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# Green Chemistry Resource List

## What Is Green Chemistry?

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- "**Green chemistry** is the utilization of a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products." - Paul T. Anastas and John C. Warner, *Green Chemistry: Theory and Practice* (Oxford University Press: New York, 1998)

- "**Green chemistry** consists of chemicals and chemical processes designed to reduce or eliminate negative environmental impacts. The use and production of these chemicals may involve reduced waste products, non-toxic components, and improved efficiency." - Environmental Protection Agency: Introduction to the Concept Of Green Chemistry

- "By providing the scientific basis for a new wave of inherently safe materials, **green chemistry** can stimulate scientific and economic innovation, avoid the unintended health consequences of inadvertently hazardous materials, and contribute to sustainable economic growth and job creation. ... While the principles guiding green chemistry appear to be common sense, they bear little resemblance to the way we do chemistry today. Currently feedstocks are generally non-renewable; products we make and their building blocks often have significant toxicity; many of our substances persist, biaccumulate and biomagnify. We have historically tried to control exposure to hazardous substances in ways that are costly and often fail." - "Green Economic Innovation for the 21st Century: The Molecular Revolution," consensus statement signed by 24 participants at Beckman Center for the National Academy of Sciences, November 2008

## Twelve Principles of Green Chemistry

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**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 (e.g., solvents, separation agents, etc.) 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 (as selective as possible) are superior to stoichiometric reagents.

**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.

From Anastas, P. T.; Warner, J. C.; *Green Chemistry: Theory and Practice*, Oxford University Press: New York, 1998, p.30. Reproduced in various publications.

## Websites

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### USA

- **Advancing Green Chemistry**: "Our mission is to promote the development and adoption of Green Chemistry. AGC's role is to strengthen and promote the science and its practitioners, to link to strategic partners, and to highlight emerging strategic opportunities for stakeholders."

- **American Chemical Society Green Chemistry Institute:** "Enabling and catalyzing the implementation of green chemistry and engineering principles into all aspects of the global chemical enterprise."

- **Beyond Benign**: "Driven by the 12 Principles of Green Chemistry, a universal sustainable approach to any science; we create tools, opportunities and partnerships to support the implementation of community involvement initiatives, workplace training, cooperative programs and K-12 education resources."

- **Environmental Protection Agency**: **Green Chemistry Website**

- **Lowell Center for Sustainable Production**, University of Massachusetts: "Fosters innovative solutions to fuel progress toward a more sustainable world by developing, studying, and promoting environmentally sound systems of production, healthy work environments, and economically viable work organizations." Projects include the Green Chemistry and Commerce Council.

- **Institute for Green Science, Carnegie Mellon University**: "The Institute for Green Science, led by Terry Collins, the Teresa Heinz Professor of Green Chemistry, has been established as a research, education and development center in which a holistic approach to green or sustainable chemistry is being developed, focused on pollution reduction. Research programs are evolving around the scientific and technological development of TAML® hydrogen peroxide activators, extensively patented and trademarked by Carnegie Mellon University."

- **State of California Green Chemistry Initiative**

- University of Oregon: **Greener Education Materials (GEMs) for Chemists**

- **Warner Babcock Institute for Green Chemistry**: "The Warner Babcock Institute for Green Chemistry combines the expertise of talented and passionate scientists and engineers with the experience of an innovative and dynamic leadership team."

**INTERNATIONAL**

- **Canadian Green Chemistry Network**

- **UK Green Chemistry Network**

- **Green Chemistry in Japan:** report by National Science Foundation (2004)

## Articles in the Media

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- Collins, T. J.; Walter, C., "Little Green Molecules." *Scientific American*. 2006, 294, (3), 83-88, 90. (full PDF)

- Collins, T.J., "Toward Sustainable Chemistry." *Science* 5 January 2001 291: 48-49

- Laber-Warren, Emily. "Green Chemistry: Scientists Devise New "Benign by Design" Drugs, Paints, Pesticides and More." *Scientific American* May 28, 2010.

## Articles in Peer-Reviewed Journals

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- Anastas, PT & Kirchhoff, Mary M. "Origins, Current Status, and Future Challenges of Green Chemistry." *Accounts of Chemical Research* 2002 35 (9), 686-694 (abstract only)

- Anastas PT & Beach ES. "Green Chemistry: The Emergence of a Transformative Framework." *Green Chemistry Letters and Reviews* 2007, 1, 9-24. (abstract only)

- Collins, TJ. "The importance of sustainability ethics, toxicity and ecotoxicity in chemical education and research." *Green Chemistry* 2003, 5(4), G51-G52. (full text)

- Collins, TJ. "Review of the twenty-three year evolution of the first university course in green chemistry: teaching future leaders how to create sustainable societies." *Journal of Cleaner Production* xxx (2015), 1-18.

- Manley JB, Anastas PT, & Cue BW. "Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing." *Journal of Cleaner Production* 2008, *16*, 743-750.

- Wilson MP, Schwarzman MR. "Toward a New U.S. Chemicals Policy: Rebuilding the Foundation to Advance New Science, Green Chemistry, and Environmental Health." *Environ Health Perspect* 2009, 117:1202-1209.

## Reports and Other Resources

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- "Green Economic Innovation for the 21st Century: The Molecular Revolution." Consensus statement signed by 24 participants at Beckman Center for the National Academy of Sciences, November 2008.

- "Growing the Green Economy Through Green Chemistry and Design for the Environment: A Resource Guide for States and Higher Education." A joint report by The Green Chemistry and Commerce Council, Lowell Center for Sustainable Production at the University of Massachusetts Lowell, and The National Pollution Prevention Roundtable. 2009. (Full text PDF, 29 pages)

- Matus, Kira JM. "Green Chemistry in Chinese Higher Education" (conference paper, 13th Annual Green Chemistry & Engineering Conference '09)