The 24 Principles of Green Engineering and Green Chemistry: "IMPROVEMENTS PRODUCTIVELY"

DOI: 10.1039/b719469m

Samantha Tang, Richard Bourne, Richard Smith and Martyn Poliakoff suggest a condensed 24 Principles of Green Chemistry and Green Engineering, with the mnemonic "IMPROVEMENTS PRODUCTIVELY"

Chemists and engineers working in the area of green chemistry are increasingly, and quite justifiably, asked to explain why their particular reaction, process or product is actually green. Already there is a lively debate on this topic[1] and sometimes the claim of a "green reaction" can ignite fierce controversy.[2]

In this context, the 12 Principles of Green Chemistry[3] have become a widely accepted set of criteria for the rapid assessment of the "greenness" of a given chemical route or for comparing the environmental acceptability of two rival processes. Unfortunately, the 12 principles do not explicitly include a number of important concepts, highly relevant to environmental impact; for example, the inherency of a product or process, the need for life cycle assessment, or the possibility of heat recovery from an exothermic reaction or heat integration. For this reason, Anastas and Zimmerman subsequently proposed a set of 12 Principles of Green Engineering,[4] see Fig. 1.

The principles of both green chemistry and green engineering are rather lengthy and thus are not in a form that can be readily communicated to an audience in the middle of a lecture to emphasize an important point. This means that much of their value can be lost in debates over green technologies. Therefore, two years ago we proposed[5] a condensed version of the green chemistry principles which fitted onto a single PowerPoint slide and incorporated the mnemonic PRODUCTIVELY, Fig. 2. This cut-down set has proved really quite effective in presentations and has been adopted by others.

Here we present a companion set of the Green Engineering Principles, with the mnemonic IMPROVEMENTS, Fig. 3. We believe that these two sets of principles are now sufficiently manageable in their condensed forms that, for the first time, they can be used together as a single set of 24 principles covering most of the key issues of green and sustainable chemistry and processing. With this combined set of principles for engineering and chemistry, it will be easier to include a discussion of environmental impact in lectures and presentations. Therefore, if a set of concepts becomes easier to communicate, then more people will both use and discuss them. Thus the entire field of green chemistry will benefit. Therefore we encourage you to use the principles to discuss your IMPROVEMENTS PRODUCTIVELY.

Principles of Green Chemistry

P - Prevent wastes
R - Renewable materials
O - Omit derivatization steps
D - Degradable chemical products
U - Use safe synthetic methods
C - Catalytic reagents
T - Temperature, Pressure ambient
I - In-Process Monitoring
V - Very few auxiliary substances
E - E-factor, maximize feed in product
L - Low toxicity of chemical products
Y - Yes it's safe

Fig. 2 The condensed 12 Principles of Green Chemistry, taken from ref. 5.

1 Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous as possible.
2 It is better to prevent waste than to treat or clean up waste after it is formed.
3 Separation and purification operations should be a component of the design framework.
4 System components should be designed to maximize mass, energy and temporal efficiency.
5 System components should be output pulled rather than input pushed through the use of energy and materials.
6 Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse or beneficial disposition.
7 Targeted durability, not immortality, should be a design goal.
8 Design for unnecessary capacity or capability should be considered a design flaw. This includes engineering "one size fits all" solutions.
9 Multi-component products should strive for material unification to promote disassembly and value retention (minimize material diversity).
10 Design of processes and systems must include integration of interconnectivity with available energy and materials flows.
11 Performance metrics include designing for performance in commercial "after-life".
12 Design should be based on renewable and readily available inputs throughout the life cycle.

Fig. 1 The 12 Principles of Green Engineering, taken from ref. 4.

We thank the EPSRC, grant number EP/D501229/1 for support.

Samantha Y. Tang, Richard A. Bourne, and Martyn Poliakoff, School of Chemistry, The University of Nottingham, University Park , Nottingham, UK NG7 2RD *E.mail: samantha.tang@nottingham.co.uk** and **Richard L. Smith**, Research Center of Supercritical Fluid Technology, Tohoku University, Aramaki

Principles of Green Engineering

I - Inherently non-hazardous and safe
M - Minimize material diversity
P - Prevention instead of treatment
R - Renewable material and energy inputs
O - Output-led design
V - Very simple
E - Efficient use of mass, energy, space & time
M - Meet the need
E - Easy to separate by design
N - Networks for exchange of local mass & energy
T - Test the life cycle of the design
S - Sustainability throughout product life cycle

Fig. 3 The condensed 12 Principles of Green Engineering, based on those given in full in Fig. 1.

Aza Aoba-6-6-11, 980-8579, Aoba-ku, Sendai, Japan

References

1 R. van Noorden, *Chem. World*, 2007, **4**(6), 14.
2 D. G. Blackmond, A. Armstrong, V. Coombe and A. Wells, *Angew. Chem., Int. Ed.*, 2007, **46**, 37987.
3 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998, p. 30.
4 P. T. Anastas and J. B. Zimmerman, *Environ. Sci. Technol.*, 2003, **37**, 94A.
5 S. L. Y. Tang, R. L. Smith and M. Poliakoff, *Green Chem.*, 2005, **7**, 761.