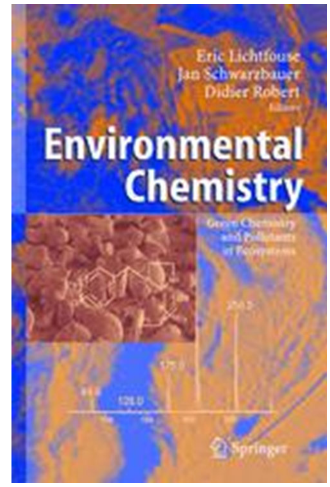
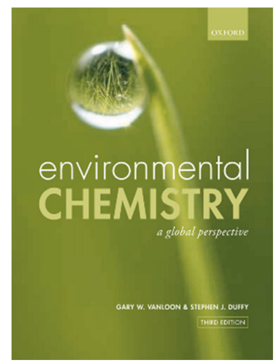
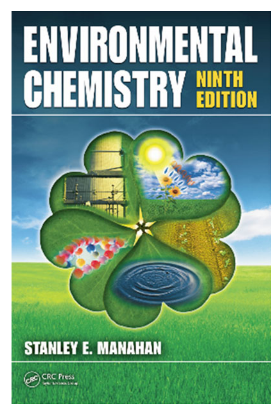
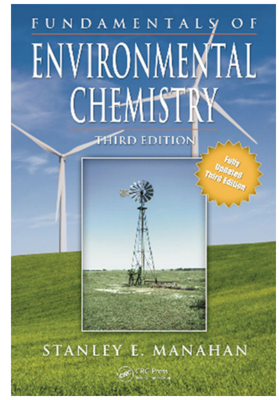
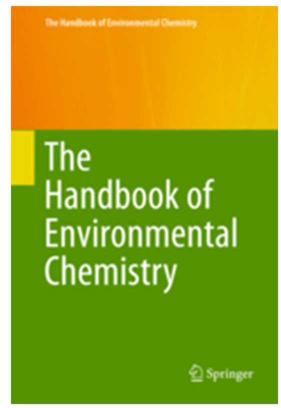
1	Environmental Chemistry. Green Chemistry and Pollutants in Ecosystems By Eric Lichtfouse, Jan Schwarzbauer and Didier Robert (Editors) 2005 ISBN: 978-3-540-22860-8	
2	Environmental Chemistry 5th Edition By Colin Baird and Michael Cann W. H. Freeman and Company, New York 2012 ISBN: 978-1-4292-7704-4	Cover page not available due to copyright restrictions
3	Environmental Chemistry: A Global Perspective 3rd Edition by Gary W. VanLoon and Stephen J. Duffy Oxford University Press, Oxford 2010 ISBN: 9780199228867	
4	Environmental Chemistry 9th Edition by Stanley E. Manahan CRC Press, Boca Raton 2009 ISBN: 9781420059205	

Table 3 continued

5	Fundamentals of Environmental Chemistry 3rd Edition by Stanley E. Manahan CRC Press, Boca Raton 2008 ISBN: 9781420052671	
6	The Handbook of Environmental Chemistry Edited by Damià Barceló and Andrey G. Kostianoy Founded by Otto Hutzinger Springer International Publishing Switzerland 2016 ISSN: 1867-979X	

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Compliance with ethical standards

Conflict of interest The authors declare no competing financial interest.

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