Principles of Green Chemistry and Green Engineering

Chemists and engineers are designers who have the unique ability to affect molecules, materials, products, processes, and systems at the earliest possible stages of their development.

- What will be the human health and the environmental impacts of the chemicals we put into the marketplace?
- How efficiently will the systems be with which we manufacture products?
- What will tomorrow's innovations look like, and from what materials will they be created?

We begin answering these questions the moment we put pen to paper, and the designs we create affect the course of entire sectors of the world economy.

Principles

The principles of green chemistry and green engineering provide a framework for scientists and engineers to use when designing new materials, products, processes and systems.

The principles focus on sustainable design criteria and have proven to be the source of innovative solutions to a wide range of problems. Green chemistry and green engineering embrace this power of design, and insist that if we use it wisely, we can make significant contributions in the drive toward sustainability for the simultaneous benefit of the environment, economy, and society.

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The Twelve Principles of Green Chemistry*

Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas et al. 2000).

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.

*Anastas, P. T.; Warner, J. C. Green Chemistry: Theory and Practice, Oxford University Press: New York, 1998, p.30. By permission of Oxford University Press.

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The Twelve Principles of Green Engineering*

Green Engineering is the development and commercialization of industrial processes that are economically feasible and reduce the risk to human health and the environment.

1. **Inherent Rather Than Circumstantial**
   Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.

2. **Prevention Instead of Treatment**
   It is better to prevent waste than to treat or clean up waste after it is formed.

3. **Design for Separation**
   Separation and purification operations should be designed to minimize energy consumption and materials use.

4. **Maximize Efficiency**
   Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

5. **Output-Pulled Versus Input-Pushed**
   Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.

6. **Conserve Complexity**
   Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

7. **Durability Rather Than Immortality**
   Targeted durability, not immortality, should be a design goal.

8. **Meet Need, Minimize Excess**
   Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.

9. **Minimize Material Diversity**
   Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

10. **Integrate Material and Energy Flows**
    Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

11. **Design for Commercial "Afterlife"**
    Products, processes, and systems should be designed for performance in a commercial "afterlife."

12. **Renewable Rather Than Depleting**
    Material and energy inputs should be renewable rather than depleting.

* Anastas, P.T., and Zimmerman, J.B., "Design through the Twelve Principles of Green Engineering", Env. Sci. and Tech., 37, 5, 95 ? 101, 2003.