How Chemistry can contribute to Sustainability

REUSE

RECOVER

RECYCLE

REPAIR

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The Biogenic Elements ‘CHNOPS’

• They make up 97% of living matter on Earth!
‘CHNOPS’: the origin of waste…
Global ‘CHNOPS’ Waste Problems

Steffen, Rockström et al., Science 2015, 347, 736
The Phosphorus Cycle in Nature

For his presidential address to the Geological Section of the Congress of the South Eastern Union of Scientific Societies, held on October 14, Dr. K. P. Oakley took as his subject “Man and the Migrations of Phosphorus”. For some time after the earth’s formation, the phosphorus cycle in the sea was simple, the phosphate ions being built up into the earliest forms of organic life and released again at their death, the only loss occurring through the precipitation of phosphate ions accumulated at the lower levels, with the formation of sedimentary rock phosphate beds. Following the emergence of life from the sea and the

COAL CONSUMPTION AFFECTING CLIMATE.

The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

Nature 1944, 154, 762–763.

Radical Change is needed..

“We cannot solve our problems with the same thinking we used when we created them.”

– Albert Einstein
Chemistry to enable a Circular Economy

Waste = resource is key for circularity

with Tom Keijer, Vincent Bakker, *Nature Chemistry, 2019, 11, 190*
12 Guiding Principles?

1. Prevent waste
2. Maximize atom economy
3. Less hazardous chemical syntheses
4. Safer chemicals and products
5. Safer solvents and reaction conditions
6. Increase energy efficiency
7. Use renewable feedstocks
8. Avoid chemical derivatives (protecting groups)
9. Use catalysts
10. Design chemicals and products to degrade after use
11. Analyze in real time to prevent pollution
12. Minimize potential for accidents

Anastas and Warner (1998)
Just a Different Feedstock…

• Biomass for $\text{C}$ chemistry (next to oil & $\text{CO}_2$)
Bio-based Plastic Soup?
Bio-degradability? (not related to biobased..)

- Polyactic acid (PLA)
- Nylon-6
- Nylon-6,6
- Kevlar
- Polyethylene terephthalate (PET)
- Polyethylene (PE, R = H)
- Polypropylene (PP, R = CH₃)
- Polyvinylchloride (PVC, R = Cl)
Bio-degradability?

- Avoid persistence in the environment and breakdown into harmful products
- Recycling vs degradation
- Development of short (reuse, recycle; retain value) and long cycles (PLA $\rightarrow$ CO$_2$)
- Waste = resource
12 Guiding Principles → Sustainable?

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Anastas and Warner (1998)
Green $\text{H}_2\text{O}_2$

A “Green” Route to Adipic Acid: Direct Oxidation of Cyclohexenes with 30 Percent Hydrogen Peroxide in $\text{H}_2\text{O}$

Kazuhiko Sato, Masao Aoki, Ryoji Noyori

- Green  YES
  - $\text{H}_2\text{O}$ as byproduct
  - Avoids nitric acid oxidation and & nitrous oxide ($\text{N}_2\text{O}$) byproduct

- Sustainable  NO
  - Cyclohexene no bulk chemical
  - $\text{H}_2\text{O}_2$ is more expensive than product
    - Violating the value chain

$\text{Na}_2\text{WO}_4 + [\text{CH}_3(\text{n-C}_8\text{H}_{17})_3\text{N}]\text{HSO}_4 \xrightarrow{\text{phase-transfer cat.}} \text{COOH} + 4\text{H}_2\text{O}$

Science 1998, 281, 1646
The drivers/hurdles of green chemistry

Drivers:
- Knowledge-based quality jobs
- Responsibility

Hurdles:
- Unawareness
- Acceptance

Drivers:
- Cost reduction
- Novel products

Hurdles:
- Regulations
- Further technology development
- Feedstock prices
- Investments

Drivers:
- Less energy
- Less waste

Hurdles:
- Further technology development
- Waste management

Profit
Economically Viable

Sustainability

People
Socially Responsible

Planet
Environmentally Sound
Not an accounting tool...

TBL’s goal was system change
12 Guiding Principles for linear processes

1. Prevent waste
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Anastas and Warner (1998)
enables a closed-loop, waste-free chemical industry

Waste = Resource

Product = Resource

Renewable

with Tom Keijer, Vincent Bakker, *Nature Chemistry, 2019, 11, 190*
making molecules and materials: green chemistry

molecules and materials: function and properties

REmaking molecules and materials: circular chemistry

safe by design: no persistent, bioaccumulative, and toxic compounds
Chemicals for a non-toxic circular economy

Circular economy
waste as a resource

Biodegradability (mineralization)

Circular chemistry:
“Design products for recycling, including all additives and other components of the product. (…) Design products not suitable for capture and recycling for complete fast mineralization at the end of their lives (e.g., pharmaceuticals, pesticides, personal care and cleaning products).”

EU Green Deal:
Non-toxic environment
Circular economy

Slootweg, Nature Chemistry, 2019, 11, 190
Kümmerer, Science 2020, 367 (6476), 369
Chemistry 2.0: Renewables & Zero emissions!
‘CHNOPS’ Waste: need for Innovation?

Can we convert CO$_2$ and CH$_4$ into value-added compounds?

Can we produce circular, zero emission energy carriers?

Can we recover and recycle ammonia/phosphate?

P-resource efficient?
Circular Chemistry: waste = resource!

- Recovery of P & N

1. Urine
2. Magnesium chloride
3. Recovery
4. Effluent

Renewable (crystals of) MAP

Recovery

Recycling

magnesium chloride

monoammonium phosphate

WO2020/169708
Renewable (crystals of) MAP

Recovery

Recycling

magnesium chloride

monoammonium phosphate

WO2020/169708
Circular Chemistry!

- Renewable
- Urban mining
- No waste
- High value
- Benign by design

GLOBAL CHEMICALS OUTLOOK II
FROM LEGACIES TO INNOVATIVE SOLUTIONS
IMPLEMENTING THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT
Chemistry to enable a Circular Economy

Life cycle thinking will reinvent chemistry

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