McGraw-Hill
ACCESS Science
Encyclopedia of Science & Technology Online

Close Window

RESEARCH UPDATE

Sustainable materials and green chemistry

The conventional process for the production and use of materials has been to extract natural resources such as fossil fuel or minerals, refine them, modify them further through manufacturing, and then distribute them as products. At the end of their useful lives, the products are discarded, usually to a landfill or an incinerator. Based on current material practices, society faces a number of problems, including the dispersion of persistent toxics and other contaminants throughout the Earth, depletion of nonrenewable resources such as petroleum, destruction of biodiversity, and the depletion and contamination of aquifers and drinking water sources. There is a growing perception that these material practices are unsustainable.

Moving toward a sustainable materials management system first requires the recognition that current practices are unsustainable. The next step is to develop and implement a model of sustainability.

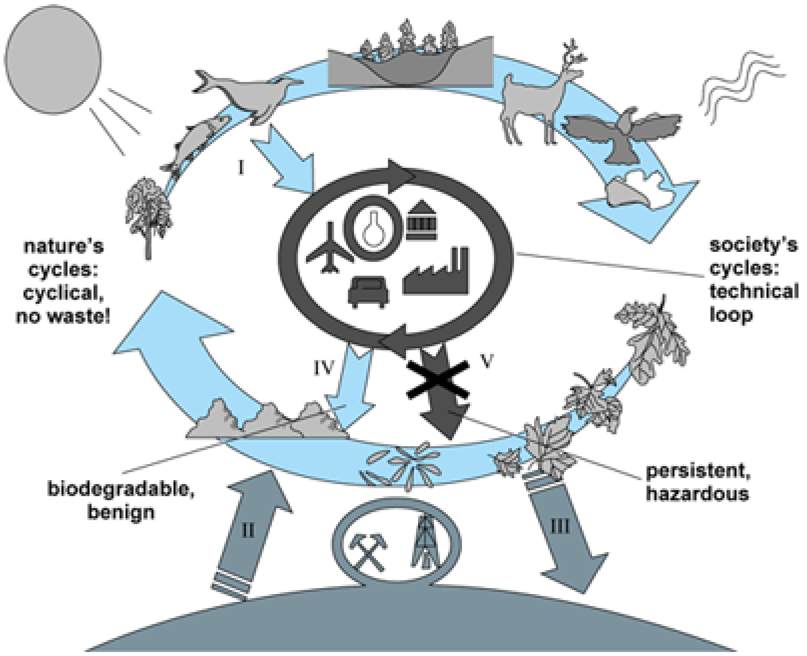
Sustainability

Sustainability and sustainable development can be problematic terms because they are overused and their meaning is not precise. The most commonly used definition for sustainable development comes from a report by the World Commission on Environment and Development—"To meet the needs of the present without compromising the ability of future generations to meet their own needs."

Some experts in this field say that sustainability is too limited a goal. They argue that practices not only should sustain but also should benefit and restore both human and environmental well-being. Regardless of the limits, sustainability is recognized as the first step toward ensuring survival of the growing human population and the Earth.

In 1989, a framework for sustainability called the The Natural Step emerged through the efforts of Karl-Henrik Robèrt, a leading Swedish oncologist. This framework provides a model and a set of system conditions that define a sustainable society based on the laws of thermodynamics and natural cycles. The Natural Step System Conditions consider rates and flows in order to avoid degradation, depletion, or pollution of the ecological system (**Fig. 1**).

Ecological aspects of The Natural Step System Conditions shown as the flow of materials in a closed system of two loops. The outer "biological" loop represents the cycling of materials within the Earth's ecosystems. In natural systems, there is essentially no waste, as all materials generated through living organisms become food or structure for other organisms. The inner "technical" loop represents cycling within the industrial/economic system. Arrow I represents the extraction of natural resources for use in the industrial/economic system. Arrows II and III represent extraction and resettling of materials from the Earth's crust—primarily fossil fuel and mined materials. Arrows IV and V represent materials that flow from the industrial/economic system to the greater ecosystem. The "persistent, hazardous" arrow represents chemicals or materials that cannot be safely assimilated into ecosystems, such as persistent, toxic, bioaccumulative, or otherwise hazardous materials. The "biodegradable, benign" arrow represents materials that can be assimilated without harm, either initially or after treatment. (*Larry Chalfan, Zero Waste Alliance, Portland, OR*)



Sustainable materials

Materials produced and used in society are diverse and evolving. There are approximately 75,000 chemicals now used commercially. Because no one formulation is uniquely sustainable, it is useful to provide an operational definition. A sustainable material is then a material that fits within the constraints of a sustainable material system. In order to be sustainable, the material must be appropriate for the system and the system must be appropriate for the material.

Two strategies have been identified to support a sustainable materials economy. One strategy, a process known as dematerialization, involves developing ways to use less material to provide the same service in order to satisfy human needs. A second is detoxification of materials used in products and industrial processes.

Dematerialization

Dematerialization means reducing the amount of material in a product without decreasing the quality of its function. Dematerialization reduces the flow of materials into and through the industrial/economic system, also known as the technical loop (Fig. 1). Strategies for dematerialization involve reducing the rate of mining of industrial metals, developing organic chemicals from biomass wastes rather than fossil fuels, and promoting recycling and secondary materials industries to keep materials in the technical loop. Designing products for repair, upgrade, or recycling, as well as substituting services for products (for example, leasing computers rather than selling new ones) support the need for fewer resources and help keep materials within the industrial/economic system. But dematerialization is effective only if the materials used can serve as biological or technical "nutrients"—meaning that their reintegration into natural or industrial/economic systems is beneficial or at least benign within the systems (as defined in this context by W. McDonough and M. Braungart).

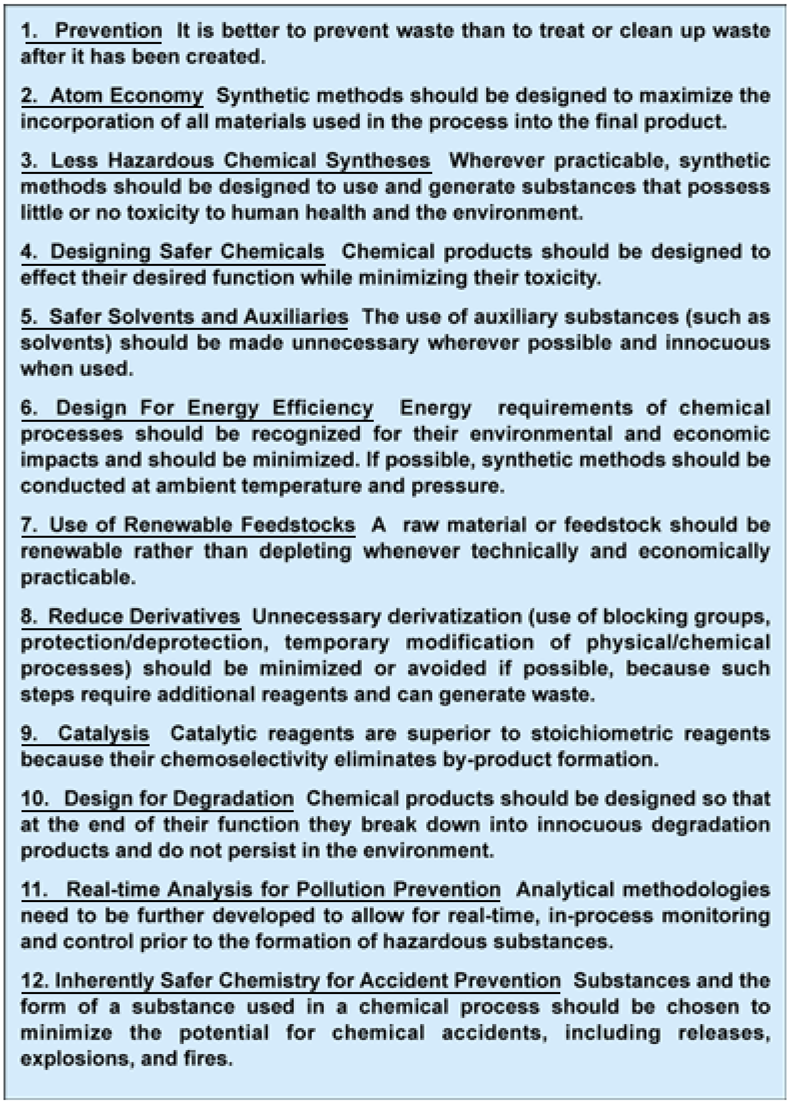
Detoxification

The strategy of detoxification includes substituting benign alternatives for problematic chemicals (for example, chlorofluorocarbons, or CFCs); phasing-out persistent, bioaccumulative, and toxic pollutants [for example, mercury and its compounds, polychlorinated biphenyls (PCBs), and dioxins]; generating toxics on demand or just-in-time to avoid the need for storage and transportation; and designing new materials that are compatible with human health and the greater ecosystem. Chemicals that can be used and assimilated into natural systems without increasing harm are biological nutrients. The design of such materials is a component of the growing field of green chemistry, which links the design of chemical products and processes with their impacts on human health and the environment in order to create sustainable materials.

Green chemistry

Green chemistry is a tool for chemists, chemical engineers, and others who design materials to help move society toward the goal of sustainability. Design at the molecular level allows decisions to be made that impact how materials will be processed, used, and managed at the end of their life (**Fig. 2**).

Twelve principles of green chemistry. (*Adapted from P. T. Anastas and J. C. Warner, Green Chemistry: Theory and Practice, p. 30, Oxford University Press, New York, 1998. By permission of Oxford University Press.*)



1. **Prevention** It is better to prevent waste than to treat or clean up waste after it has been created.
2. **Atom Economy** Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Syntheses** Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals** Chemical products should be designed to effect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries** The use of auxiliary substances (such as solvents) should be made unnecessary wherever possible and innocuous when used.
6. **Design For Energy Efficiency** Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks** A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives** Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. **Catalysis** Catalytic reagents are superior to stoichiometric reagents because their chemoselectivity eliminates by-product formation.
10. **Design for Degradation** Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-time Analysis for Pollution Prevention** Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. **Inherently Safer Chemistry for Accident Prevention** Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Green chemistry focuses on eliminating hazard rather than risk. The term “hazard” includes any of the impacts identified earlier as consequences of an unsustainable materials system. Hazard may include acute (short-term) or chronic (long-term) human or ecological toxicity, safety, and the potential for damage to the ozone layer, water resources, or biodiversity. Risk is a function of the inherent hazard and probability of exposure. Traditionally, risk management focuses on controlling the potential for exposure. However, exposure control failures, such as the deadly accident in Bhopal, India, will occur. Exposure to a material with a high degree of inherent hazard may result in a high-risk situation. By addressing the inherent hazard of a material, it is possible to reduce risk and eliminate the need for exposure controls that can also be very expensive.

Examples of green chemistry

In recent years, the application of green chemistry has shown that materials can be environmentally compatible and can fit within a sustainable materials system through the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.

Antifoulants

In 1998, Rohm and Haas Company received a Presidential Green Chemistry Challenge Award for designing the environmentally safe marine antifoulant called Sea-Nine™. Fouling, the unwanted growth of plants and animals on a ship's surface, costs the shipping industry approximately $3 billion a year. A significant portion of this cost is the increased fuel consumption needed to overcome hydrodynamic drag. The main compounds used worldwide to control fouling are organotin antifoulants, such as tributyltin oxide (TBTO). They are effective at preventing fouling, but have widespread environmental problems due to their persistence in the environment and the effects they cause, including acute toxicity, bioaccumulation, decreased reproductive viability, and increased shell thickness in shellfish. Rohm and Haas Company sought to develop an antifoulant that would prevent fouling from a wide variety of marine organisms without causing harm to nontarget organisms. Compounds from the 3-isothiazolone class were chosen. In particular, 4,5-dichloro-2-*n*-octyl-4-isothiazolin-3-one was selected as it was found to degrade extremely rapidly in seawater and even faster (1 h) in sediment. TBTO bioaccumulates as much as 10,000 times, while Sea-Nine™ bioaccumulation is essentially zero. Both TBTO and Sea-Nine™ were acutely toxic to marine organisms, but TBTO had widespread chronic toxicity, while Sea-Nine™ antifoulant showed no chronic toxicity.

Pest control

In 2001, EDEN Bioscience Corporation received a Presidential Green Chemistry Challenge Award for their product, Messenger®, which is based on a new class of nontoxic, naturally occurring proteins called harpins. Harpins trigger a plant's natural defense systems to protect against disease and pests, and simultaneously activate certain plant growth systems without altering the plant's DNA. When applied to crops, harpins increase plant biomass, photosynthesis, nutrient uptake, and root development, leading to greater crop yield and quality.

The estimated annual losses to growers from pests is $300 billion worldwide. In order to be successful, growers have generally pursued two approaches to limit economic losses and increase yields: (1) use traditional chemical pesticides; or (2) grow crops that are genetically engineered for pest resistance. Each approach has consequences that have come under increasing criticism from a variety of sources. The use of harpins has been shown to have virtually no adverse effect on any of the organisms tested, including mammals, birds, honey bees, plants, fish, aquatic invertebrates, and algae. Harpins are fragile molecules that are degraded rapidly by ultraviolet light and natural microorganisms; they have no potential to bioaccumulate or to contaminate surface- or ground-water resources. Unlike most agricultural chemicals, harpin-based products are produced in a water-based fermentation system that uses no harsh solvents or reagents, requires only modest energy inputs, and generates no hazardous chemical wastes.

Oxidation

Terrence J. Collins of Carnegie Mellon University received a Presidential Green Chemistry Challenge Award in 1999 for his work in the area of oxidation chemistry. Oxidation is used for bleaching wood pulp and textiles, as well as for disinfecting drinking water and wastewater. Many oxidation processes rely on chlorine chemistry which can form chlorinated pollutants, including dioxins. By developing a series of iron-based activators, called TAML™ (tetraamido-macrocyclic ligand), which contain no toxic functional groups and are effective with the natural oxidant hydrogen peroxide, Collins devised an environmentally benign oxidation technique with widespread application.

Research chemists tend to select simple designs and draw from the full range of elements from the periodic table, many of which are mined (relatively rare) and are persistent pollutants. Collins recognized that in nature selectivity is achieved through complex mechanisms using a limited set of elements available in the environment. He circumvented the problem of persistent pollutants in the environment by employing reagents and processes that mimic those found in nature.

Degradable polymers

In the 1990s, BASF developed a material called Savant™, made from nylon 6 fiber. Savant™ can be depolymerized and reused. BASF has initiated a take-back program for used carpet called 6ix Again. Recovered nylon 6 can be depolymerized and used in Savant™. Rather than downcycling it into a material with less value, the used nylon is "upcycled" into a product of high quality.

These examples show how innovative science and technology can support sustainability through the development of sustainable materials. Technology is not a panacea for sustainability, but it can provide innovative solutions when the challenges are defined by social choice to promote human and ecological well-being.

See also: Conservation of resources; Ecology, applied; Environmental management; Fossil fuel; Human ecology; Industrial ecology; Mineral resources; Recycling technology; Systems ecology; Toxicology

Lauren Heine

Bibliography

- P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, New York, 1998
- K. G. Geiser, *Materials Matter: Toward a Sustainable Materials Policy*, MIT Press, Cambridge, MA, 2001
- A. Grübler, *Technology and Global Change*, Cambridge University Press, Cambridge, 1998
- W. McDonough and M. Braungart, *Cradle to Cradle*, North Point Press, New York, 2002
- W. McDonough and M. Braungart, The next industrial revolution, *Atlantic Mon.*, October 1998
- World Commission on Environment and Development, *Our Common Future*, Oxford University Press, Oxford, 1987

Additional Readings

- 2002 The Natural Step
- U.S. Environmental Protection Agency, Presidential Green Chemistry Challenge

---

How to cite this article

Lauren Heine, "Sustainable materials and green chemistry", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.YB030505