Sustainable Chemistry as the Overarching Guiding Principle to Embed Chemistry Into Sustainability

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Research & Education
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Sustainable Chemistry and Resources

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UNIVERSITÄT LÜNEBURG

ISC3 Spotlight 2024

Where We Start and What We Are Aiming For

Conventional Industrial Chemistry

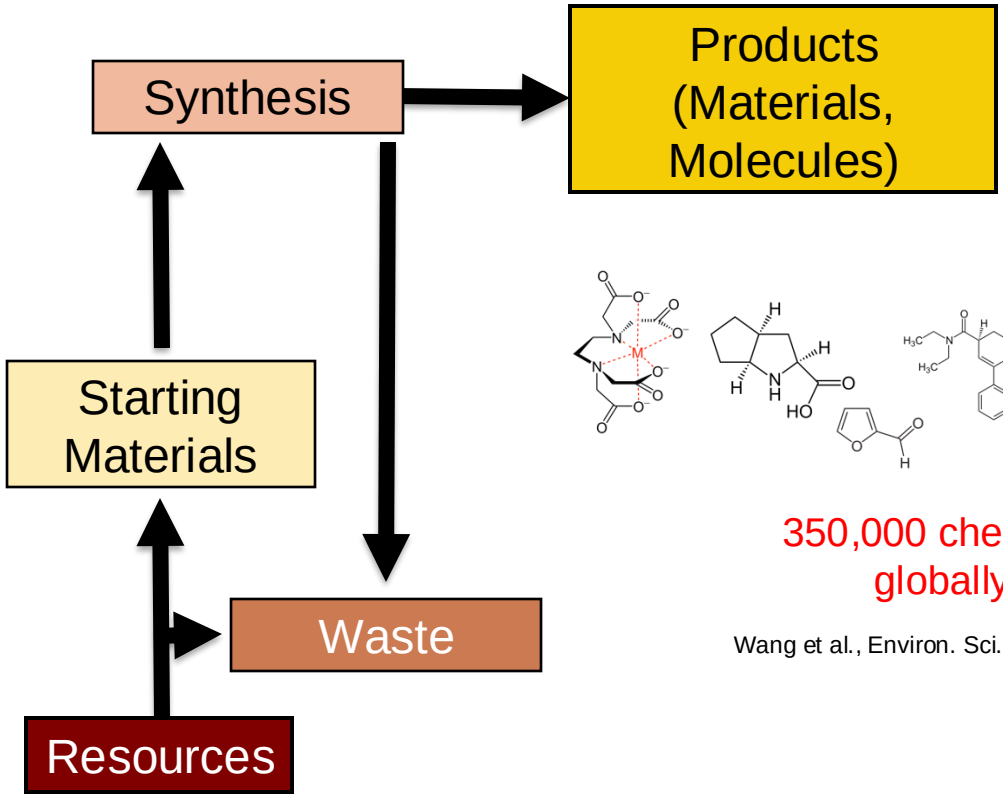
Processes
Compounds
Materials
Products

Non sustainable

Increasingly sustainable

Conventional Industrial Chemistry

Processes
Compounds
Materials
Products



350,000 chemicals/mixtures globally marketed

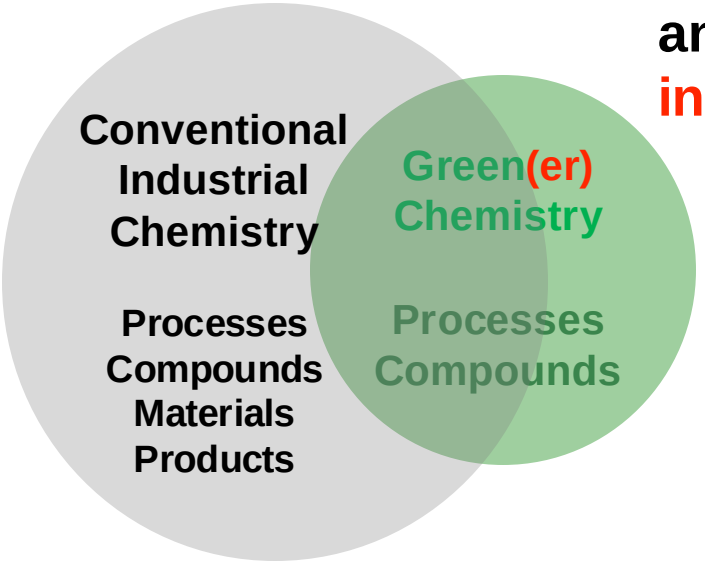
Wang et al., Environ. Sci. Technol. 2020, 54, 2575–2584

Products of the Chemical and Pharmaceutical Sector

The Down Side
of the Success Story of Chemical Industries

- 350,000 chemicals/mixtures globally marketed (Wang et al., Environ. Sci. Technol. 2020, 54, 2575–2584)
- Thereof approx. > 30,000 environmentally relevant, products of incomplete degradation not included (Umweltbundesamt, 2010)
- Hazardous to health 62 % of chemicals volume used in Europe 2016 (Source: European Environmental Agency)
- Ca. 1.6 mill. deaths in 2016 attributable to chemicals, many more affected (Source: World Health Organization)
- Neurological behavioural disorders caused by chemicals: Costs >170 Bill. US $ per year in EU (Source: UNEP Environment 2019)
- **Several hundred synthetic chemicals present in humans** (Source: UNEP Environment 2019)

Greener Chemistry: Pollution Prevention



Focus on synthesis and properties of individual chemicals

- **Less waste (from synthesis)**
- **Less energy**
- **Less hazard**
- **Renewable resources**

- Already practiced and commercialized within industry in the 1970s and 1980s
- Term Green Chemistry introduced by US EPA in the early 1990s based on work of many individual and organizations
- Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control
- **All long before its publication as 12 principles 1998**

- United Nations. *Non-Waste Technology and Production. A Seminar of the United Nations Economic Commission for Europe* (Pergamon 1978). Royston, M. G. *Pollution Prevention Pays.* (Pergamon 1979).
- Clark J.H., et al. Chem. Com. 18, 1353 – 1354 (1989).
- Sheldon, R.A. *Chem. Ind.* 903–906 (1992)
- Tundo, P., Aricó, F. *Chem. Int.* 29, 4-7 (2007)
- Murphy, M.A. Early industrial roots of green chemistry "Pollution prevention efforts during the 1970s and 1980s. *Chem. Int.* January-March, 21-25 (2021).

Non sustainable **Greener**

Waste and Pollution by Products Are Increasing

www.schuler-rohstoff.de/

www.badenova.de

www.welcome-to-sodom.com/

Textile Waste

- 600 chemicals
- most stay on fibres
- Until end of life
- Pollute ground water

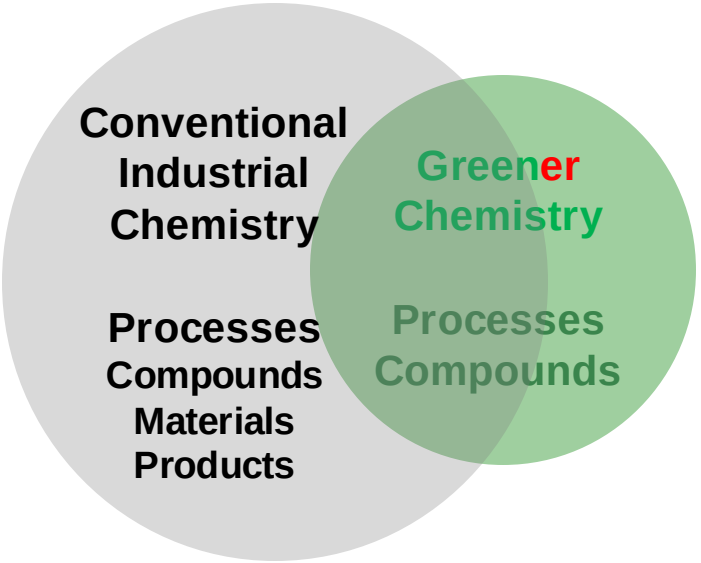
Macro and Micro Plastics

- Highly complex mixture
- Within and of polymers
- Additives
- 2/3 on sea floor already

Electronic Waste

- Many elements
- Plastics
- Additives
- Steep increase

Greener Chemistry - Limitations



Non sustainable Greener

Within principles

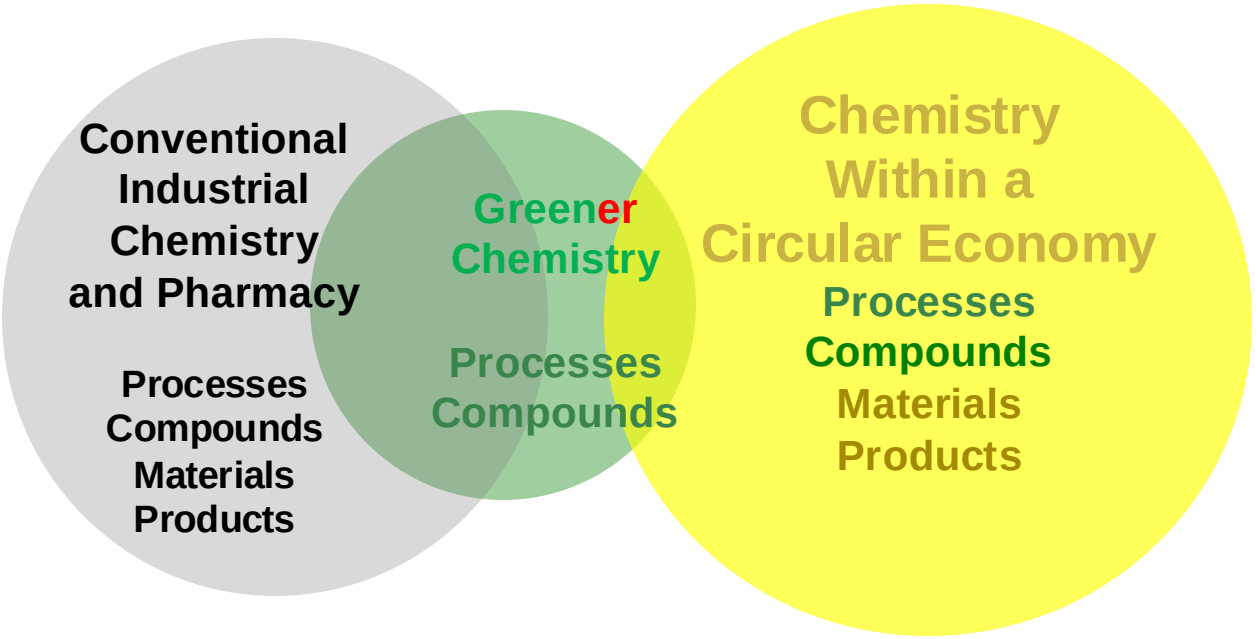
In general ot addressed e.g.

- **Total flows of substances, materials, products**
- **Mixing and complexity**
- **Recycling**
- **Ethics***
- **…**

*

- Kovac, J. *The Ethical Chemist: Professionalism and Ethics in Science.* 2nd ed. Oxford University Press 2018)
- Mehlich, J., Moder, F., Van Tiggelen, B., Campanella, L., Hopf, H. The Ethical and social dimensions of chemistry: Reflections, considerations, and clarifications. Chemistry – A European Journal **23**, 1210-1218 (2017

Chemistry Within a Circular Economy



Increasingly circular

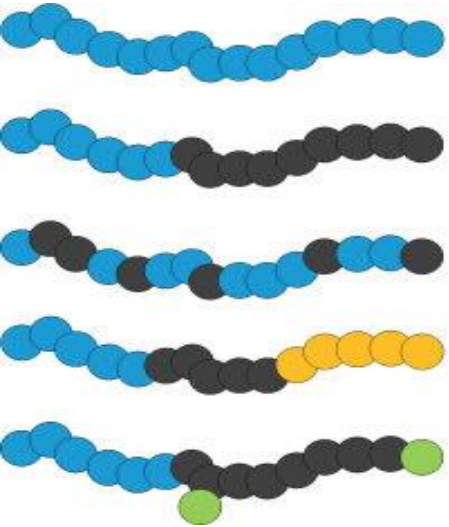
- Commoner, B. *The Closing Circle: Nature, Man, and Technology* (Knopf 1971).
- Stahel, W.R. The product-life factor. in *An Inquiry Into the Nature of Sustainable Societies: The Role of the Private Sector* ed. Grinton Orr, S.) 72-104 (Houston Area Research Center 1982).

Decades before Ellen Mac-Arthur Foundation or Cradle to Cradle etc.

Keijer, T., Bakker, V. & Slootweg, J.C. **Circular chemistry to enable a circular economy**. *Nature Chem* **11**, 190–195 (2019)

Increase in Volume and Complexity (Plastics and Plastification)

Atomic and molecular level



Homopolymer

Block co-polymer

Statistical co-polymer

ABC Triblock co-polymer

Polymer with functional groups

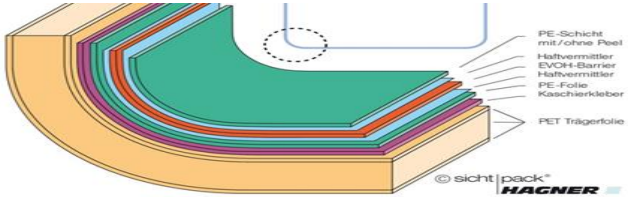
Molecular and product level

- Filler
- Plasticiser
- Colorant
- Flame retardant
- Antioxidants
- Thermal stabilizer
- Antifouling
- UV Screen
- Antistatic
- Antireflection
- Whitener
- ...

10 500 chemicals as additives in plastics

- Packaging: 2489
- Textiles: 2429
- Food contact material: 2109
- Toys: 522
- Medical devices: 247

Wiesinger, H., Wang, Z., & Hellweg, S. Environmental Science & Technology; 2021

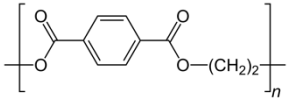


http://german.alibaba.com/product-gs-img/kunststoff-additive-antistatik-masterbatch-157783695 8.html

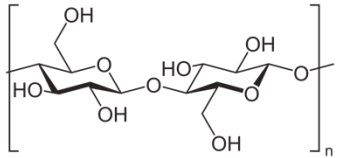
Thermo sets, Thermoplastics

Increase in Volume and Complexity – Textiles and Fast Fashion

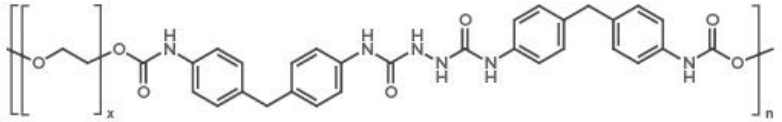
Polyester (PET)



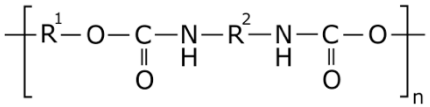
Cotton



Elastan



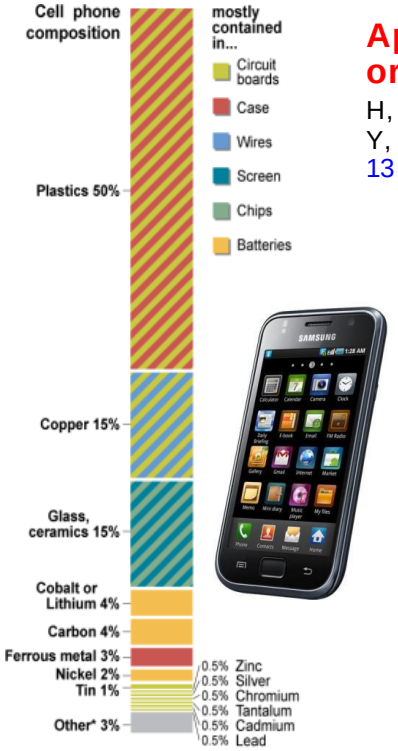
Polyurethane



Dyes

.... ca. 600 chemicals for textile manufacturing

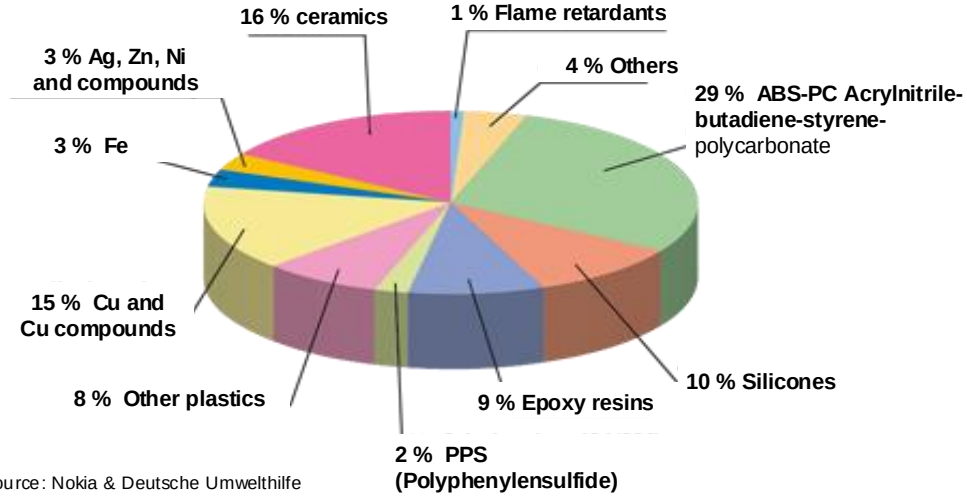
Increase in Volume and Complexity – Electronics (e.g. Communication)



Approx. 40 elements, plus their compounds, plus small organic molecules, polymers; mixed on molecular level

H, Li, Be, C, N, O, F, Al, Si, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Br, Sr, Y, Zr, Ru, Pd, Ag, Cd, In, Sn, Sb, Ba, Ta, W, Pt, Au, Hg, Pb, Bi, Nd

13,7 g Copper, 0,189 g Silver, 0,028 g Gold, 0,014 g Palladium



Source: Nokia & Deutsche Umwelthilfe

Quelle: Nokia, Deutsche Umwelthilfe

There is Neither Endless Recycling Nor Up-Cycling, Only Down Cycling!

Unavoidable losses

- **Quantity**
- **Quality**

- **Need of energy**
- **Increase of entropy**
- **Generation of waste**
- **NIAS** **(non intentionally added substances)**
- **Legacy chemicals**

Georgescu-Roegen N. *The entropy law and the economic process* (Harvard University Press 1971)

Daly, H.E., ed. *Toward a Steady-state Economy* (W.H. Freeman 1973).

Zink, T. & Geyer, R. Circular economy rebound. J. Industr. Ecol. 21, 593 – 602 (2017).

Soddy, F. *Wealth, Virtual Wealth and Debt: The Solution of the Economic Paradox* ([1926] Omnia Veritas Ltd 2021).

De Man, R. Circularity dreams: Denying physical realities. in *The impossibilities of the circular Economy* (ed Lehmann, H., Hinske, C., de Margerie, V., Slaveikovka Nikolova, A. 3-10 (Routledge 2023).

Whitman A.N.,
Thermodynamics: Basic Principles and Engineering Application (Springer 2024)

Thermodynamics - 3 Basic Laws

1. You cannot win, you can only end up in a draw
2. You can only end up in a draw at perfect conditions
3. You will never reach perfect conditions

Summarizing:

We cannot win, we can only try to loose as little as possible

Reduction of Substance, Material, and Product Flows

- **Diversity**
- **Volume**
- **Dynamics**
- **Scale (time and space)**
- **Intensity**

Kümmerer K., Time & Society (1995), **5**, 209-235

Kümmerer K. (2017) Angew. Chem. Int. Ed. (2017), **56**, 16420 – 16421

Kümmerer, K. Olsson, O., D.D. Dionysiou, Fatta-Kasinos, D. (2018) Science **361** 222 ff

Weiser, A., Lutz, L.M., Lang, D.J., Kümmerer, K. (2017), J. Cleaner Production, **162**, 273-285

Weiser, Lang, D.J., Kümmerer, K. (2017) Sustain. Chem. Pharm., **5**, 105-112

Zuin-Zeidler V., Kümmerer K. (2022) Nature Rev. Materials, https://doi.org/10.1038/s41578-022-00415-2

Greener by Design for Recycling

Reduce complexity

Avoid complex products (e.g. multiple components or building blocs)

- **Keep atomic, molecular complexity and mixing to the minimum** required for the desired performance
- **Minimise use of components that cannot easily be separated/recycled**
- **Minimise mixing:** Avoid entropic losses and transfers (e.g. dissipation of metals, mixing of plastics)

- **Avoid materials not suitable for capture and recycling at end of life**
- **Keep change of complexity of building blocs low**
- **Processes should**
  - **be kept as simple as possible** with a minimum number of steps, auxiliaries, energy and unit operations (e.g. separations, purification)
  - **be designed** for optimal recovery of **auxiliaries, unused substrates, and unintended by-products** (quality and quantity!)

K. Kümmerer, J. Clark, V. Zuin, Science, 367, 369-370

Challenges: Not everything can be circulated!

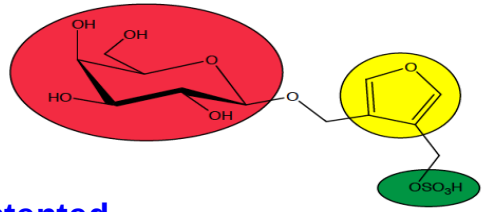
Products:
- Detergents
- Pesticides
- Pharmaceuticals
- Odorants
- …

Abrasion:
- Tyres
- Facades
- Catalytic converters
- …

Degassing:
- Flame retardants
- Plasticizers
- …

Measures at the Source-Molecules - Design for Environmental Mineralization

Anti-Cancer Drugs:

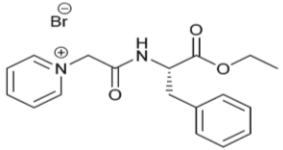


Patented

Marano G. et al. EP 2 474 552 A1

& Kümmerer K (2019): Sustainable Chemistry and Pharmacy, 12 (2019) 100136

Ionic liquids



Organosilicones:

Towards the design of organosilicon compounds for environmental degradation by using structure biodegradability relationships

Elisa Grabitz, Oliver Olsson, Klaus Kümmerer*

Institute of Sustainable and Environmental Chemistry Leuphana University of Lüneburg Universitätsallee 1, 21335, Lüneburg, Germany

HIGHLIGHTS

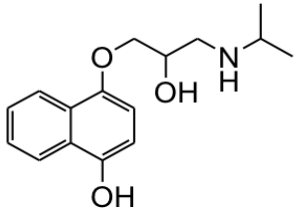
- Collection of biodegradation data of the ECHA database and own experiments.
- Grouping of the substances to derive general findings.
- 12 out of 182 organosilicon substances were readily biodegradable.
- Hydrolysis was a mandatory step prior to biodegradation.

GRAPHICAL ABSTRACT

On the way to greener ionic liquids: identification of a fully mineralizable phenylalanine-based ionic liquid†

Annette Haiß,[a] Andrew Jordan,[b] Janin Westphal,[a] Evgenia Logunova,[a] Nicholas Gathergood*[c] and Klaus Kümmerer*[a]

ß- Blockers:



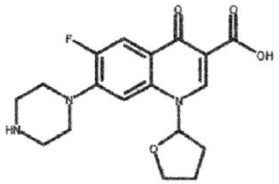
Rastogi T, Leder C, Kümmerer K (2014) Chemosphere, 111, 493–499 (**Metoprolol**)

Rastogi T, Leder C, Kümmerer K (2015) RSC Advances, 5, 27-32 (**Atenolol**)

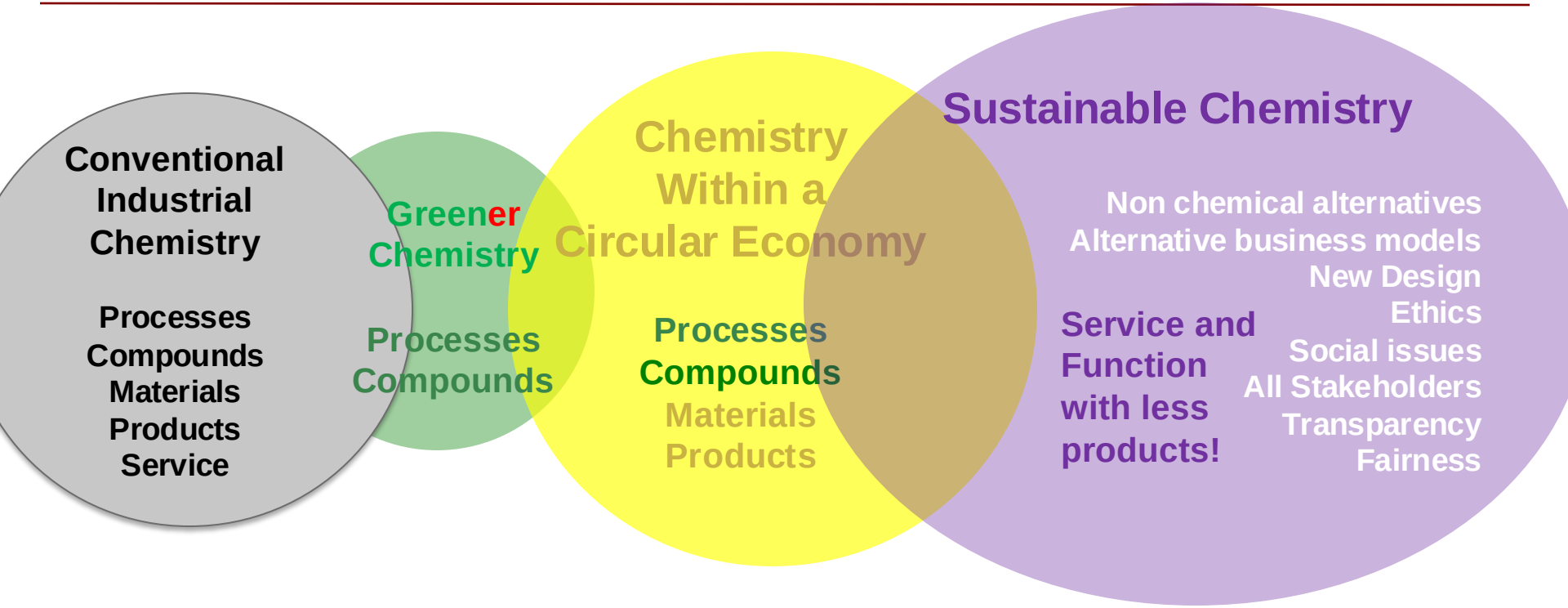
Antibiotics:

Two patents (WO2019072905A1, WO2019072907A1)

Leder et al. (2021) Sustainable Chemistry and Engineering, under revision



Embedding Chemistry Into Sustainability



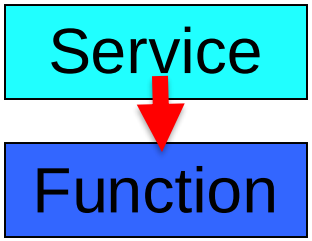
Kümmerer K. Nat. Rev. Chem., submitted

Increasingly sustainable

Why Do We Use Products?

Service

Why Should We Use Chemical Products if There is a Non-Material Alternative!

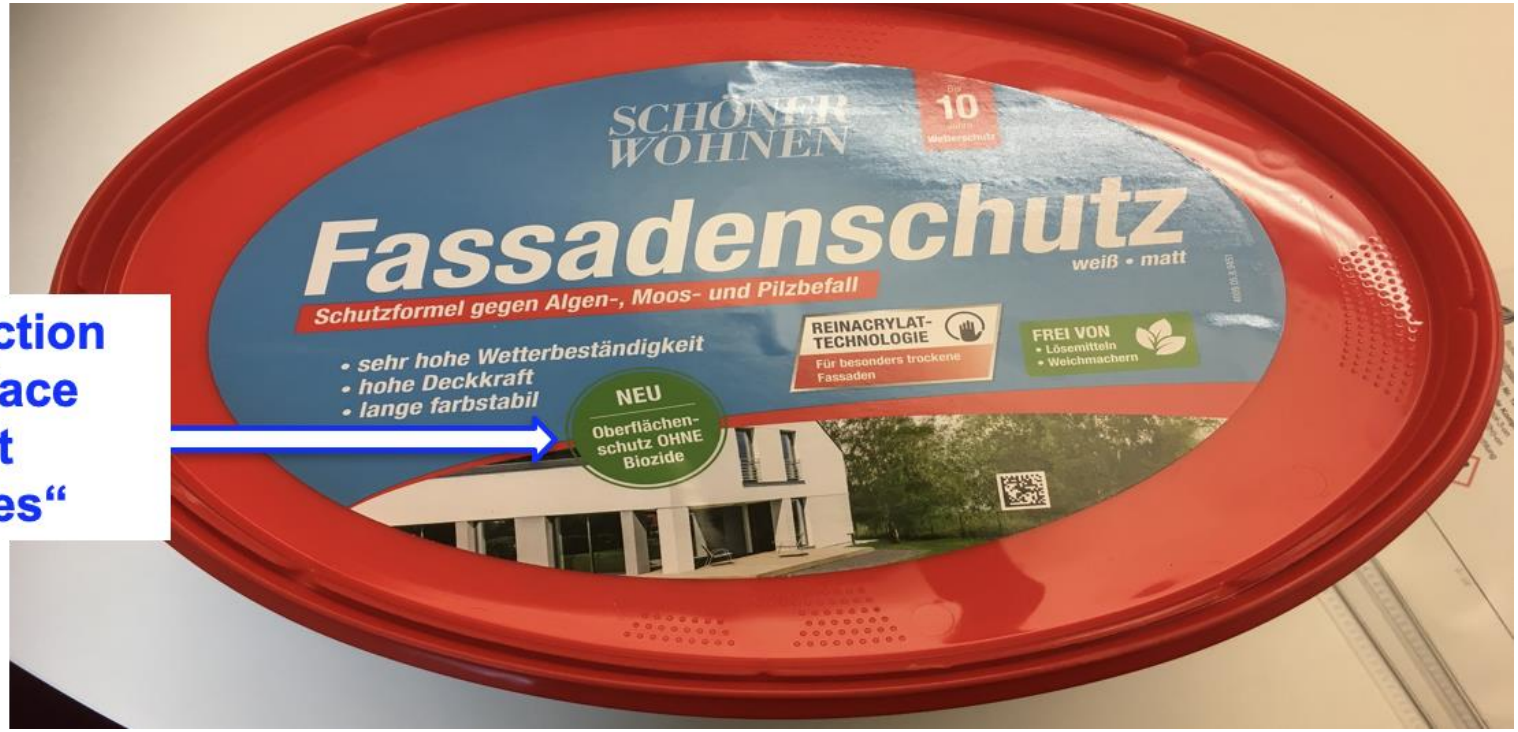


~~Apply identified non~~ chemical alternative

e.g.

- Alternative construction
- Alternative design
- Alternative Behaviour
- Information
- Training
- Alternative Technology
- …

Same Function with Less - No Biocides in Front Paintings



Same Function With Less!

The example of PFAS („Eternity Chemicals“)

- ➢ > 10 000 different compounds in use
- ➢ Extremely persistent in the environment
- ➢ Toxic
- ➢ Manifold applications **e.g. Water Repellent**

https://static.bergzeit.com/

– ***Ski Wax:***

- **Service**: increased speed, needed?
- **Alternative without chemicals:** A bit lower speed; applies for everyone-> no disadvantages

© EMPA

– ***Textile fibres:***

- **Service:** longer dry/faster drying (check if needed)
- **Alternative without chemicals:** physical laser treatment
- Alternative Chemical: Coating with poly siloxanes -> think of recycling, greener synthesis!

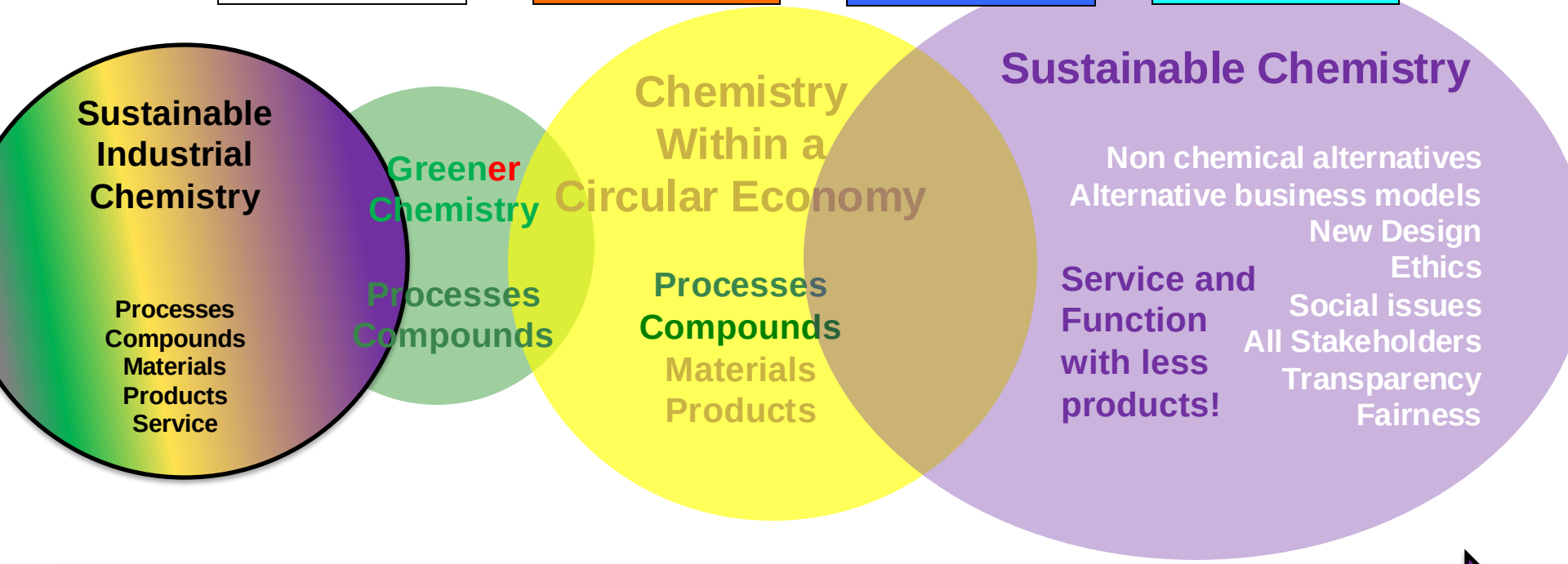
https://www.priam.at

– ***Hydrophobic Metal Surface:***

- **Service**: water repelling surface (check if needed)
- **Alternative without chemicals:** physical laser treatment
- (Coating with Polymer -> think of recycling, greener synthesis!)

Practicing Chemistry Within Sustainability

Synthesis ⇦ Design ⇦ Function ⇦ Service



Kümmerer K. Nat. Rev. Chem., submitted

Increasingly sustainable