A Survey of Environmental Chemistry Around the World: Studies, Processes, Techniques, and Employment

A white paper examining the current state of key research areas and technologies in environmental chemistry and how they protect human health and the world.

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I. EXECUTIVE SUMMARY

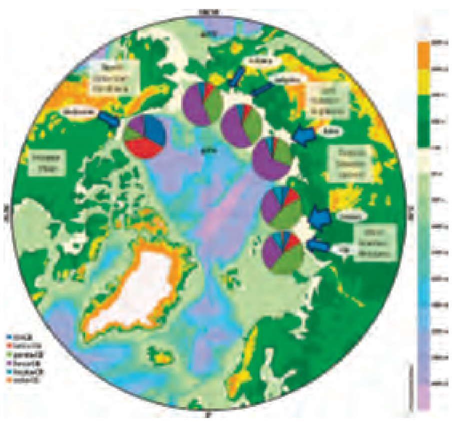
Environmental chemistry is a major route through which we learn about the Earth's natural processes as well as humanity's impacts on the planet. [1] This is one of the reasons why environmental chemists are well-positioned to help humanity solve some of our toughest challenges related to energy, health, food, and natural resources, many of which are related to humanity's impacts on the planet. [2,3] Environmental chemists monitor what is in the air, water, and soil to study how chemicals enter the environment, what affects they have, and how human activity affects the environment. They monitor the source and extent of pollution and contamination, especially compounds that affect human health, and they promote sustainability, conservation, and protection. [4] As concerns about geochemistry and the natural environment increase, environmental chemists also study the processes that affect chemicals in the environment. Gases emitted by a pine forest may create a mist when mixed with car exhaust, for example. In other instances, the environment may have effects on chemicals that can be toxic. Environmental chemists examine the ways both chemicals and the environment are changed by interacting. [5]

In the service of monitoring those impacts, environmental chemists can work everywhere. Their jobs can take them from the upper recesses of the Earth's atmosphere to the depths of the oceans, from the ice in the North Pole, to the dirt near a shuttered factory, to the dust in someone's home, from the top of a coal-burning power plant's smokestack to a leather tannery in India, to a site where old electronics are dumped in Nigeria. These are but a few of the places where environmental chemists have either taken samples in person or found a way to capture samples that they have then analyzed to learn more about our world.

Environmental chemists have a skill that is valued in today's labor market, according to the U.S. Bureau of Labor Statistics. [6] The bureau expects job opportunities for environmental scientists to grow 19% between 2010 and 2020. [6] Environmental chemists are in demand in industry, government, and academia, as well as by contract labs and consulting groups.[5] They can be involved in analytical testing or new product development in the lab, or work with users of chemicals in the field, and safety and regulatory issues in an office. [4] The chemical industry employs a large number of environmental chemists to ensure that a given company is in compliance with government regulations.[5] As a result, companies in a variety of industries are placing greater emphasis on compliance and environmental processes. [5] Government agencies such as the U.S. Departments of Agriculture and Defense and the U.S. Environmental Protection Agency, as well as agencies at the state and sometimes local level, hire chemists for environmental work. [5] In addition, waste management companies and consulting firms employ such chemists as consultants, sometimes related to remediation work. [5] Opportunities are expected to grow in contract labs and consulting, because businesses are increasingly outsourcing this work. [5] Colleges and universities are hiring more environmental chemists to serve as instructors and educators as they establish programs in environmental chemistry.

II. ENVIRONMENTAL CHEMISTRY AROUND THE WORLD

Scores of research articles document the unique fragility of the Arctic and Antarctic environments, including the tendency of some persistent, bioaccumulative, and toxic chemicals to concentrate there. While some samples from these environments are captured with automatic equipment, scientists must still travel there to place and to monitor the equipment. Other trips involve collecting samples to investigate potential new problems and expand our awareness of these regions' unique environmental chemistry. Recent trips to the Arctic have helped improve understanding of how bromine cycles through the environment, [7] how the uptake of mercury by lake trout and Arctic char fish affects the area's food chain,[8] and how polychlorinated biphenyls (PCBs), which were once widely used in commercial and industrial applications, cycle through Arctic rivers. [9]



The relative congener contributions (grouped by chlorination degree) to the PCB fluxes of the six Great Arctic Rivers.

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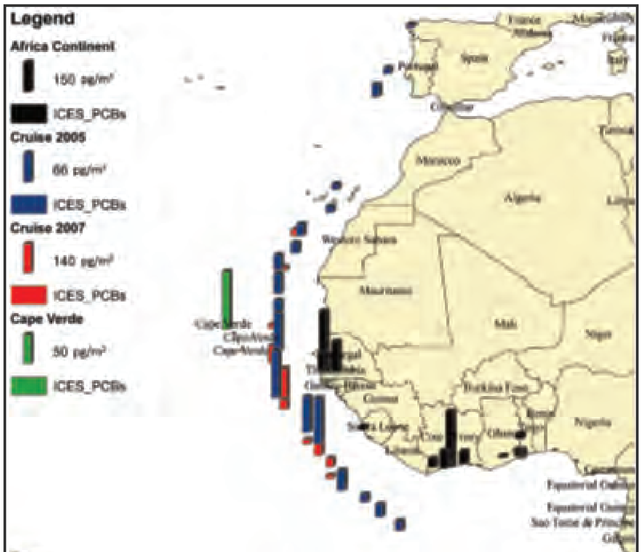
A group aboard the icebreaking research expedition vessel *Xuedong* (Snow Dragon) collected air samples from areas in the Arctic Ocean and investigated how atmospheric levels of the insecticide hexachlorocyclohexane (HCH) are affected by the melting and refreezing of sea ice. [10] By analyzing peregrine falcon eggs collected in Greenland, environmental chemists showed that the levels of polybrominated diphenyl ether (PBDE) flame retardants in the eggs had risen rapidly between 1986 and 2003. [11]

Another trip with the goal of sampling levels of legacy pollutants such as PCBs in the atmosphere required scientists to install passive air samplers in both the Arctic and the South Pacific. [12]

A group of researchers at the Antarctic's McMurdo research station showed that the station and its human inhabitants were a major local source of PBDE flame retardants, used in certain manufactured products, and that can accumulate in the environment and in human tissues. [13] Other teams have documented levels of PCBs and organochlorine pesticides in sediments and bottom-dwelling animals living off of the continent's coast. [14] In support of the European Project for Ice Coring in Antarctica, chemists found a way to measure levels of levoglucosan, a molecular marker for biomass burning, at the pictogram-per-milliliter level in less than 1 milliliter (mL) of ice from the continent. [15] And scientists who traveled to Queen Maud Land in East Antarctica collected snow samples they analyzed for levels of platinum, iridium, and rhodium, noble metals that are extremely rare in the Earth's crust. Their work shows that there has been large-scale atmospheric pollution of platinum and probably rhodium since the 1980s, which they attribute to increasing emissions of these metals from anthropogenic sources such as automobile catalysts. [16]

III. AFRICA, ASIA, AUSTRALIA, AND SOUTH AMERICA

To help explain unexpectedly high levels of PCBs measured off of the West African coast, researchers aboard the German Polarstern research vessel collected samples and deployed passive samplers at Cape Verde Island. Their work pointed to emission sources in the Ivory Coast and Gambia that had not previously been accounted for, suggesting illegal dumping of PCB-containing waste, perhaps generated during the demolition of old ships. [17]



PCB concentrations in Cape Verde (green bar, 99 pg m-3), 2007 (red bars, highest value 190 pg m-3) and 2005 cruise (blue bars, highest value 104 pg m-3), and on the West African countries (black bars, highest value 280 pg m-3).

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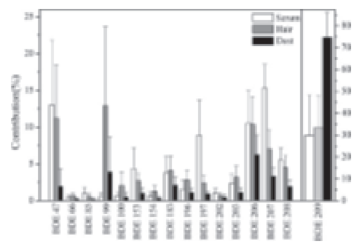
To study the utility of using enzyme-substrate microbial water tests, originally developed for use in laboratories to evaluate microbial contamination of drinking water, environmental scientists from Israel traveled to a rural part of southern Zambia. [18] A group of British scientists collected sediment core samples from lakes in Uganda's Rwenzori Mountains. Their analysis of the sediments from the high-altitude equatorial lakes showed that levels of mercury had increased about threefold since the mid-19th century, an increase similar to that shown in other remote regions throughout the world. [19]

In Asia, environmental chemists have played an important role in documenting pollution from electronic waste recycling in Southern China. Their work has shown that people living close to where electronic waste is recycled had very high levels of PBDEs, [21,22,23] as well as other newer flame retardants such as Dechlorane Plus,[24] in their blood serum. Researchers also conducted the first investigation into the concentrations of short-chain chlorinated paraffins, which are used in a variety of commercial and industrial applications, in East Asia's air. They traveled to urban and rural locations in China, Japan, and South Korea to place and collect samples from passive air samplers. [25]

The topics of research carried out in Australia are often similar to projects in the U.S., Canada, and Europe. Recent Australian projects include investigations into the uptake of persistent organic pollutants in adults and children, [26] the ability of an advanced water treatment plant to remove estrogenic compounds, [27] and the presence of antibiotic resistance genes in surface water. [28]



PBDE congener profiles in hair, serum, and dust samples from e-waste recycling areas.

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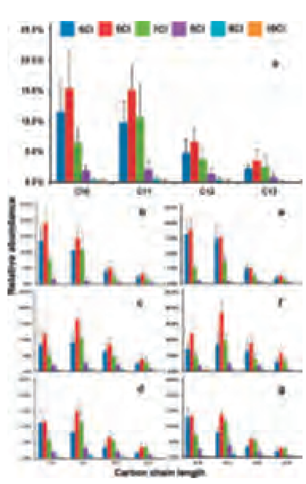
To go beyond what previous studies have reported about the presence of antibiotic resistance among culturable bacteria in surface water, groundwater and drinking water, the researchers looking for antibiotic resistance genes used polymerase chain reaction techniques. These techniques allow sensitive and specific detection of antibiotic-resistance in the environment without the need to culture bacteria. This is important because only a fraction of microorganisms—<1% in aquatic environments—can be cultured by standard methods. [29] Recent research projects in South America included trips to Brazil to measure methane emissions from shallow tropical lakes [30] and the impact of pollution from cities on the natural jungle environment in a downwind site. [31] A project in Chile used inexpensive passive samplers to measure levels of persistent organic pollutants in the air. [32]



Average proportions of SCCP congener group profiles throughout East Asia. a, East Asia; b, all samples from China; c, all samples from Japan; d, all samples from South Korea; e, two rural sites in China; f, two rural sites in Japan; g, two rural sites in South Korea.

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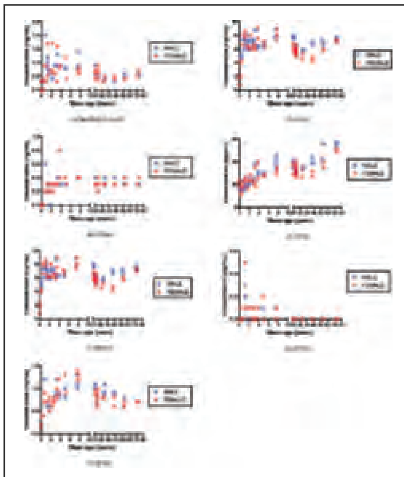
Research projects aimed at collecting data on chemicals in the environment have also taken researchers to remote mountain sites in the U.S., Canada, and Europe. [33,34,35,36] Other projects have inspired scientists to visit bird nesting sites on a regular basis and even collect tree bark. [37,38,39,40,41] Researchers have gone as high as the stratosphere to collect data on the impact of exhausts from the Space Shuttle and other NASA rockets. [42] At lower altitudes, teams of scientists including environmental chemists flew through hazy pollution plumes to collect data on how tiny carbon-containing aerosol particles are affecting the Earth's climate. [43]



Concentrations (ng/mL) of Me-PFOSA-AcOH, PFDeA, PFHxS, PFNA, PFOA, PFOS, and PFOSA by gender and age (note the change of scale on y-axis between PFCs; values at zero years for mean age represent cord blood samples).

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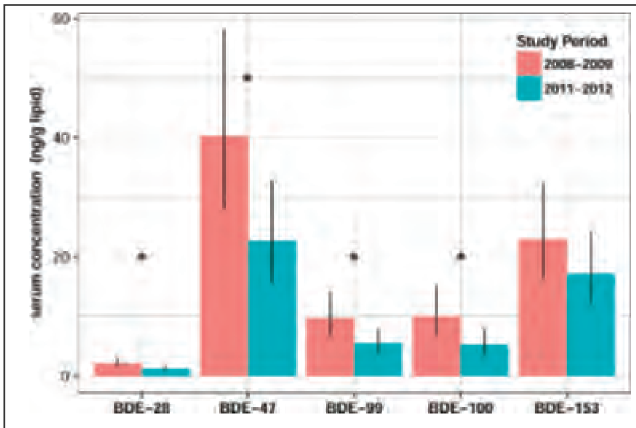
IV. IDENTIFYING PBT CHEMICALS

A major job for environmental chemists is to identify chemicals that are persistent, bioaccumulative, and toxic. Over the last several decades, chemists have begun measuring many more chemicals in the global environment.[44] Some of the most well-known of these are the PBDE flame retardants, the perfluorinated alkyl acids (PFAAs), and compounds associated with pharmaceuticals and personal care products (PCPPs).

According to nationally representative biomonitoring data on chemical exposure collected by the U.S. Centers for Disease Control and Prevention, the average U.S. citizen has detectable levels of more than 100 different xenobiotic compounds in his or her blood or urine. [45] One type of PBDE, BDE-47, was found in the serum of nearly all participants in the National Health and Nutrition Examination Survey (NHANES). [46] Most NHANES participants also had detectable levels of one PFAA, perfluorooctanoic acid (PFOA). It was a synthesis aid in the manufacture of a commonly used polymer, polytetrafluoroethylene, which is used to create heat-resistant non-stick coatings in cookware. [46]



Least square geometric mean serum concentration for individual PBDE congeners by cohort after adjustment by maternal age, gestational age, race/ethnicity, parity, and insurance status. Error bars indicate 95% confidence intervals and asterisks reflect statistically significant differences ($p < 0.05$).

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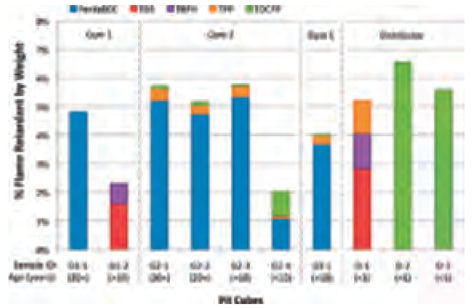
PBDEs were once widely used as flame retardants in polyurethane foam and other consumer goods, but all U.S. uses of the compounds ceased at the end of 2013. Even so, the compounds' persistent presence across the globe continues to be monitored. The levels of PBDEs in many populations, including pregnant women in California, appear to be declining in recent years. [47]

They're still sometimes discovered in new populations, too. One recent example is a former competitive gymnast's research documenting that gymnasts who spend long hours in facilities with specialized gymnastics equipment can be exposed to high concentrations of some PBDEs, as well as other flame retardants. [48,49]

PFAAs are a class of chemicals with unique water-, dirt-, and oil-repelling properties; high stability; and resistance to degradation. They are used as surfactants in many industrial



Flame retardants identified in pit cubes.

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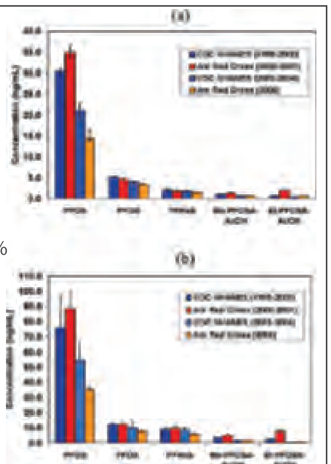
processes and consumer products, such as oil and water repellents for fabrics and food-packaging materials. [50] The recent news about these compounds is mostly good. 3M, one of the largest former manufacturers of chemicals related to an important PFAA, perfluorooctane sulfonate (PFOS), completed a voluntary phase-out of PFOS-related production in 2002 [51] The European Union, Canada, and the U.S. now restrict the use of PFOS or other PFAAs in certain industries. While studies showed increasing temporal trends of PFAA concentrations from the 1970s to the early 2000s, more recent studies have reported decreases of PFOS concentrations after 2000. The animal populations for which decreases have been documented include Canadian Arctic ringed seals, [52] harbor seals from the German Bight, [53] and sea otters off the coasts of California [54] and Alaska. [55] PFOS levels in U.S. citizens have also been declining. [56]

Temporal trends for five polyfluoroalkyl concentrations (ng/mL) from the CDC NHANES and American Red Cross study populations for (a) the population geometric means (95% confidence intervals), and (b) the geometric mean (CDC NHANES) or estimated 95th percentile tolerance limit (American Red Cross) with their upper 95th percent confidence limits.



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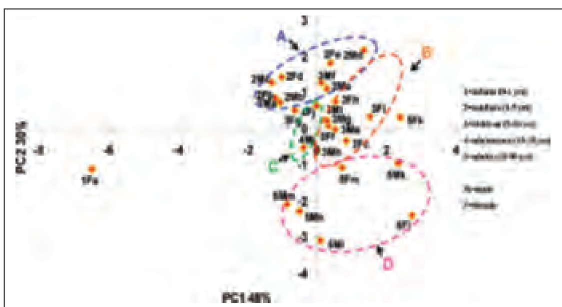
However, some studies show that, because of their persistence in the environment, levels of PFOS and other PFAAs continue to increase in some areas like the Baltic Sea and in some populations, such as Chinese infants. In the Baltic Sea, a mass balance study suggested that PFAA inputs were higher between 2005 and 2010 than during the previous 20 years, despite efforts to reduce emissions of the compounds. [57] The research team which undertook the study hypothesizes that this is due to retention and delayed release of PFAAs from atmospheric deposition in the soils and groundwater of the watershed. Other recent research indicates that the levels of PFAAs in Chinese infants are higher than levels reported for infants from other countries, suggesting that the use of PFC-containing products may be increasing in China. [58]



Plot of first two factors of principal component analysis of levels of six PFCs in whole blood from China. The encircled clusters identified as A, B, C, and D represent samples for infants and toddlers, children, adolescents and adults, respectively; small letters such as a, b, c, d, e, f, g, h, i, j, k, l, m, n represent 0–1, 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, 7–8, 8–10, 10–18, 18–60,

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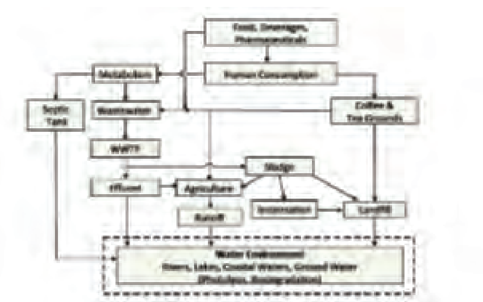
In the late 1990s, researchers began to discover widespread sexual disruption in wild fish and to question whether the presence of pharmaceuticals and personal care products (PPCPs) in the environment could explain this. [59] The first extensive search for PPCPs in U.S. water bodies, which showed that they were ubiquitous, was published over a decade ago in the journal *Environmental Science & Technology*. [60] Since then, many researchers have reported a variety of methods for finding an ever-wider array of compounds and detecting their effects in the environment. [61,62,63,64,65,66] Researchers have also been looking for and detecting other bioactive substances that human activities deposit into water, such as caffeine. [67]



Caffeine routes into the environment.

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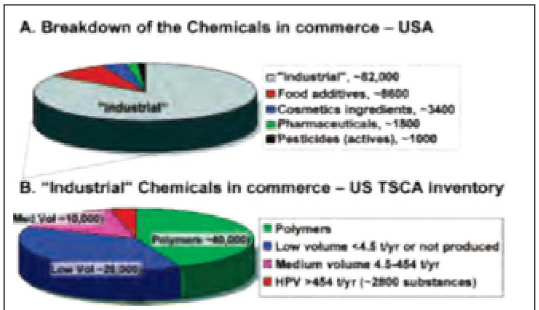
Environmental chemists have made important strides in identifying the transport and fate of many persistent and bioaccumulative chemicals in the environment as well as the trends in uptake of the chemicals by people and wildlife. However, the total number of chemicals currently measured in the environment represents only a small fraction of the approximately 30,000 chemicals that are now widely used in commerce. [44]

Major efforts are underway to screen existing and new chemicals for qualities related to persistence in the environment and the tendency to bioaccumulate—or to produce transformation products with these qualities. For example, in 2006, Environment Canada (the Canadian environmental protection agency) identified about 5.5% of 11,317 chemicals on the country's Domestic (existing) Substances list as having characteristics that make them likely to be persistent and/or bioaccumulative. [44] Since then, researchers have investigated potential compounds of concern from a number of different functional chemical groups. [68,69,70} Efforts such as these help environmental chemists understand what compounds they should be looking for. But in order to be able to detect a compound in the environment, there needs to be a method for analyzing the compound. [44] Developing methods to detect compounds either found in, or likely to be found in, the environment is another important task for analytically minded environmental chemists.



Estimated number and categories of chemicals in commerce registered for use in the United States over the past 30 years. Not all chemicals may be in current use. Similar proportions would be anticipated in other countries.

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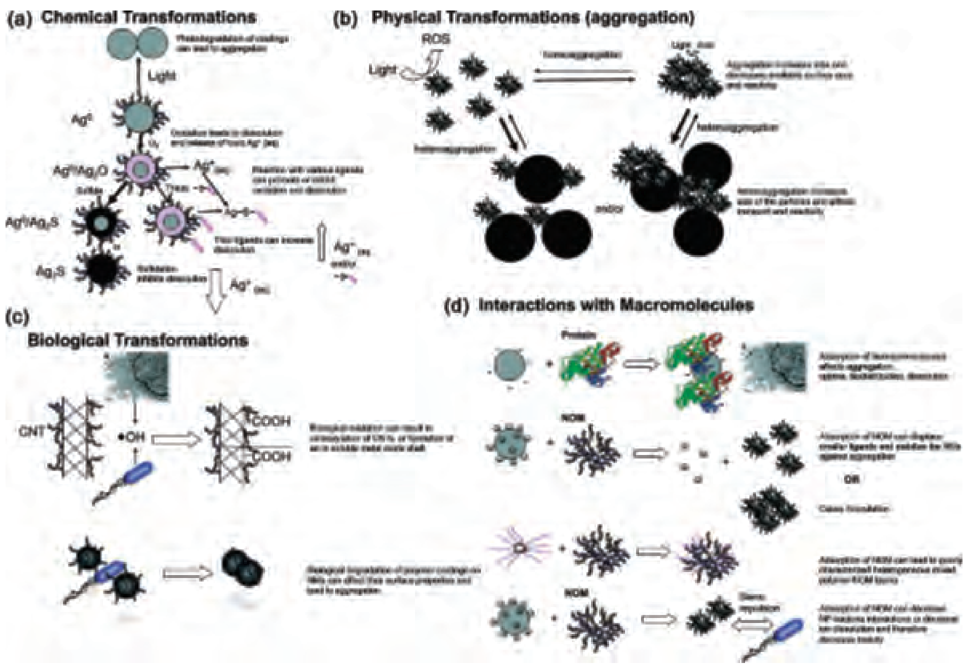
The term that environmental chemists use to describe newly detected chemicals is "emerging contaminants." However, an article in a 2006 special issue on emerging contaminants points out that the definition "is a bit elusive, because what is emerging is a matter of perspective as well as timing." [71] The author of a 2012 article described some of the subcategories of chemicals recently judged to be emerging. [72] One group is "new" emerging contaminants, which are chemicals that are recently manufactured and suddenly appear everywhere, such as decabromdiphenyleth*ane* being a sudden replacement for decabromyldiphenyleth*er*. [73] Another category includes "old" emerging contaminants, which are the ones that actually had been around for several decades, but simply were not on the radar or for which analytical methods did not exist until recently. One example is hexabromobenzene, whose ubiquitous presence is just now gathering attention, despite it likely being produced at high volumes since the 1970s. [74] Sometimes emerging contaminants are simply impurities associated with chemical formulations. [75,76] Metabolites of the emerging substances may also prove to be important. [77]

When the first data on a "new" or emerging contaminant comes to light, little is known about it, from its production volumes, to its physical–chemical properties, to its effects on humans and the environment, to how best to regulate the unknown risks it poses. [72] These unknowns can only be addressed with adaptation, exhaustive lab work, and extensive trial-and-error. Payoffs for taking on these challenges can go beyond environmental protection. For instance, research into poly- and perfluorinated chemicals led to improvements in models that predict physical-chemical properties and advanced liquid chromatography methods. It also shed new light on uptake mechanisms of protein-bound organic chemicals. [72]

Although they haven't yet been pegged as emerging contaminants, nanomaterials are an emerging area of interest to scientists of all stripes, and environmental chemists are no exception. As a recent article pointed out, nanoparticles' high surface-area-to-volume ratio can result in highly reactive and physiochemically dynamic materials in environmental media. [78]

This suggests (according to the article's authors) that many transformations, such as reactions with biomacromolecules, redox reactions, aggregation, and dissolution, may occur in both environmental and biological systems. These transformations and others may alter the fate, transport, and toxicity of nanomaterials. The nature and extent of these transformations must be understood before significant progress can be made toward understanding the environmental risks posed by these materials, as stressed by the authors.[78]



Representative chemical transformations of metal nanomaterials and the potential impacts on their behavior and effects in the environment. AgNPs are used to exemplify the types of transformations that may occur. The magnitude of arrows approximately correlates with potential for these processes to occur as determined from the limited data available on these processes. (b) Effects of physical transformations including aggregation and heteroaggregation on the reactivity and transport of nanomaterials. The magnitude of arrows approximately correlates with potential for these processes to occur as determined from the limited data available on these processes. (c) Biologically mediated transformations of nanomaterials and their coatings, and the subsequent impact on fate, transport, and effects. Arrows do not indicate the relative potential for these processes to occur due to the limited data currently available for that assessment. (d) Effects of nanomaterial interactions with macromolecules such as proteins and natural organic matter. Adsorbed macromolecules can affect aggregation, nanoparticle-biointeractions, biouptake, and fate, transport, and effects in the environment. Arrows do not indicate the relative potential for these processes to occur due to the limited data currently available for that assessment.

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V. GROWING INDOOR FOCUS

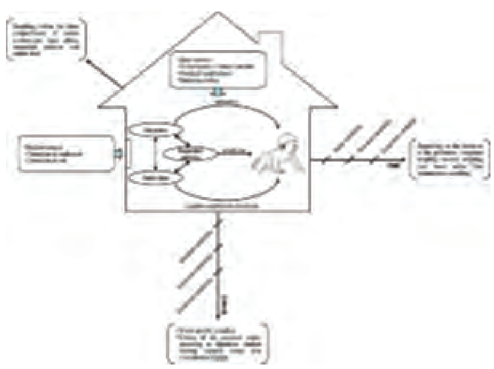
A growing body of work shows that human exposure to many pollutants may be higher indoors—sometimes by orders of magnitude—than outdoors. [79] This may make sense intuitively, but environmental chemists are at the forefront of the effort to dig up details to support this theory.

A symposium held during the American Chemical Society national meeting in San Francisco in 2010 was intended to bring together the atmospheric and indoor chemistry communities. [80] It was sponsored by the ACS Division of Environmental Chemistry and the National Science Foundation's Division of Chemical, Bioengineering, Environmental & Transport Systems. During the symposium, one of the symposium's organizers said that the field of indoor chemistry "is in the early stages of development, especially compared with its older sister, outdoor atmospheric chemistry, but techniques that are developed specifically for outdoor air may also be applicable indoors." [80] This is important because indoor concentrations of chemicals and resulting human exposures often substantially exceed corresponding outdoor concentrations, because there are significant indoor emission sources and much lower dilution volumes. [79] For example, typical concentrations measured for tetrachloroethylene and formaldehyde in the ambient environment are less than 9 and 24.6 $\mu g/m^3$, respectively, [81,82] , whereas they are several orders of magnitude higher in many industrial or household settings. [82,83] Moreover, people spend most of their time indoors, which for industrial countries amounts to more than 20 hours a day, on average, when considering both time spent at home and at the workplace or school. [84]

One recent study into indoor sources of particulate emissions in Amsterdam and Helsinki identified some significant sources of indoor particulates (in addition to the ones that enter the indoor environment from outside). [85] The study found one set of indoor-based particulates with an abundance of potassium and small amount of calcium, and a second characterized by copper. Although they weren't able to positively identify the sources, the researchers noted that known indoor sources of potassium are smoking, cooking, personal care products, and household chemicals. Similarly, the researchers noted that electric devices that use copper commutators for motor rotation, including electric fans and vacuum cleaners, are possible indoor sources of copper. Copper is also used as a paper coating pigment, in house plant fertilizers, and in cosmetics. [85] The researchers also discovered some chlorine-containing particulates that were not linked to outdoor levels. They suspected that the source could be chlorine-based cleaning products and city-supplied water, which other research has suggested as indoor sources of chlorine. [86]

Another recent study looked for potential endocrine-disrupting compounds inside the homes of non-smokers in two California cities, industrial Richmond and rural Bolinas. [87] The researchers detected 63 of the 104 analytes they analyzed for indoors, and 39 outdoors. They found that while levels of 32 of the analytes were higher indoors than outdoors; only 2 were higher in outdoor samples. Indoor concentrations of the most ubiquitous chemicals were generally correlated with each other (4-*t*-butylphenol, *o*-phenylphenol, nonylphenol, several phthalates, and methyl phenanthrenes), indicating possible shared sources. The researchers say their findings highlight the importance of considering mixtures in health studies. [87]

Recent research has shown that indoor dust can also be a significant route of human exposure to some indoor pollutants, particularly for young children. [88] House dust containing PBDE flame retardants has been correlated with elevated concentrations of the contaminants in the blood of people living in California (which historically has had the nation's strictest flame retardant standards). [89] Several studies of children both inside and outside of the U.S. have shown that their levels of PBDEs can be higher than those of adults, which researchers attribute to breastfeeding and children's higher frequency of hand-to-mouth behaviors. [90,91,92,89] Other research has documented that even though some PBDEs were phased out of use at the end of 2004, those PBDEs were still found in some house dust five years later, albeit in lower concentrations. [93] Other flame retardants, some with properties that suggested they may be toxic, are also found in newer dust samples. [93]



Critical issues to be considered when sampling indoor settled dust for exposure assessment purposes.

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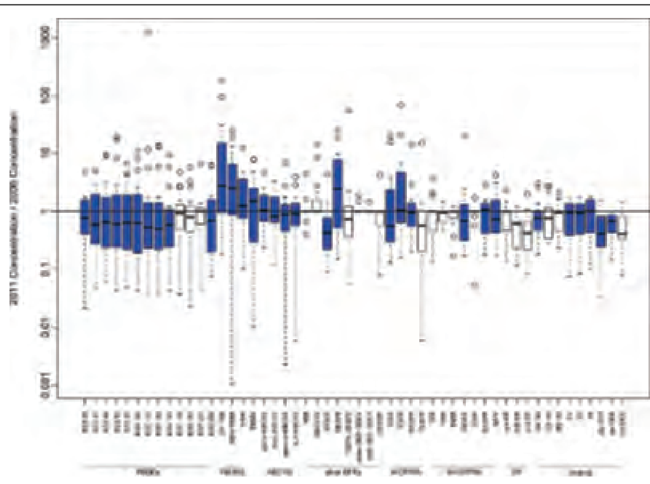

Distributions of concentration ratios (2011/2006) in dust collected from 16 homes. Nondetectable levels set to detection limit. Chemicals with median ratios above 1 were higher in 2011 samples compared with 2006 samples. Darker shaded boxes used for chemicals with >75% simultaneous detects.

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Recent research showing that competitive gymnasts at a college in the Northeast were exposed to high levels of PBDE flame retardants suggested that both dust and air could be significant sources of exposure to both PBDEs and newer flame retardants. [49] Although diet is the main route of exposure to PFOS, indoor dust can also be a significant source in some cases. [94] And house dust can also be a source of exposure to older contaminants, such as PCBs, particularly in older homes. [95]

Up until very recently, the health effects from indoor exposure have not been included in Life Cycle Assessments (LCAs). Such an omission may result in product or process optimizations at the expense of worker or consumer health. [79] One of the models now available allows for the assessment of household exposure to chemicals and radiation emitted to indoor air. [96] Another approach uses bulk-mixing models for occupational exposure in conjunction with multimedia models for the assessment of cumulative chemical exposure from ambient and indoor environments. [79] Studies done with both models illustrate that indoor exposure models are compatible with environmental models used in LCA. Moreover, they reveal the significance of health effects associated with occupational and household exposure in comparison to the total human-toxicity potential from all pathways. [79]

VI. REGULATORY SUPPORT

Like other environmental scientists and specialists, many environmental chemists are employed by local, state, or federal government agencies. [4] In those organizations, they can play a vital role in the development, implementation, and enforcement of both methods and regulations designed to protect and preserve the environment. [4]

An example is the Environmental Chemistry Laboratory operated by the U.S. Environmental Protection Agency's (EPA) Office of Pesticide Programs (OPP). The environmental chemists who work there evaluate test methods for pesticides in soil and water and work with chemists and other environmental specialists in EPA regional, federal, and state laboratories who use these methods. They also develop new methods for analyzing pesticides and related compounds of interest, such as dioxin, a toxic byproduct of combustion, and are also involved in monitoring studies. [97]

The role of environmental chemists and other environmental specialists in government has been increasing. This growth has occurred because many state and local governments have responded to growing pressure to protect the public from exposure to hazardous chemicals by restricting the use of chemicals not addressed by federal legislation, such as some of the PBDEs. Between 1990 and 2009, at least 18 states, 6 counties and 6 city governments enacted laws restricting PBDEs, lead, chromated copper arsenate, phthalates, bisphenol A, dioxin, perchloroethylene and/or formaldehyde. [98]

STATE AND LOCAL GOVERNMENT REGULATION OF INDUSTRIAL CHEMICALS NOT REGULATED FEDERALLY

While state and local governments have used different types of policies to target industrial chemicals not regulated federally through the U.S. Toxic Substances Control Act, the most widely used approach focuses on the restriction of single chemicals. Chemicals targeted by these policies include PBDE flame retardants, chromated copper arsenate, phthalate plasticizers, bisphenol A (BPA), perchloroethylene, and formaldehyde. [1]

In 2012, the U.S. EPA proposed amending its Significant New Use Rules related to compounds associated with the PBDE flame retardants. It also proposed covering PBDE flame retardants under the Toxic Substances Control Act (TSCA).[2] Prior to that, 12 states enacted legislation restricting the use of PBDE flame retardants in an array of products, including building materials, electronics, furnishings, plastics, polyurethane foams, and textiles. Four states (Maine, Oregon, Vermont, and Washington) restrict the pentaBDE, octaBDE, and decaBDE formulations. Five states (Illinois, Maryland, Minnesota, New York, and Rhode Island) restrict the pentaBDE and octaBDE and require further study of decaBDE. Three states, California, Hawaii, and Michigan, restrict the pentaBDE and octaBDE. A number of other states also proposed restrictions on some PBDE formulations. [3]

In 2010, the EPA initiated rulemaking to add eight phthalates to the Concern List under TSCA section 5(b)(4), designating them as chemicals that present or may present an unreasonable risk of injury to health or the environment.[4] Three states (California, Vermont, and Washington) and one city (San Francisco, CA) have enacted legislation banning phthalates in children's toys and childcare products. Many more states have proposed legislation to ban the plasticizers. Much of the legislation and proposed legislation also includes provisions that require the replacement of the phthalates in these products with safer alternatives. Hawaii has enacted legislation to further investigate the use of phthalates, while Minneapolis, MN, has enacted legislation urging the state to phase out of phthalates in children's products. [5]

Two states (Connecticut and Minnesota), one county (Suffolk County, NY) and two cities (Chicago, IL and San Francisco, CA) have enacted legislation banning BPA, which is commonly found in plastics and children's products. More than 20 states and a few other counties have proposed legislation restricting the use of BPA in children's toys, childcare products, and/or packaging. Much of the legislation and proposed legislation also includes provisions that require the replacement of the BPA in these products with safer alternatives. Hawaii has enacted legislation to further investigate the use of BPA. Pennsylvania has enacted a resolution urging Congress and the FDA to reduce the levels of BPA in plastic food containers, plastic bottles, and the lining of cans. Chicago, IL, has enacted a resolution urging the FDA to expedite its safety review of the compound. Minneapolis, MN, has enacted legislation urging the state to phase out of BPA in children's products. [6]

These are just some examples of existing and pending legislation banning or focusing on individual chemicals or chemical classes of concern by state, county and city governments. Other states, counties, and cities have enacted legislation or passed resolutions focused on persistent, bioaccumulative and toxic chemicals. Another approach that state, county and city governments are using is targeting product categories, including cleaning products, children's products and toys, and cosmetic and personal care products. [7]

[1] Lowell Center for Sustainable Production. "State Leadership in Formulating and Reforming Chemical Policy." University of Massachusetts Lowell: Lowell, MA, 2009: http://www.chemicalspolicy.org/downloads/StateLeadership.pdf.

[2] U.S. Environmental Protection Agency. "Polybrominated diphenylethers (PBDEs) Significant New Use Rules (SNUR)." Online at http://www.epa.gov/oppt/existingchemicals/pubs/qanda.html.

[3] Lowell Center for Sustainable Production. "State Leadership in Formulating and Reforming Chemical Policy." University of Massachusetts Lowell: Lowell, MA, 2009: http://www.chemicalspolicy.org/downloads/StateLeadership.pdf.

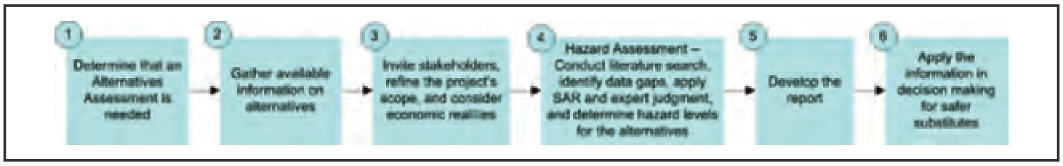
[4] U.S. Environmental Protection Agency. "Phthalates Action Plan Summary." Online at http://www.epa.gov/oppt/existingchemicals/pubs/actionplans/phthalates.htm.

[5] Lowell Center for Sustainable Production. "State Leadership in Formulating and Reforming Chemical Policy." University of Massachusetts Lowell: Lowell, MA, 2009: http://www.chemicalspolicy.org/downloads/StateLeadership.pdf.

[6] Lowell Center for Sustainable Production. "State Leadership in Formulating and Reforming Chemical Policy." University of Massachusetts Lowell: Lowell, MA, 2009: http://www.chemicalspolicy.org/downloads/StateLeadership.pdf.

[7] Lowell Center for Sustainable Production. "State Leadership in Formulating and Reforming Chemical Policy." University of Massachusetts Lowell: Lowell, MA, 2009: http://www.chemicalspolicy.org/downloads/StateLeadership.pdf.

A newer role for government environmental chemists is in assessing data about alternatives selected to replace chemicals identified as problematic. [99] What are known as alternatives assessments are methods for and efforts to assess chemical alternatives, to seek substitutes that are safer, and to avoid "regrettable substitutions."



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An example of a regrettable solution is the decision to replace methylene chloride, a chlorinated solvent, as an automotive brake cleaner with *n*-hexane. Although n-hexane performs well as a brake cleaner, its neurotoxic properties injured some auto mechanics in the late 1990s. [100] A more recent example is bisphenol S (BPS), a replacement for BPA in thermal paper that is also being detected in people. [101,102] Research suggests that, like BPA, BPS may exhibit hazardous estrogenic activity. [103,104]

VII. ALTERNATIVE CHEMICAL ASSESSMENTS

There are dozens of methods for evaluating new chemicals that are meant to replace substances found to be hazardous or otherwise problematic. [105] Exactly how these methods are used to help companies choose new chemicals is evolving, and it varies according to each specific set of circumstances. In some cases, governments are overseeing the process. Some methods come to differing conclusions based on the criteria that they use. One thing that all alternatives assessments always include is an evaluation of chemical hazards. [105] In order to avoid unintended consequences from switching to a poorly characterized chemical, alternatives assessments aim to identify and characterize chemical hazards and promote the selection of less hazardous chemical ingredients. [105] The assessments can also include information such as cost, availability, performance, and social and environmental life-cycle attributes. [105]
In addition to replacing one chemical with another that has been shown to be less hazardous and that fulfills the same purpose, the possible actions include reformulations, process changes, and product redesigns. Environmental chemists can help with all of this.

Chemical and pharmaceutical manufacturers are already conducting alternatives assessments in response to the European Commission's Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) program. [99] California's recently enacted Safer Consumer Product Regulations require manufacturers or other responsible entities to seek safer alternatives to harmful chemical ingredients in widely used products. [106] Because of the size of California's market, the state's program, which joins alternatives assessment to a decision process for selecting a course of action that leads to a reduction in toxic threats, is expected to have a

REGRETTABLE SUBSTITUTIONS

If a toxic chemical is removed from a product, it is usually replaced by some other substance—or substances—that carry out the removed ingredient's function, such as softening plastic or helping remove grease. Such a switch is intended to resolve the problem. But if the toxicity and other potential environmental impacts of the replacement aren't carefully evaluated, chemical replacements can lead to what is known as "regrettable substitution." [1]

Throughout the world, interest is burgeoning in approaches and policies that ensure that any new substances substituted for chemicals deemed to be problematic are assessed as carefully and thoroughly as possible. [1,2]

A number of groups are either working on or have recently published recommendations or guidance for assessing chemical alternatives. A coalition of regulatory agencies from 11 states known as the Interstate Chemicals Clearinghouse, or IC2, published a guide called the IC2 Alternatives Assessment Guide in January 2014. [3] In November 2013 a group of leaders from business, government, academic, and environmental groups known as BizNGO released a set of principles to guide retailers and product manufacturers in assessing alternatives and avoiding regrettable substitution. [4] Internationally, the Organisation for Economic Cooperation & Development, which includes 34 of the world's richest countries, is working to harmonize practices among its members on what it calls substitution of harmful chemicals.

The National Academy of Sciences Board on Chemical Sciences & Technology is also studying the design and evaluation of safer chemical substitutions at the behest of the EPA. [5] At a public meeting in November, James J. Jones, assistant administrator of EPA's Office of Chemical Safety & Pollution Prevention, said that alternatives assessments voluntarily conducted by the private sector will play a key role in improving safety of commercial chemicals in years to come. That's because regulatory processes for controlling commercial chemicals can take years to implement, he told the committee. [1]

[1] Hogue, C. "Assessing Alternatives To Toxic Chemicals." Chemical & Engineering News 2013, 50, pp 19-20. http://cen.acs.org/articles/91/i50/Assessing-Alternatives-Toxic-Chemicals.html

[2] Organisation for Economic Co-operation and Development. CURRENT LANDSCAPE OF ALTERNATIVES ASSESSMENT PRACTICE: A META-REVIEW Series on Risk Management No. 26. Online at http://search.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/JM/MONO(2013)24&docLanguage=En

[3] Interstate Chemicals Clearinghouse. Alternatives Assessment Guide Version 1.0. Online at http://www.newmoa.org/prevention/ic2/IC2_AA_Guide-Version_1.pdf.

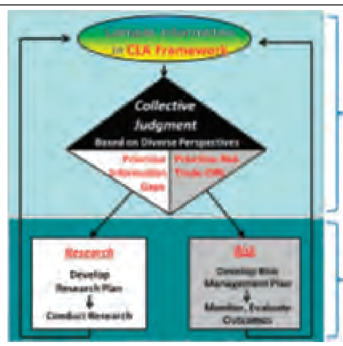
[4] http://www.bizngo.org/alternatives-assessment/chemical-alternatives-assessment-protocol

[5] U.S. National Academies Division on Earth and Life Sciences. Online at http://www8.nationalacademies.org/cp/projectview.aspx?key=49569

widespread impact. Canada's Chemicals Management Plan and the U.S. EPA's Enhanced Chemical Management Program are also driving forces behind chemical substitutions. [106]

Some chemical and pharmaceutical companies have also been using their own proprietary alternatives assessment approaches to identify chemical alternatives, as well as less energy-intensive processes that use fewer hazardous materials. Some product manufacturers have used such assessments to seek substitutes to controversial chemicals or precursor materials, such as the PBDEs. Some retailers such as Wal-Mart and Staples use such assessments to certify the superior environmental performance of the products they sell. Other manufacturers like HP, Dell, Nike, and Bissell have taken steps to go beyond regulatory restrictions in selecting the chemicals used to make their products as part of their own sustainability programs. [99]

Environmental chemists can also play a role in other assessments related to environmental decision making and sustainability. A more comprehensive kind of assessment is known as a comprehensive environmental assessment (CEA). Its creators define it "as a holistic way to manage complex information and to structure input from diverse stakeholder perspectives to support environmental decision-making for the near- and long-term. [107]



The CEA process builds on information compiled in the CEA framework and uses collective judgment to prioritize issues in support of research planning and/or risk management.

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The CEA has already been used in implementing recommendations related to risk assessment research in an EPA Nanotechnology White Paper. It has also formed part of the EPA Office of Research and Development

Nanomaterials Research Strategy. Other organizations have taken steps to adapt CEA as an aid in evaluating or planning research on environmental issues.[111,112]

In an era of increasing concern about global climate change and carbon emissions as a causal factor, many companies and organizations are pursuing "carbon footprint" projects to estimate their own contributions to global climate change. [110] Environmental chemists' education positions them to help businesses use comprehensive environmental life-cycle assessment methods to track total emissions across the entire supply chain. [110] The scope of protocol definitions from carbon registries varies, and many registries suggest estimating only direct emissions and emissions from purchased energy. Following narrowly defined estimation protocols can lead to large underestimates of carbon emissions for providing products and services. Direct emissions from an industry are, on average, only 14% of the total supply chain carbon emissions, while direct emissions plus industry energy inputs are, on average, only 26% of the total supply chain emissions. [110]

Environmental chemists are also well-positioned to assess the sustainability of chemical process design. A recent paper laid out a systematic, general approach for sustainability assessment and design selection in the chemical industry, through integrating hard (quantitative) economic and environmental indicators along with soft (qualitative) indicators for social criteria into design activities. [111]

Environmental chemists are arguably in an ideal position to use what they have learned about emerging contaminants to help industry make commercially viable, environmentally benign replacements. [72] In many ways the process is similar to research on emerging contaminants. The same analytical methods, toxicity assay procedures, property tests, and models can be used. [72] In theory, at least, the models and test systems that were developed to estimate persistency, bioaccumulation, and toxicity in the environment can also be used to ensure that new chemical alternatives are persistent in the material they are applied to but not in the environment, either because of rapid degradation, negligible sorption to organisms, low toxicity, or all three. [72]

EXCERPTS FROM THE EPA WHITE PAPER ON NANOTECHNOLOGY

Understanding the physical and chemical properties… is necessary in the evaluation of hazard…. The diversity and complexity of nanomaterials makes chemical identification and characterization not only more important but also more difficult. A broader spectrum of properties will be needed to sufficiently characterize a given nanomaterial for the purposes of evaluating hazard and assessing risk. Chemical properties such as [, composition, structure, molecular weight, melting point, boiling point, vapor pressure, octanol-water partition coefficient, water solubility, reactivity, and stability] may be important for some nanomaterials, but other properties such as particle size and size distribution, surface/volume ratio, shape, electronic properties, surface characteristics, state of dispersion/agglomeration and conductivity are also expected to be important for the majority of nanoparticles.

A given nanomaterial can be produced in many cases by several different processes yielding several derivatives of the same material. For example, single-walled carbon nanotubes can be produced by several different processes that can generate products with different physical-chemical properties (e.g., size, shape, composition) and potentially different ecological and toxicological properties. [1,2] It is not clear whether existing physical-chemical property test methods are adequate for sufficiently characterizing various nanomaterials in order to evaluate their hazard and exposure and assess their risk. It is clear that chemical properties such as boiling point and vapor pressure are insufficient. Alternative methods for measuring properties of nanomaterials may need to be developed both quickly and cost effectively.

Because of the current state of development of chemical identification and characterization, current chemical representation and nomenclature conventions may not be adequate for some nanomaterials. Nomenclature conventions are important to eliminate ambiguity when communicating differences between nanomaterials and bulk materials and in reporting for regulatory purposes.

EPA's Office of Pollution Prevention and Toxics is participating in new and ongoing workgroup/panel deliberations with the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), and the International Organization for Standardization (ISO) concerning the development of terminology and chemical nomenclature for nano-sized substances, and will also continue with its own nomenclature discussions with the Chemical Abstracts Service (CAS).

[1] Thomas, K. and Sayre, P. "Research Strategies for Safety Evaluation of Nanomaterials, Part I: Evaluating Human Health Implications for Exposure to Nanomaterials." *Toxicol. Sci.* 2005 87(2): 316 321.

[2] Oberdörster, G., Oberdörster, E., Oberdörster, J. "Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles." *Environ. Health Perspect.* 2005 113(7): 823839.

VIII. GREEN CHEMISTRY

In essence, the approaches mentioned in the previous section are an application of the growing "green chemistry" movement that began in academia and is beginning to impact industry. [112,72] As defined by the EPA, green chemistry is the "design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances." [113] Green chemists' goals are to design new chemicals that are inherently safer. [114,115] This involves a consideration of safer chemical synthetic approaches, environmental and biological fate of chemicals, and how and where a chemical is transported in these systems. [116] Green chemists are also taking into account other issues like carbon and contaminant emissions during the life cycle of chemical production and the products the chemicals are applied to. [72] Chemists who follow these principles can simultaneously "bring about environmental improvement benefiting human health and economics and profitability," according to one of the movement's founders. [117]

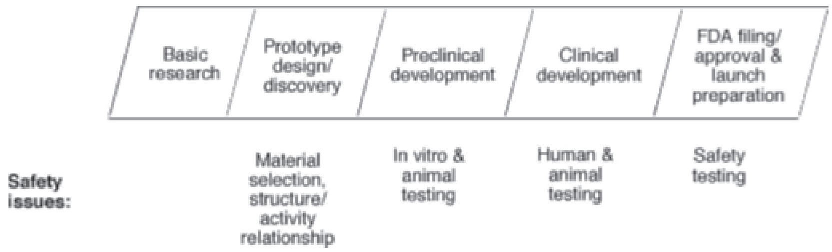
Thousands of innovations have already resulted from green chemistry, including compounds used in electronics, aerospace, cosmetics, agriculture, and energy. [117] A market analysis report published in spring 2011 predicts that the green chemical industry will soar to $98.5 billion by the year 2020. [118] Access to information about the growing number of green chemicals can help those who conduct alternatives assessments identify safer substitutes. [119]

IX. 21ST CENTURY TOXICOLOGY

Toxicological testing to determine how much of a given compound can be safely taken into the body has always gone hand-in-hand with environmental chemistry. Recent advances in the development of toxicological test methods capitalize on the latest methods in biochemistry and molecular biology that have enhanced scientists' understanding of the nature and mechanisms underlying how chemicals cause adverse effects. [120] The new tests include high-throughput in vitro methods, systems biology, and computer-based modeling. Their implementation is expected to result in a dramatically decreased reliance on animal testing. The new tests have the potential to be much quicker and less expensive than the tests traditionally used to evaluate toxicity. [121]

The result is a conceptual shift in toxicological studies from describing *what* happens to explaining *how* the adverse outcome occurs, thereby enabling a deeper and improved understanding of how biomolecular and mechanistic profiling can inform hazard identification and improve risk assessment. [122] Some of the advances and tools that are starting to be applied using this new approach to evaluating chemical toxicity were originally developed for use in the pharmaceutical industry. [123]

The path of drug discovery and development:



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Of course, before scientists will be able to understand how a chemical will behave in a living system simply by running it through a panel of cell-based screening assays or plugging it into a computational model, they need a clear understanding of the cellular pathways that are involved in toxicity and the responses that are indicative of adverse outcomes. [124] In the U.S., a group of government agencies, including the EPA, the National Institutes of Health, and the Food & Drug Administration, are collaborating on a project called Tox21 to research innovative chemical testing methods. The project's goals include collecting a list of all human pathways and designing assays that can measure the chemical responses of these pathways. [125] The researchers are also investigating how exposure to chemical compounds may disrupt processes in the human body, called "toxicity pathways," and how this connects to adverse health effects. [126] A significant contribution to the Tox21 effort comes from ToxCast, an EPA program that builds predictive toxicology models with data from high-throughput screening assays. [127] The mandate in the European Commission's REACH law that industry had to eliminate the use of animals in toxicity testing by the end of 2013 has also driven the use of new toxicity testing methods. [124]

Some of the newest alternative testing systems being developed are known as "organs on a chip." [128] One of the first successful reports of reconstituting organ-level functioning on a computer chip-based apparatus involved a system that mimics the functioning of human lungs. [129] Research groups around the world are now working on similar systems. Some show promise for toxicity testing, such as a chip containing components of liver and kidney organs that was able to accurately recapitulate the known liver and kidney toxicity associated with exposure to several known toxicants, including ammonia. [130]

Some experts believe that training in the chemical sciences is a good way to help prepare future toxicologists to be able to embrace the new tools and systems becoming available to recognize hazard and determine risk. This can both prevent risky chemicals from reaching the public and also reduce false-positive calls, thus allowing more development to proceed. [131] Testing with the new tools becoming available is depositing a tidal wave of new information in the public domain, which may prove useful for chemical alternatives assessments and other work undertaken by the environmental chemists of the future. [131] New approaches to toxicity testing are also expected to be important for evaluating the environmental health and safety of engineered nanoparticles, which can have novel physicochemical properties that could generate hazardous biological outcomes. [132,133,134] Experts are also calling for chemists to be well grounded in toxicology. [117]

X. MICROFLUIDICS

Over the past few years, a growing number of researchers have recognized the utility of microfluidic devices for environmental analysis. [135] Microfluidic devices offer a number of advantages, and in many respects they are well suited to environmental analyses. [135] Challenges faced in environmental monitoring, including the ability to handle complex and highly variable sample matrices, have led to continued growth and research. [135]

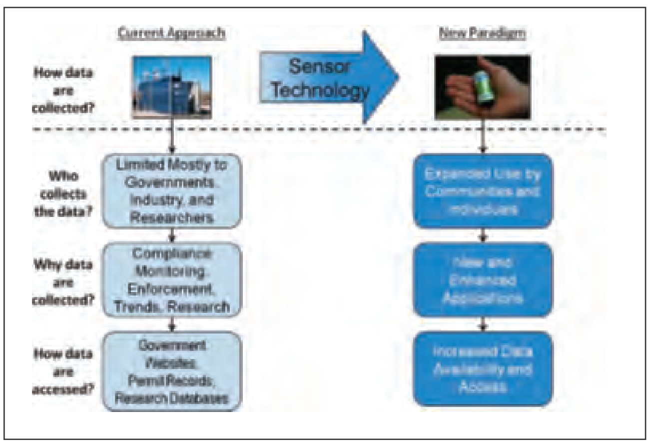
Although a microfluidic device can be coupled with conventional instrumentation, the stand-alone integrated detection systems being developed are considered to have more promise, because they are more compact and less expensive platforms. [136] In recent years, microfluidic devices have been integrated onto computer chips to create "lab-on-a-chip" technology for analyzing water quality, air quality, and aerosol monitoring. [135] The lab-on-a-chip approach can offer many advantages to environmental analysis. It can reduce analysis time, improve detection limits, and allow on-line, real time monitoring. [135] Other new devices with environmental applications that incorporate microfluidics include new technologies for testing toxicity. [137,138]

The lab-on-a-chip devices that have been developed to date for environmental sensing include equipment capable of detecting low concentrations of chromium Cr(VI), mercury ion (Hg^{2+}), and nitrite in water. [135,139,140,141] Microfluidic devices for identifying air pollutants include devices and methods for determining the atmospheric concentration of aldehydes, ambient aerosol compositions, and airborne detection of benzene, toluene, ethylbenzene, and xylene (BTEX) gases. [142,143,144] However, the need to operate for days to months in the field requires further development of robust, integrated microfluidic systems. [135]

XI. AIR POLLUTION MONITORING

Advances in microfluidics and low-cost portable sensors are among the reasons behind the rapid change in how air pollution is being monitored. Historically, approaches for monitoring air pollution generally involve expensive, complex, stationary equipment, which limits who collects data, why data are collected, and how data are accessed. [145] The development of portable, lower-cost air pollution sensors capable of reporting data in near-real time at a high-time resolution, as well as increased computational and visualization capabilities, and wireless communication and infrastructure, are all contributing to this paradigm shift. [146]

Recent advances in multiple areas of electrical engineering have contributed to these improvements, including microfabrication techniques and microelectro-mechanical systems (MEMS) that can incorporate microfluidic, optical, and nanotube elements. [147] Low-cost and portable sensors capable of reporting data in near real-time are commercially available for pollutants covered by the Clean Air Act's National Ambient Air Quality Standards (NAAQS), including CO, NO_2, O_3, and PM mass. [146] Inexpensive sensors capable of measuring particle scattering and absorption, which have direct relationships to visibility and climate change, are also available.



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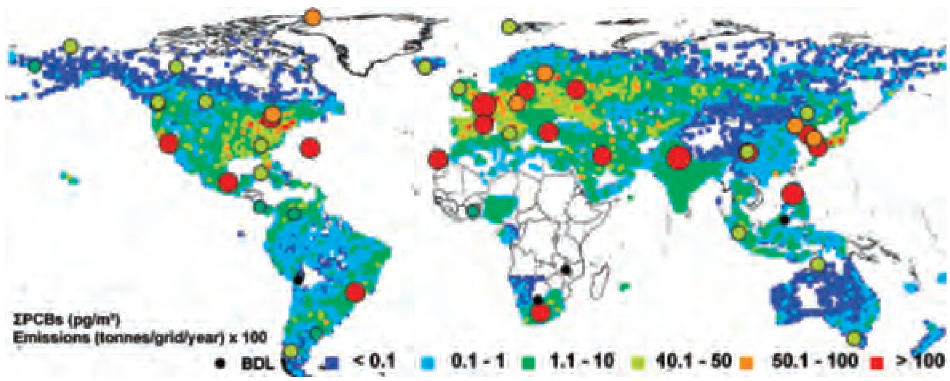
These advances have the potential to support traditional air quality monitoring by supplementing ambient air monitoring and enhancing compliance monitoring. Such sensors are beginning to provide individuals and communities with tools that may enable the development of individual and community-based strategies to reduce pollution exposure, as well as understand linkages to health indicators. [146]

A second class of air pollution sensing equipment that is helping environmental chemists and other scientists collect important data on air pollutants is passive samplers. [148] These simple, inexpensive, yet robust samplers have expanded environmental chemists' ability to investigate how air pollutants travel throughout the globe by providing access to samples from a much wider range of geography than the more expensive active samplers used in the past. [149] This has increased knowledge about ambient air concentrations, sources, and



Mean concentrations in air for PCBs across GAPS sites during 2005, superimposed over the global PCB inventory for 2005 reported by Breivik 16. Air concentrations for PCBs are in units of pg·m−3 and PCB emissions are in t·year−1 for 1o × 1o longitude and latitude resolution.

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sinks, as well as atmospheric transport of chemical contaminants across the globe. [150]

Passive air samplers are particularly suitable for capturing persistent organic pollutants (POPs) data in developing countries, because they can operate without electricity and are much less expensive than the high-volume samplers conventionally used to capture POPs data. [148] Passive samplers from a test network set up by the Canadian government collected the first data from Africa and South America on air pollutants associated with the Stockholm Convention on POPs. Because all of the data are from one network, they avoid the difficulties associated with trying to amass global data by harmonizing information collected through regional networks of conventional high-volume samplers using varying analytical and sampling protocols. [151]

Passive samplers are now being used to collect data on some of the POPs covered by the Stockholm Convention on POPs. [151] The Stockholm Convention, administered by the UN Environment Programme, targets POPs for worldwide elimination because of their links to "serious health effects, including certain cancers, birth defects, dysfunctional immune and reproductive systems, greater susceptibility to disease, and even diminished intelligence," according to the treaty's website. Data from passive sampling has also brought to light unexpectedly high levels of some pollutants, including the pesticide endosulfan prior to its incorporation into the POPs treaty. [150]

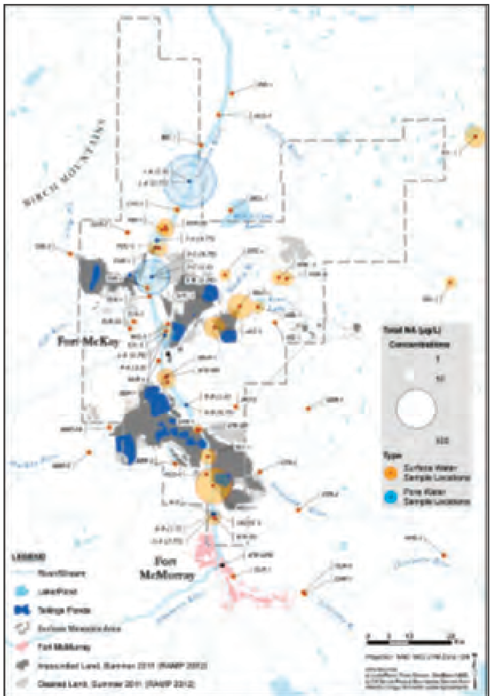
XII. FUTURE WATER QUALITY

Environmental chemists can play an important role in helping ensure that the United States—as well as the rest of the world—maintains high-quality supplies of water in the nation's rivers, lakes, and underground reservoirs. According to the U.S. Geologic Survey, which has conducted detailed surveys of environmental contaminants in these waters, continual advances in our understanding of an increasingly complex set of underlying controlling factors is required to sustain our nation's water quality. [152]

The majority of current water-quality problems are caused by diffuse nonpoint sources from agricultural land, urban development, forest harvesting, and the atmosphere. Compared to point sources such as industrial discharge pipes, these nonpoint sources are more difficult to effectively monitor, evaluate, and control. [152] When the Clean Water Act was passed in 1972, the main concerns were related to the sanitary quality of U.S. rivers and streams, such as temperature, salinity, bacterial counts, oxygen levels, and suspended solids. [152] Largely due to improvements in laboratory techniques, scientists have identified microbial and viral contaminants, pharmaceutical compounds, and endocrine disrupters in our waters. Hundreds of synthetic organic compounds, such as pesticides and volatile organic compounds in solvents and gasoline, are introduced into the environment every day. [60,152]

Among *Environmental Science & Technology's (ES&T)* top papers of 2012 are six related to identifying new water-quality issues. [153] Two of these papers were by research teams which independently identified that hydroxylated polybrominated diphenyl ethers (OH-PBDEs) can generate brominated dioxins via photolysis. [154,155] OH-PBDEs are both transformation products of PBDE flame retardants and naturally occurring compounds. As one of the papers points out, the research helps explain the high levels of polybrominated dibenzo-*p*-dioxins (PBDDs) that have been found in Baltic Sea biota. [154] Some of the studied OH-PBDE compounds are capable of photochemically generating to produce other compounds of concern, including brominated phenols and a dibenzofuran. [155]

Another *ES&T* paper outlines new research that shows how quantitative structure activity relationships (QSAR) can be used to predict acute toxicities for different aquatic species' exposure to metals. [156] Metals are widely distributed pollutants in water and can have detrimental effects on some aquatic life, as well as humans. Over the past few decades, the EPA has published a series of guidelines with criteria maximum concentrations (CMCs) for 10 metals. However, CMCs for other metals are still lacking because of financial, practical, or ethical restrictions on toxicity testing. The researchers used a novel model to predict acute toxicities of 25 metals and metalloids, for species in five phyla and eight families of organisms.



Map of study area showing sampled surface water and groundwater seep locations. Colors of circles represent surface water or sediment pore water sample collection sites. The size of each circle is proportional to the total naphthenic acids (NA) concentration measured.

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The model can provide a beneficial supplement to existing methodologies for developing preliminary screen level toxicities or criteria for metals, for which little or no relevant information exists on the toxicity to particular classes of aquatic organisms.

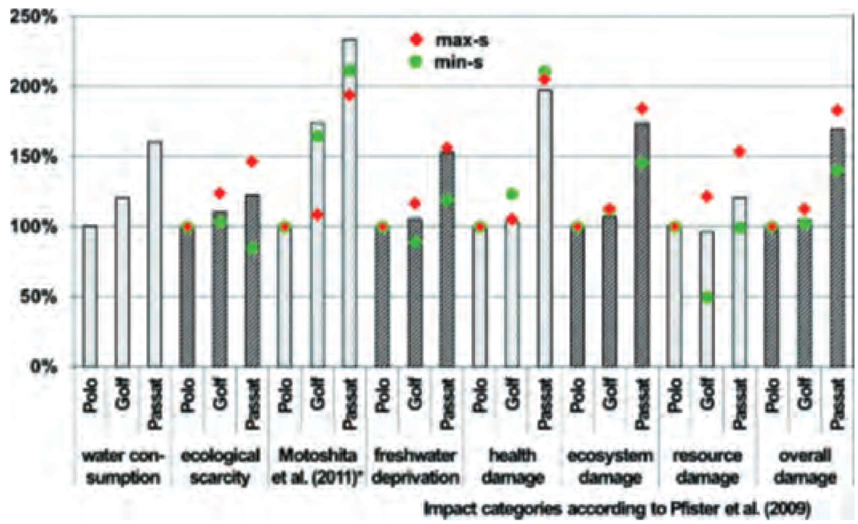
Investigations by environmental chemists can bring to light important new evidence on high-profile topics. A case in point is recent research investigating the presence of naphthenic acids (NAs; $C_nH_{2n-Z}O_2$), which are associated with Canada's oil sands industry, in rivers and surface waters near the industry's activities. [157]

NAs are toxic components of oil sands process-affected water, but are also natural components of bitumen and regional groundwaters, and they may enter surface waters through anthropogenic or natural sources. The researchers used a selective high-resolution mass spectrometry method to examine total NA concentrations and NA profiles in oil sands process water, as well as samples from surface water bodies in the region, including the Athabasca River. They found that NA concentrations in surface water were 100-fold lower than previously estimated, and they were able to highlight two tributaries to the Athabasca River as possibly receiving oil sands process water seepage.

Many scientists are concerned about how engineered nanoparticles may affect water supplies. A recent paper described a method for detection, characterization, and analysis of engineered nanoparticles in both ultrapure water and in complex waters, such as simulated wet land ecosystem water and wastewater. [158] The methodology is based on hyperspectral imagery with enhanced darkfield microscopy. By analyzing 12 different nanoparticle sample types, researchers showed that the method could provide information about spectral characteristics unique to each nanoparticle type at a sensitivity of a single nanoparticle (size ≥10 nm), as well as information about spatial distribution. The existence of a promising tool for detection and characterization of engineered nanoparticles in environmental systems can facilitate studies on fate and transformation of these particles in various types of water samples.

The recognition that industrial processes' use of water has an effect on freshwater availability was the inspiration for a recent investigation into the water consumption and other environmental impacts associated with producing Volkswagen's Polo, Golf, and Passat car models. It represents the first application of impact-oriented water footprint methods on complex industrial products. [159]

The researchers found that water consumption along the life cycles of the three cars ranges from 52 to 83 m^3/car, of which more than 95% is consumed in the production phase, mainly resulting from producing iron, steel, precious metals, and polymers. Results show that water consumption takes place in 43 countries worldwide, and that only 10% is consumed directly at Volkswagen's production sites. The impacts on health tend to be dominated by water consumption in South Africa and Mozambique, resulting from the production of precious metals and aluminum, while consequences for ecosystems and resources are mainly caused by water consumption of material production in Europe.



Relative comparison of results on the inventory and impact assessment levels for the Polo, Golf, and Passat normalized to the results obtained for the Polo in the default scenario (bars), the min-s scenario (circles), and the max-s scenario (diamonds).

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Because the investigation of water chemistry-related issues is typically of an interdisciplinary nature, the field is expected to continue to benefit from advances in materials characterization, molecular biology, and mass spectrometry in coming years. [160] Water chemists work across scales ranging from molecular to global, and they are poised to make additional contributions to improve our understanding of important, societally relevant water issues. These include the nature and behavior of natural organic matter and related organic matter in wastewater effluents, the role of biomolecules (e.g., genes, prions) as pollutants, critical biogeochemical processes involving carbon, and nitrogen and phosphorus in natural systems. [160]

XIII. EARTH SYSTEM RESEARCH

In recent years, a growing body of research has attempted to consider the interconnections between the chemistry of the atmosphere, oceans and water bodies, and the land, as well as the enormous impact that human activities can have on all three. Examples of these links include the effects of changing climate on the recovery of the ozone hole and vice versa, as well as the implications of global climate change on the chemistry of natural waters, including the problem of ocean acidification. [161]

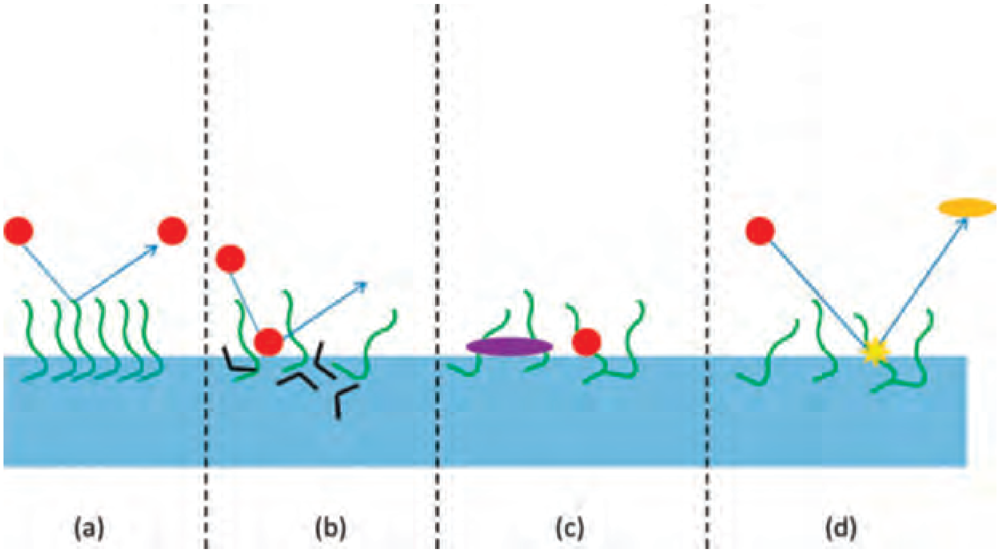
The Intergovernmental Panel on Climate Change's 4th Assessment stresses that interactions between climate and atmospheric oxidants, including ozone, provide important coupling mechanisms in the Earth system. [162] The concentration of tropospheric ozone has increased substantially since the pre-industrial era, especially in polluted areas of the world, and this has contributed to radiative warming. Emissions of chemical ozone precursors (such as carbon monoxide, methane (CH_4), non-methane hydrocarbons, and nitrogen oxides) have increased as a result of larger use of fossil fuel, more frequent biomass burning, and more intense agricultural practices. Changes in atmospheric chemical composition that could result from climate changes are less well quantified. Photochemical production of the hydroxyl radical (OH), which efficiently destroys many atmospheric compounds, occurs in the presence of ozone and water vapor, and is likely to be enhanced in an atmosphere with increased water vapor, as projected under future global warming.

Other chemistry-related atmospheric processes that may be affected by climate change, according to the IPCC, include production of nitrogen oxides as a result of lightning flashes in thunderstorms. Lightning is a major source of nitrogen oxides in the atmosphere, which are a precursor for ozone production in the troposphere. Because ozone is also a greenhouse gas, changes in lightning may result in additional warming in the climate system. [163] Scavenging mechanisms that remove soluble species from the atmosphere may also be impacted. The natural emissions of chemical compounds, such as biogenic hydrocarbons produced by vegetation, nitrous and nitric oxide generated by soils, and dimethylsulfide (DMS) from the ocean, and the surface deposition of molecules on vegetation and soils could also be affected. Changes in atmospheric circulation, such as the more frequent occurrence of stagnant air events in urban or industrial areas, could enhance the intensity of air pollution events. The importance of these effects is not yet well quantified. [162]

Researchers investigating these topics include a team with members at the U.S. National Atmospheric and Oceanic Administration and at ETH in Switzerland who are studying climate-chemistry interactions, such as how changes in the composition of the stratosphere may affect the climate and the links between changes in stratospheric ozone, UV radiation, and tropospheric chemistry. [164]

Other recent research that investigates the interconnections between the chemistry of the atmosphere, oceans and water bodies, and the land includes an investigation into how changes in climate and atmospheric deposition of base cations can alter the ionic composition of soil and surface waters. [165] The research investigated how these changes can affect the structure and function of sensitive ecosystems, and it suggests that greater emission controls on sources of nitrogen and sulfur may be needed in the future to reduce acidic deposition.

Another recent paper used data from measurements and models to analyze how mineral dust emissions to the atmosphere may affect marine biogeochemistry. [166] Scientists have a poor understanding of the mechanisms and quantities of dust deposition, but the iron that is sometimes present in mineral dust can impact marine phytoplankton growth. Model estimates of dust deposition vary by more than a factor of 10, and the fraction of the iron in dust that is available for use by the phytoplankton is uncertain. The researchers say that there is an urgent need for a long-term marine atmospheric surface measurement network to collect data pertinent to this issue. Another important issue is the abundance of organic compounds at the surface of the oceans, and their link with both oceanic biogeochemistry and atmospheric chemistry. [167] Physicochemical processes at and near the air-water interface affect the formation and growth of marine boundary layer aerosols, as well as their evolution in the atmosphere.



Schematic displaying different ways in which an organic coating at an aqueous surface may influence chemistry there. (a) coating blocks interfacial transport of the molecule shown as the red circle; (b) coating prevents surface hydrolysis of impinging gas phase species; (c) coating enhances surface concentrations of reagents (shown as the red and purple shapes);(d) coating constituents react with gas phase species (red circle) to form products (yellow shape).

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XIV. THE FUTURE

Although the environmental risks of chemicals are usually assessed substance by substance, efforts are underway to evaluate the effect of exposure to mixtures of contaminants, including "emerging contaminants within complex mixtures" (e.g., industrial effluents, oil residues, or hospital effluents) where either the mixture itself or newly identified (subgroups) of components within may be considered emerging contaminants. [72,168]

Also getting more attention are "transformation derived" emerging contaminants, which are pernicious metabolization or transformation products of emerging contaminants, legacy contaminants, or benign chemicals. [72] Transformation products are becoming a topic of interest not only with regard to their formation in the environment, but also during advanced water treatment processes, where disinfection byproducts can form from benign precursors. [169] Efforts to detect human and veterinary pharmaceuticals in the environment also require environmental scientists to look for transformation products, because most pharmaceuticals are not excreted into wastewater in their original form. [169]

On the analysis front, an up-and-coming approach is "non-targeted analysis" that attempts to identify everything in a sample, rather than trying to measure one thing at a time. "We really have to make strides in this area if we're going to fully understand links between exposure and human health," says one prominent environmental chemist. [170] The instruments used for these kinds of analyses include gas chromatography coupled with time-of-flight mass spectrometry (GC/TOF-MS) and the Thermo Scientific Orbitrap Velos Pro hybrid quadrupole mass spectrometer with a dual-pressure linear ion trap.

Low-cost, paper-based diagnostic and analytical devices are another emerging technology for environmental analysis. [135] The advantages of paper-based analytical devices include their simplicity, portability, disposability, and cost-effective fabrication. Paper-based microfluidic sensors include devices based on colorimetric and electrochemical sensing, as well as a combination of the two. [171,172] A paper-based analytic device has also been developed for measuring human exposure to particulate matter. [173]

Upcoming issues in water chemistry include the role of biomolecules, such as genes and prions, as pollutants, and increased understanding of critical biogeochemical processes involving carbon, nitrogen, and phosphorus in natural systems. [160] Water chemistry will continue to play a critical role in the goal to provide sufficient and safe water for the world's growing population, and water treatment and reuse will require further technological advances. [160] Improvements in computational techniques may improve scientists' ability to predict what chemicals may pose a threat to aquatic systems prior to their release. [160]

Experts have recommended terming the geologic era in which we are living the Anthropocene in response to the dramatic impact that humanity has had on the world. [2] Some experts believe that environmental chemists are particularly well positioned to help change the world in positive ways. In time, for example, environmental scientists and chemists may also begin to use the knowledge they've gained through studying emerging contaminants to produce what one visionary calls "decontaminants." [72] He argues that chemists could draw from the same toolbox that is used to study emerging chemicals: the same analytical methods, toxicity assay procedures, property tests, and models. Scientists could "simply… turn… the focus of emerging contaminant research on its head. The models and test systems developed to estimate persistency, bioaccumulation and toxicity in the environment would be used to ensure that emerging decontaminants are persistent in the material they are applied to but not in the environment, either because of rapid degradation, negligible sorption to organisms, low toxicity, or all three." [72]

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XVI. APPENDIX A: ENVIRONMENTAL CHEMISTS AROUND THE WORLD

KURUNTHACHALAM KANNAN

Research Scientist, New York State Department of Health's Wadsworth Center
Professor, State University of New York, Albany

As a research scientist for the New York State Department of Health's Wadsworth Center, Kurunthachalam Kannan spends his time investigating the sources, pathways, distribution, dynamics and fate of chemical pollutants to which humans can be exposed. He believes that these investigations are crucial for laying the groundwork to allow scientists to devise solutions to current and future environmental problems.

"I always wanted to work in a field that would benefit the well-being of the society," Kannan says. "Environmental issues have direct bearing on not only people's quality of life but also a nation's economy." When environmental issues grow in tandem with a nation's Gross Domestic Product, the resulting impacts on ecosystems can impair the health and prosperity of that nation's citizens, he points out.

Kannan majored in Agricultural Sciences as an undergraduate at Tamil Nadu Agricultural University, in Coimbatore, India, where he won the Governor's gold medal in 1986 for being the top ranking student in an undergraduate program. He went on to graduate studies in environmental chemistry in Japan at Ehime University and completed his Ph.D. under the supervision of Ryo Tatsukawa and Shinsuke Tanabe, who are known for their pioneering research on global ocean pollution and global transport of pollutants. Kannan had the opportunity to work on environmental samples collected from all over the world to support his research, which was focused on understanding the distribution and dynamics of persistent organic pollutants in the global environment.

Next, Kannan moved to the U.S. for postdoctoral training at the Skidaway Institute of Oceanography and Michigan State University. While he was in Michigan, he conducted groundbreaking research in collaboration with ecotoxicologist John Giesy (who is now at the University of Sasketchewan). The team collected and analyzed hundreds of samples from bald eagles, polar bears, albatrosses, and various species of seals from both urbanized areas in North America and Europe and more remote areas including sites in the Arctic and North Pacific Oceans. Their work showed that perfluorooctanesulfonate (PFOS), a fluorinated organic compound, was a global contaminant with a tendency to bioaccumulate. [1,2] Their work led the 3M Company, which used PFOS in its initial formulation of the Scotchguard fabric protectant, to announce that it would voluntarily cease essentially all production of PFOS-containing products. [3]

From there, Kannan moved to his current position at the New York State Department of Health's Wadsworth Center. His publications include a widely used analytical method to detect perfluorochemicals in environmental samples. [4,5] His group also published the first study to use dried blood spots from a newborn screening program to assess exposure of newborns to environmental chemicals. [6] His team is currently "building this area of research." He was also involved in the first study to show that personal care products can be an important source of human exposure to siloxanes. [7]

In 1999, Kannan's accomplishments earned him the Society of Environmental Toxicology and Chemistry (SETAC) Weston F. Roy Award in Environmental Chemistry. He also received a Super Reviewer Award from *Environmental Science & Technology* in 2013.

Kannan says that in his experience as an environmental chemist, "laboratory analytical work is directly applied and used for making regulatory and policy decisions." Because environmental chemistry is a relatively young science, "there are so many new things to be discovered," he says. This is one of the reasons he enjoys educating and training students and young researchers in his capacity as a professor of environmental chemistry at the State University of New York's Albany campus.

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KRISTOPHER MCNEILL

Professor of Environmental Chemistry, ETH Zurich

Many of the world's most prominent environmental chemists and environmental scientists have spent at least a little time researching in Switzerland, most likely at Eawag, the Swiss Federal Institute of Aquatic Science and Technology, or at the Swiss Federal Institute of Technology (ETH) in Zurich. "Switzerland is a pretty special place for environmental chemistry," says Kristopher McNeill, an American who has been a professor of environmental chemistry at ETH-Zurich for five years.

Prior to becoming a European, McNeill lived and pursued chemistry all around the U.S. He was born in Arizona and attended Reed College in Portland, OR, where he majored in chemistry. He went to graduate school at the University of California at Berkeley, where he initially focused on physical organic chemistry and mechanistic organometallic chemistry. Then "sometime in the middle of my PhD, I became fascinated with environmental chemistry problems," McNeill says. "The problems seemed wild and uncontrolled compared to the clean solutions I had been working with as a PhD student. And the answers seemed important and relevant compared to the more esoteric results I was chasing in the organometallic field," he recalls.

McNeill's next move was to the Massachusetts Institute of Technology for postdoctoral studies, where he took on an environmentally focused topic: how methane cycling in lakes influences the fate of organic pollutants. From there, he went to the University of Minnesota, where he served as an assistant and associate professor.

In the Twin Cities, McNeill began a very productive research collaboration with his colleague William Arnold. Their work included a thorough investigation of the environmental impacts associated with triclosan, a compound used as an antibacterial agent in many personal care products. Their research included analyzing triclosan's photochemistry, how it is impacted by water chlorination, its ability to produce dioxins, and how these dioxin products accumulate in the water body sediments. [1,2,3] McNeill and Arnold are coauthors of one of *ES&T's* top papers in 2012, on the photochemical formation of brominated dioxins and other products of concern from hydroxylated metabolites of PBDEs, OH-PBDEs. [4]

McNeill's biggest discovery was the microscopic distribution of singlet oxygen in sunlit waters containing natural organic matter, which was published in *Science*.[5] In 2011, he became a fellow of the Royal Society of Chemistry. In 2012, he served as an "Erudite Scholar-in-Residence" at Mahatma Gandhi University in Kerala, India.

McNeill's honors and awards also include many teaching commendations. So it may be no surprise that the accomplishment McNeill is most proud of is the students and postdocs who have left his lab and "gone on to successful careers."

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MYRTO PETREAS

Chief, California Department of Toxic Substances Control's Environmental Chemistry Branch

When she was in high school, Myrto Petreas visited a picturesque Greek beach and was surprised to emerge from the water with tar stuck to her feet and bathing suit. "At that time ships would dump wastes with no regulations," she recalls. The experience inspired her to study environmental chemistry as an undergraduate at the University of Thessaloniki in Greece.

Petreas came to the U.S. to pursue graduate studies at the University of California at Berkeley, and she hasn't left the state since. While earning her M.S., she continued to focus on waste-water contaminants and treatment, but she also discovered public health. For her Ph.D., she switched to occupational exposures to solvents, which she studied by measuring perchloro-ethylene and styrene in dry cleaners' and boat builders' breath and blood. "Along the way I got my Master of Public Health (MPH) in Epidemiology for a better grasp on exposure assessment," she says.

While Petreas was earning her Ph.D., she worked for the state of California. She continued on at the Hazardous Materials Laboratory of the state's Department of Toxic Substances Control afterwards. "I started with volatile organic compounds in indoor air, then moved to dioxins and persistent organic pollutants in environmental and biological samples," she recalls.

In 2002, Petreas played a major role in discovering that Californians could be exposed to very high levels of polybrominated diphenyl ether (PBDE) flame retardants. She directed the analytical work for a group of scientists at the Hazardous Materials Laboratory who measured the compounds in harbor seals from the San Francisco Bay and in breast adipose tissue from 23 California women.[1] The levels of PBDEs in these women's tissues were the highest reported to date at the time.

Petreas and her colleagues discovered that the women's PBDE levels were inversely correlated with their ages, an uptake pattern very different from conventional persistent organic pollutants such as polychlorinated biphenyls (PCBs), which tend to increase with age. There was no correlation between the concentrations of PCBs and PBDEs in the samples, pointing to different sources of exposure. By comparing the concentrations of PBDEs in samples taken from the San Francisco Bay harbor seals over the previous decade, the researchers showed that the levels had increased dramatically. The seals' current levels were among the highest reported for the species. [2]

Petreas' group subsequently analyzed additional samples collected in the late 1990s from women in the San Francisco Bay area. The researchers confirmed their earlier findings of high PBDE levels in the area women's blood. The levels ranged far more widely than PCBs, and median concentrations of one PBDE congener, BDE-47, were 3-10 times higher than median levels in Europe. [3] By analyzing archived samples from the 1960s, which did not contain detectable levels of PBDEs, Petreas and her colleagues were able to show that human uptake of the flame retardant was a relatively recent phenomenon.

Petreas went on to "close the loop" by returning to the indoor environment to study PBDE flame retardants in house dust, which proved to be a major source of exposure. [4] Along the way to becoming the chief of the Department of Toxic Substances Control's Environmental Chemistry Branch, she also helped start the state of California's Biomonitoring Program. The program's data can serve as an early warning system for exposure to toxic chemicals, potentially preventing "another PBDE-like adventure."

Over the years, Petreas has authored numerous publications and been awarded several research grants. She was recently appointed as Editor of *Chemosphere*.

For Petreas, working for a state government has involved "waves of initiatives, emergencies and changing priorities… It always changes with the chemical du jour." She enjoys working as an environmental chemist in this environment because she's always learning new things and she's confident that she's on the "right" side.

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HEATHER STAPLETON

Associate Professor of Environmental Chemistry at Duke University's Nicholas School of the Environment

The trajectory of a career is hard to predict. Before she became an environmental chemist, Heather Stapleton planned to study sharks as a marine biologist. She majored in marine biology at Southampton College, a small liberal arts college on Long Island that specialized in marine sciences and had a marine science research center.

Stapleton's gradual shift to environmental chemistry began with an undergraduate class in the subject. Another inspiration was what she learned during her part-time work at Southampton's marine science center. She often went out to collect samples for research projects on research boats in the Atlantic Ocean or the estuary in the Long Island Sound. "Particularly in the estuary sampling, I remember often taking notice of the pollution and human impact on the environment. It manifested in me a desire to focus on environmental science, and to understand the impact of chemicals on the health of our environment," Stapleton recalls.

By the time Stapleton entered her PhD program at the University of Maryland at College Park's interdisciplinary Marine Estuarine Environmental Science (MEES) program, her area of specialization was environmental chemistry. She worked under Joel Baker (who is now at the University of Washington at Tacoma) on a project investigating the fate and transport of polychlorinated biphenyls (PCBs) and organochlorine pesticides in the food web of Lake Michigan.

"While I was working on that project I started reading and learning more about emerging contaminants, and particularly the flame retardant chemicals, PBDEs," Stapleton says. "They were so similar in structure to PCBs that I remember being shocked that someone would use them in large volumes in furniture, particularly after we knew so much about the toxicity and persistence of PCBs. It was that interest that pushed me to start exploring the accumulation and metabolism of PBDEs for a PhD project."

After receiving her PhD in 2003, Stapleton moved to Gaithersburg, MD, and started a postdoctoral research position at the National Institute of Standards and Technology (NIST). Stapleton was helping NIST develop methods to accurately measure flame retardant chemicals in different types of samples when she came across a Standard Reference Material for Indoor Dust. “I remember thinking to myself that it would be interesting to analyze the sample given that flame retardants were used in so many products indoors….it seemed likely that they would be detectable,” she says, explaining that up until that point, most people were making measurements in the outdoor environment.

“When I analyzed the dust samples I was shocked at how high the levels were, and that led to my first independent project investigating levels of PBDEs in indoor dust,” Stapleton says. After that, she began to focus on understanding how people--particularly children--were exposed to these chemicals, to discover if the levels she was measuring in indoor dust suggested that they could be a source exposure.

In the following years, Stapleton’s work played an important role in establishing that dust was indeed a major route of exposure to PBDEs, as well as other flame retardants. [1,2] This in turn helped explain why younger people tended to take up higher concentrations of the compounds, because babies and children tend to inadvertently consume more dust than adults. In the process, she earned an appointment at Duke University’s Nicholas School of the Environment, where she now holds a tenured position.

In 2008, the National Institute of Environmental Health Sciences honored Stapleton with its Outstanding New Environmental Scientist Award. *Environmental Science & Technology* has named two of her research articles as top papers of the year. Most recently, research she conducted into the presence of flame retardants in products intended for use by babies and children was designated the Top Science Paper published in *Environmental Science & Technology* in 2011. [3,4] She has been an Editorial Advisory Board Member for *Environmental Science & Technology* since 2011.

“I love being an environmental chemist and working in this area of research,” Stapleton says. “We live in a chemical soup and it’s difficult for us to know which chemicals are safe, and which are harmful. I think it’s incredibly important for us to understand how man-made chemicals are used, where they end up and how people are exposed to them -- and if that exposure is associated with increased health risks,” she explains. A variety of diseases are being linked to the environment, including cancer, autism, and ADHD, she points out.

Stapleton says she is most proud of the research she and her colleagues conducted on identifying flame retardant chemicals in baby and children’s products. “Our research on chemical applications in baby products helped to change the use of flame retardants in these products. I actually received a letter from one manufacturer of a baby product saying thank you for the research you have done. Apparently our data helped them make more informed decisions on what chemicals needed to be in their products, where they needed them and where they did not.” Her work also helped influence the state of California, whose strict flame Retardancy standards have driven much of the U.S. use of flame retardants, to alter the standards to exempt some of the baby products.

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GREGG TOMY

Assistant Professor of Chemistry at the University of Manitoba

An undergraduate class in analytical mass spectrometry at the University of Manitoba in Canada inspired Gregg Tomy to become an environmental chemist. "My professor, John Westmore, was this wonderful person; tremendously knowledgeable about mass spectrometry, inspiring and ever so humble," Tomy recalls.

Soon thereafter, Tomy met Derek Muir, an environmental chemist who worked as a research scientist at the Freshwater Institute, which is part of Canada's federal Department of Fisheries and Oceans. It is located in Winnipeg, Manitoba, on the university campus. Tomy recalls that Muir, who is now with Environment Canada, the country's environmental protection agency, had a "seemingly endless knowledge of environmental chemistry together with high standards and enthusiasm."

A native of the Caribbean, Tomy was so inspired by Westmore and Muir that he stayed in chilly Winnipeg so he could pursue graduate studies with the two as his main mentors. "Being able to marry analytical mass spectrometry with environmental chemistry and work with John and Derek was a dream for me," Tomy says. The focus of his studies was developing analytical methods based on mass spectrometry to measure a class of compounds known as the chlorinated paraffins.

After earning his Ph.D., Tomy went to postdoctoral studies at the nearby Freshwater Institute. Afterwards, he accepted a permanent position and in short order, he was in charge of the institute's high resolution mass spectrometry facilities. "My work focused on using high resolution mass spectrometry to study the behavior and fate of environmental contaminants," he says. Initially, he "did a lot of fundamental mass spectrometry." He analyzed a wide range of compounds, including polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls

(PCBs), fluorinated organic compounds, and a variety of flame retardants. [1,2,3,4,5] Tomy is particularly well-known for his work with a heavily used bromine-based flame retardant, hexabromocyclododecane (HBCD).

"I particularly like to unearth new chemicals that we come into contact on a daily basis and discern what effects, if any, they pose to humans and aquatic wildlife," Tomy says. His group developed the analytical method to measure HBCD. [6] After that his group "spent a great deal of time studying the toxicological impacts of this compound on aquatic wildlife" in collaboration with scientists and graduate students both at DFO in Winnipeg, where he was employed and with colleagues at Environment Canada in Burlington, Ontario.

In 2009, Tomy was asked by the members of the Persistent Organic Pollutant Review Committee (POPRC) of the United Nations' Stockholm Convention to present the state of the science on HBCD and address whether the flame retardant met the treaty's criteria of persistence (P), bioaccumulative (B) and inherently toxicity (iT). He also helped write the draft risk profile on HBCD for POPRC. In 2010, he attended the meetings in Geneva where the decision was made that HBCD warranted global regulatory action.

Tomy also earned some major accolades in 2009 and 2010. In 2009, he received the Environmental Science Award, which the Royal Society of Chemistry and Society of Environmental Toxicology and Chemistry give to recognize the outstanding work by young researchers. "I suspect they got desperate that year and picked my name out of a hat," he says with characteristic self-deprecation. In 2010, Tomy's work on HBCD for the Stockholm Convention helped him earn one of the highest awards that can be given to a governmental scientist in Canada, the Ministerial Distinction Award.

In recent years, Tomy found himself becoming more and more interested in ecotoxicology. "I would like to believe a progression as such is natural for most scientists," he says. He feels that toxicology complements and rounds off his abilities as a researcher. After new chemicals are detected in the environment toxicology enables researchers to elucidate possible adverse effects and "put things more into perspective," as Tomy puts it.

Tomy has also shaken things up a bit by moving from the Canadian government to academia. He has come full circle by accepting a fulltime position at the University of Manitoba's chemistry department. It's highly likely that his students will come to revere him in the same way as he looked up to his chemistry professors Westmore and Muir. After all, this is a man who says, "what I am most proud of in my time as a researcher is that I have been able to work and surround myself with people that I genuinely consider to be friends. That means the world to me."

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