

The 19th Helsinki Drug Research Congress (HDR-2008)  
June 9-11, 2008, Helsinki, Finland



University of Oulu, 50th  
Anniversary  
1958-2008



## Sustainable Production The Role of Green Chemistry and Engineering, and Catalysis

Prof. Riitta Keiski  
University of Oulu  
Department of Process and Environmental Engineering  
P.O.Box 4300, FIN-90014 University of Oulu  
riitta.keiski@oulu.fi

Sustainability and Sustainable Production  
Green Chemistry and Green Engineering  
Chemistry and Chemical Engineering in Support for Sustainability  
The Role of Catalysis in Support for Sustainability  
Process Intensification, Examples  
Future Trends

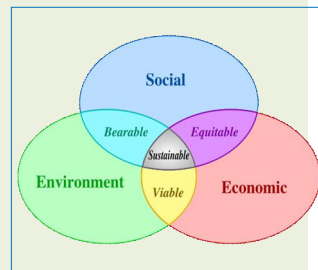


## Sustainable Development

"Satisfies the needs of the present without compromising  
the ability of future generations to meet their own  
needs" (Brundtland report)

Key Issues Towards Sustainability

- Population and Human Resources
- Food Security
- The Urban Challenge
- Energy
- Industry
- Species and Ecosystems
- Conflict and Environmental Degradation
- Managing the Commons



## Sustainable Production

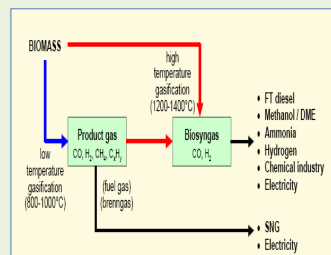
"Sustainable Production is the creation of goods and services  
using processes and systems that are:

- non-polluting;
- conserving of energy and natural resources;
- economically efficient;
- safe and healthful for workers, communities, and consumers; and,
- socially and creatively rewarding for all working people."

(Lowell Center for Sustainable Production)

## What is Green Chemistry?

- Interdisciplinary
  - Economics
  - Engineering
  - Political science
  - Ethics and psychology
  - Environmental science
  - Chemistry
  - Biology
  - ...
- A new way of thinking!



## Green Chemistry and Engineering as Tools of Industrial Ecology

In Green Chemistry and Green Engineering are sets of principles that reduce or eliminate the use or generation of hazardous substances in the design, manufacture, and application of chemical products

12 principles are understood in terms similar with criteria such as yield, or selectivity.



## The 12 Principles of Green Chemistry

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

- 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.

## The 12 Principles of Green Chemistry

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

- 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.

## The 12 Principles of Green Engineering

By P.T. Anastas & J.B. Zimmerman, ENVIRONMENTAL SCIENCE & TECHNOLOGY, MARCH 1, 2003, p. 94A-101A

- Principle 1: Inherent rather than circumstantial: Designers need to strive to ensure that all material and energy inputs and outputs are as **inherently nonhazardous** as possible.
- Principle 2: Prevention instead of treatment: It is better to **prevent waste** than to treat or clean up waste after it is formed.
- Principle 3: Design for separation: Separation and purification operations should be designed to **minimize energy consumption and materials use**.
- Principle 4: Maximize mass, energy, space, and time efficiency: Products, processes, and systems should be designed to **maximize mass, energy, space, and time efficiency**.
- Principle 5: Output-pulled versus input-push: Products, processes, and systems should be **"output pulled"** rather than "input pushed" through the use of energy and materials.
- Principle 6: Conserve complexity: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.



## The 12 Principles of Green Engineering

By P.T. Anastas & J.B. Zimmerman, ENVIRONMENTAL SCIENCE & TECHNOLOGY, MARCH 1, 2003, p. 94A-101A

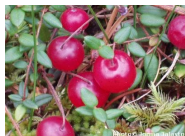
- Principle 7: Durability rather than immortality: **Targeted durability**, not immortality, should be a design goal.
- Principle 8: Meet need, minimize excess: Design for **unnecessary capacity or capability** (e.g., "one size fits all") solutions should be considered a design flaw.
- Principle 9: Minimize material diversity: **Material diversity** in multicomponent products should be **minimized** to promote disassembly and value retention.
- Principle 10: Integrate local material and energy flows: Design of products, processes, and systems must include **integration and interconnectivity with available energy and materials flows**.
- Principle 11: Design for commercial 'afterlife': Products, processes, and systems should be designed for performance in a **commercial "afterlife"**.
- Principle 12: Renewable rather than depleting: Material and energy inputs should be **renewable rather than depleting**.

Green issues are becoming more and more important with respect to chemical processing.

Green Chemistry and Engineering are new fields that seek to reduce the environmental consequences of e.g. chemical industry:

- by **modifying engineering practices**,
- by **developing new processes** (e.g. catalytic processes),
- by **modifying existing chemical processes**,
- by **bioremediation**.

Green Chemistry and Engineering have the greatest impact and cost effectiveness when applied **early to the design and development phase** of a process, product, service or concept (has been scientifically proven to be true)



## Green Engineering and Chemistry Cover

1. The **application of innovative technologies** to established industrial processes
2. The **development of environmentally improved reaction and process routes** to important products
3. The design of new Green chemicals and materials (**environmentally benign products**)
4. The use of sustainable resources (**renewables**)
5. The use of biotechnology alternatives (**combining biotechnology and chemical engineering**)
6. Methodologies and tools for evaluating environmental impact

Examples: Green Processing, Green Applications of Carbon Dioxide, Environmentally Benign Catalysis, Green Separations



## Chemistry and Chemical Engineering in Support of Sustainability; CERC3 – Examples

### New starting materials

- New building blocks from sustainable energy sources (sugar, bio-ethanol)
- Better use of natural gas
- Activation of alkanes (selective catalytic oxidation)

### New catalyst systems

- Nanostructured supports and active phases
- New solid basic catalysts
- Surface modification of inorganic materials
- New polymers and new functionalization
- Soluble mesoscopic supports
- Multicatalyst systems
- Chemo-enzymatic catalyst systems
- Libraries of catalysts



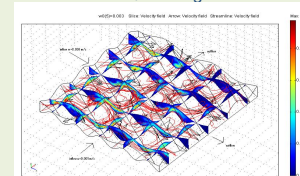
### New reaction media

- Super critical fluids, ionic liquids
- Microwaves
- Water, non-solvent

## Intensification systems

- Modelling and calculation
- Surface science applied to catalysis
- Process integration & intensification
- Combining chemo-, bio- and electrocatalysis
- Combinatorial approach of catalysts
- New atom-economic reactions and processes (i.e. more efficient recycling; no protective groups)

Example: Fouling of surfaces; Molecular modeling, CFD calculations, Thermodynamics, Process analysis, Corrosion studies, Fouling kinetics



## Chemistry for sustainable energy

- Catalysts for photo-activation
- New functionalised materials (defined Materials for energy and H<sub>2</sub> storage)
- Bio-routes to hydrogen

## Microreactors/Flowthrough Systems

- Fundamentals (Flow Distribution, Profiles, Coalescence)
- Integration (Substrate Stream, Conversions and Down Stream Processing)
- Gradient Controlled Microreactors (Concentration, T, pH, Catalyst concentration)
- Periodic Operations (e.g. Catalyst Regeneration)

## Improving the Conversion of Renewable Resources

- Energy Production from Renewable Resources (e.g. Biomass)
- Design of Solid Catalysts for Cleaner Processes
- Reforming of Biomass for Hydrogen Production
- Replacement of Liquid Bases and Toxic Catalysts
- Integrated Processes Combining Chemo-, Electro- and Biocatalysis

## Non-conventional Techniques / Media / Reactions

- Supercritical Fluids and Ionic Liquids as Reaction Media
- Microwave for Energy Transfer
- Catalysis for the Generation of new Materials
- Synthesis or Biosynthesis with Catalysis

## Manufacturing techniques for

- Nanostructured materials for novel solar cells and rechargeable ceramic batteries (fundamental research)
- Nanostructured materials for intermediate-temperature solid oxide fuel cells: fundamental and applied research
- Nanostructured materials for storage of hydrogen produced by sustainable energy sources (fundamental research)
- Combined heat-power microstructured reactors (fuel cell-based): applied research
- Photoelectrolysis for the production of hydrogen: fundamental research
- Enzymatic routes to sustainable hydrogen: fundamental research
- Reformers upstream the fuel cells (to make H<sub>2</sub>)



## Renewable Raw Materials

by Green Chemistry, 1999

### The strengths of renewable products

- Low environmental impact
  - New opportunities
  - New functionality
- Non-toxic, biodegradable, CO<sub>2</sub>-neutral, domestic feedstock, flexible feedstock

### The weaknesses of renewable products

- Natural variability
- Cost, seasonal
- Complexity
- Unknown technology
- Re-evaluation of the manufacturing process and the establishment of new supply chains



## Process Design

Pereira, C.J. 1999. Chemical Engineering Science 54, 1959-1973.

### Pollution prevention and integrated environmental approaches:

*four design criteria, technical, economical and environmental feasibility as well as safety considerations are as important and are all taken into account from the very beginning of the process design project (ethical criteria?)*

### The process design of the 21<sup>st</sup> century brings

- The integration principles into chemical process design:
  - Raw material consumption and waste impacts
  - The environmental impacts throughout the production chain and the design project
  - 12 principles of Green Chemistry and Engineering
- Higher product selectivity and conversion, improved energy efficiency, use of benign solvents, raw material substitution, conversion of hazardous products to less hazardous products prior to shipment, on-site production of hazardous materials, conversion of by-products to products, lower secondary emissions, and low aqueous waste

OULUN YLIOPISTO  
UNIVERSITY OF OULU



## Process Intensification - Microreactor Technology

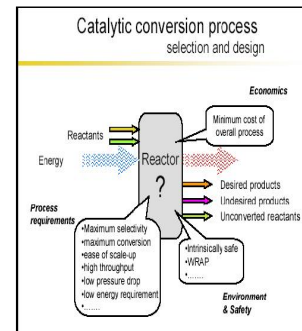
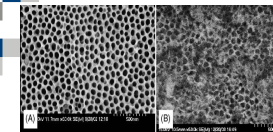
- Effective heat transfer, fluid profile laminar, isothermal
- Volume is decreased (several  $\mu\text{l}$ ), large surface to volume ratios
  - The number of units increases
- The research on materials and processes comes quicker
- More flexible production and product marketing
  - Easier start-up procedure
  - Scale-up to the production size is easier
  - Smaller equipment size
- Lower material, energy and transportation costs
  - Versatile and relatively inexpensive

MSR for gas phase reactions: Kiwi-Minsker & Renken, Catal. Today 110(2005)2

MSR for gas phase reactions: Kolb & Hessel, Chem. Eng. J. 98(2004)1

- **New concepts of chemical synthesis** - an increasing demand for miniaturization and more complex systems
- **Microreactor technology a hot topic** - opens completely new possibilities for chemical engineering, combinatorial chemistry, and biotechnology
- **Small, inexpensive, independent, and versatile devices** - maximum selectivity, minimum waste, minimum investment, a better control of the process, safe manufacture and production on demand - to create a more efficient process.

Ehfeld, W., Hessel, V. & Lowe, H. Microreactors. Weinheim 2000, Wiley-VCH Verlag GmbH. 288 p.



Kiwi-Minsker & Renken, Catal. Today 110 (2005) 2-14

### Microstructured reactors suitable for fast, highly exothermic/endothermic reactions because they lead to:

- Process intensification
- Inherent reactor safety
- Broader reaction conditions including up-to the explosion regime
- Distributed production
- Faster process development
- Easy to fabricate

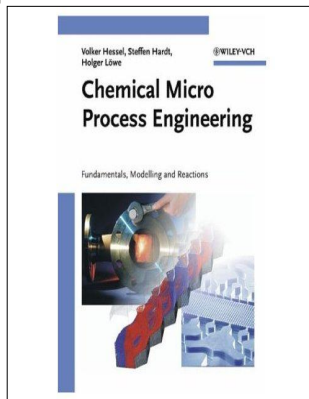
### They have, however,

- Usually a high-pressure drop during the passage of gases:
  - Catalytic wall microreactors or String reactors (channels formed between the catalytic parallel filaments or wires)
- Difficulty of the introduction of solid catalyst into microchannels

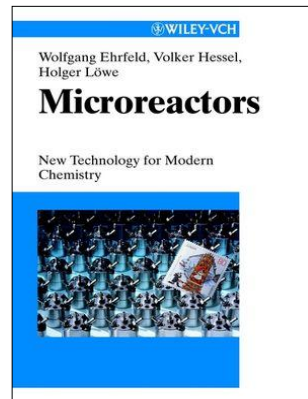
OULUN YLIOPISTO  
UNIVERSITY OF OULU



## Text Books in Microreactor Technology



Prof. Riitta Keiski 2.6.2008



OULUN YLIOPISTO  
UNIVERSITY OF OULU

## Examples of Green Solvents and Reaction Conditions

Development of **environmentally benign solvents and reaction conditions**

Traditional solvents, such as **chlorofluorocarbons** and **volatile organic compounds**, have been implicated in a number of environmental problems and so have been highly regulated

### Supercritical Fluids

- The use of **supercritical carbon dioxide** as a substitute for organic solvents already represents an important tool for waste reduction in the chemical industry and related areas
- The extension of this approach to chemical production, **using CO<sub>2</sub> as a reaction medium**, is a promising approach to pollution prevention
- **Supercritical H<sub>2</sub>O**

OULUN YLIOPISTO  
UNIVERSITY OF OULU

## Alternative Reaction Media

- **Most acceptable**
  - None (rarely possible)
  - Water
  - Oxygenated (e.g. alcohols, ketones, esters)
  - Aliphatic hydrocarbons (e.g. cyclohexane)
  - Aromatic hydrocarbons (e.g. xylene, mesitylene)
  - Dipolar aprotic (e.g. DMSO)
  - Chlorinated solvents
  - Ozone depleters (e.g. CFCs)
- **Least acceptable**
  - Toxic and carcinogenic solvents (benzene)

### Ionic Liquids

- Green solvents
- Recyclable – yes, with correct design; but many moderately or very toxic
- Negligible vapour pressure –  $10^{-5}$  –  $10^{-6}$  bar, the lower the viscosity the higher the vapour pressure
- Non-flammable – not energetic ILs, can ignite as fine aerosols
- Potential formulations at least  $10^{18}$
- Wide liquid range: -100 to 400 °C
- Polar

OULUN YLIOPISTO  
UNIVERSITY OF OULU

## Ionic Liquids

- High thermal stability
- High and unusual solvation properties – e.g. cellulose, minerals, carbohydrates can be dissolved in high concentrations
- Tunable properties
- Sc-CO<sub>2</sub> unlimited solubility in ILs, ILs do not dissolve in Sc-CO<sub>2</sub>
- ILs couple strongly with microwaves
- Purity and humidity have strong effect on the physico-chemical properties of ILs
- High viscosity at room temperature
- High molecular weight, densities close to that of water

### New reaction media:

- **ionic liquids, water, supercritical fluids**
- Obstacles to implementation in industry: **Lack of information, cost, risk, unproven technology**

OULUN YLIOPISTO  
UNIVERSITY OF OULU

Example: CO2UTIL, Towards utilization of CO<sub>2</sub> as a green and versatile commodity chemical - Clean Synthesis of Methanol and Dimethyl Carbonate

**DMC selectivity 100 % Better activity**

- Under one phase reaction conditions
- Recycling of Catalytic Species
- Water trapping

**Future activities**

- Catalyst Design for Continuous Flow Reactors
- Heterogenization of the catalyst
- New catalytic materials

- Developing green chemicals via a sustainable process in accordance with Green Chemistry principles
- Value enhancement of a secondary resource, CO<sub>2</sub>
- The conventional method for methanol production is based on fossil feedstock and the production of DMC involves the use of toxic phosgene or CO
  - Reduction of the hazard from solvents and chemicals
  - Explore safe and environmentally sound reaction routes and energy-efficient processes
  - Identify new, effective catalysts for methanol and DMC syntheses
- Develop a dynamic simulation system that can be used in studying the realization of different process routes from process control viewpoint

by E. Pongráz, 2007



OULUN YLIOPISTO UNIVERSITY OF OULU

Major Drawbacks of Current Industrial Processes  
Industrial Routes to Produce, Dimethyl Carbonate (DMC)

By Prof. D. Ballivet-Tkatchenko, 2006

Harmful Reactants

Undesirable Co-products

<i>SNPE</i>	COCl <sub>2</sub>	HCl	Stoichiometric
Phosgene			
<i>EniChem</i>	CO + 1/2O <sub>2</sub>		Selectivity 95%
Carbon Monoxide	CuCl <sub>2</sub> -based catalyst		
<i>UBE</i>	CH <sub>3</sub> ONO	NO	Selectivity 90-95%
Carbon Monoxide	PdCl <sub>2</sub> -based catalyst		

OULUN YLIOPISTO UNIVERSITY OF OULU

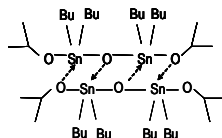
A Green Alternative for DMC Production

Direct Synthesis from CO<sub>2</sub>-Alcohol



Carbon Dioxide

- Non toxic
- Non-inflammable
- Easy to handle, transport, store
- Abundant C<sub>1</sub> feedstock
- Oxygen carrier
- Powerful solvent (SCF)



By Prof. D. Ballivet-Tkatchenko, 2006

OULUN YLIOPISTO UNIVERSITY OF OULU

Catalysis in Support of Sustainability

- New heterogeneous and homogeneous catalysts:
  - New Materials (New Carbon modifications for Nanotubes), New Polymers, Ligands for Selective/Efficient Catalysis
- Alternative reaction media and activation for catalytic reactions:
  - Supercritical Fluids and Ionic Liquids as Reaction Media, Microwave for Energy Transfer, Catalysis for the Generation of new Materials, Synthesis or Biosynthesis with Catalysis
- New catalytic atom-economic reactions and processes
- Catalytic systems for the conversion and storage of energy:
  - Nanostructured materials for fuel cells, solar cells, ceramic batteries
  - Nanostructured materials for the storage of hydrogen from sustainable energy sources
- Chemo-enzymatic transformations
  - (including use of renewable feedstock)
- Microstructured catalytic reactors
  - (including membrane reactors)
- Catalysts for photo-activation and New functionalised materials
  - (defined textures, inorganics, membranes, etc.)
- The role of catalysis in process intensification
- High throughput methods for catalyst discovery
- Enzymatic routes to hydrogen

- Environmental, health, safety and economic targets**
- Atom efficiency
  - Safe
  - Simple
  - One step
  - 100 % yield
  - Available materials
  - No waste reagents
  - Environmentally acceptable

## Green Chemistry and Catalysis

(Anastas et al. 2000)

- Catalysis – environmental and process catalysis – has proved its role as a tool in pollution prevention
- Catalysis has long been utilized in increasing yield, selectivity and efficiency of chemical processes (energy, material)
- Nowadays catalytic procedures are often implemented according to the green chemistry principles and good industrial examples are found that fulfil several of the twelve principles of green chemistry at the same time

## EXAMPLE: Environment and Products Drive the Catalyst Market

by Focus on Catalysts, May 2002, p. 2

- Rise in environmentally friendly refinery and chemical products
- The polymerization catalyst sector is seen to be the fastest growing sector:
  - Metallocene catalysts to overtake Ziegler-Natta catalysts by 2010
- In pharmaceutical production enzyme-based and chiral catalysts will become more widely utilized
- Demand for oxidation and syngas catalysts is increasing
- Catalysts for chemicals, fuels, polymers, environmental protection

Chemistry and catalysis will play a central role in the pursuit of sustainability as this product-oriented science is present in every household world wide; Three major fields which are regarded to be essential in this context.

Energy: solar, H<sub>2</sub>, biomass

Production: safety, efficiency, selectivity

Products: quality of life



## Combining Good Features of Homogeneous and Heterogeneous Catalysis

- Nanometer-scale: Better control of activity, selectivity, deactivation of catalysts
- Recent advances: Design, synthesization, characterization, and manipulation of nanoscale catalysts → catalysis nanoscience
- Research in catalysis nanoscience: Relationships between catalyst synthesis, active site structure on the atomic/nanoscale, reaction mechanisms, and catalyst activity, selectivity, lifetime
- Advances lead to: Design of catalysts for novel catalytic reactions that take advantage of self-assembly of catalytic sites in predetermined two- and three-dimensional configurations

Recent attempts: to bridge different catalysis areas from biocatalysis to homogeneous and heterogeneous catalysis.

The goal is to combine the high selectivity of homogeneous cluster catalysts with the stability and versatility of supported heterogeneous catalysts.

Somorjai, G.A. Nature 430(2004) 730.  
Grunes, J. et al. Chem. Comm. (2003) 2257.

OULUN YLIOPISTO  
UNIVERSITY OF OULU

## Catalysis Research by the Oulu Group

New innovations in catalysis, Resources use optimization and waste minimization efforts in industry and society

- Catalytic routes in CO<sub>2</sub> utilization
- Catalytic oxidation of VOCs, CVOCs, malodorous compounds
- Reforming and Water gas shift reaction
- Catalytic oxidation and reduction of flue and exhaust gases
- Catalytic wet oxidation and Photocatalysis
- Formaldehyde production from contaminated methanol
- Abatement and health effects of fine particulates
- Deactivation of catalysts
- Catalytic materials and their characterization
- Control of the surface poisoning phenomena
- Catalytic routes from biomass to (higher alcohols) (methanol, ethanol, biobutanol, biopentanol)
- Methanol and DMC syntheses



**Integrated Design of Catalytic Nanomaterials for a Sustainable Production, IDECAT- EU Network of Excellence:**  
Catalysis for Renewables; May 16 - 18, 2006, The Netherlands

Theme A: Renewable Resources

- Biomass and biomass conversion
- Hydrogen production
- Solar cells, CO<sub>2</sub>

Theme B: Bioconversion processes

- Integration of biocatalysis with chemo-catalysis
- Catalytic options in biomass to fuels: thermochemical processes
- Biomass Gasification to H<sub>2</sub> and Fisher-Tropsch

Prof. Riitta Keiski 2.6.2008

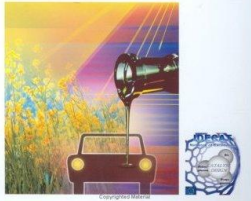
Literature

Edited by Gabriele Centi and Rutger A. van Santen

WILEY-VCH

**Catalysis for Renewables**

From Feedstock to Energy Production




OULUN YLIOPISTO UNIVERSITY OF OULU

**Summary - The Ideal Synthesis**  
by Clark, J.H. Green Chemistry, 1999

A number of environmental, health, safety and economic targets:

- Atom efficiency
  - Safe
  - Simple
  - One step
  - 100 % yield
- Available materials
- No waste reagents
- Environmentally acceptable



OULUN YLIOPISTO UNIVERSITY OF OULU

**Summary - Nanostructured Catalytic Materials from the Engineering Point of View**

- **A great impact on chemicals manufacturing in the future, re-engineering**
  - Designing catalytic materials from the atom-scale via combining the best features of biocatalysis, homogeneous and heterogeneous catalysis
- **New tools for chemical process integration at the nanoscale**
  - Design of a chemical plant with a better integration of its units to conserve energy and raw materials
  - Combining multiple chemical reactions through atom-up design of nanomaterials for catalysis
- **Catalysis by nanomaterials optimized to direct the chemical transformation of raw materials into desired products – Sustainable production**
  - Minimizing energy use, waste generation and environmental hazards, and improving process safety – Green chemistry and engineering approach

→ → → This changes the way how chemicals and other products are manufactured, distributed, and used in our society in the future

OULUN YLIOPISTO UNIVERSITY OF OULU

**Contact information**



Prof. Riitta Keiski, D.Sc.(Eng.)  
Head of Research, Docent, Vice-rector (Provost in education)

Senior researchers and research advisors: Dr. Esa Muurinen, Dr. Satu Ojala, Dr. Tanja Kolli, Dr. Mika Huuhtanen, Doc., Dr. Eva Pongrácz

PhD students: Riitta Raudaskoski, Esa Turpeinen, Tiina Pääkkönen, Reeta Ylönen, Markus Riihimäki, Satu Pitkäaho, Minna Pirilä, Ritva Lenkkeri, Kaisu Ainassaari, Kati Oravisjärvi, Nora Pap, Veronica García, Jungal Landaburu-Aguirre, Heikki Miettunen, Allii Majala, Virpi Väisänen

Co-operation with: Dr. Krisztián Kordás, Dr. Jyri-Pekka Mikkola, Dr. Eini Puhakka, Prof. Daniel Duprez, Prof. Danielle Ballivet-Tkatchenko, Prof. Kauko Leiviskä, Prof. Ulla Lassila and many other researchers

Laboratory of Mass and Heat Transfer Process Engineering  
Department of Process and Environmental Engineering  
FI-90014 University of Oulu, POB 4300  
Phone: +358-8-553 2348, +358-40-726 3018, Fax: +358-8-553 2369  
E-mail: [riitta.keiski@oulu.fi](mailto:riitta.keiski@oulu.fi), [firstname.lastname@oulu.fi](mailto:firstname.lastname@oulu.fi)  
<http://cc.oulu.fi/~polamwww/>

Many thanks to Doc., Dr. Eva Pongrácz for providing me with some of the slides!

OULUN YLIOPISTO UNIVERSITY OF OULU

