Greener Synthesis Toolbox: Sonochemistry

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Description of Concept

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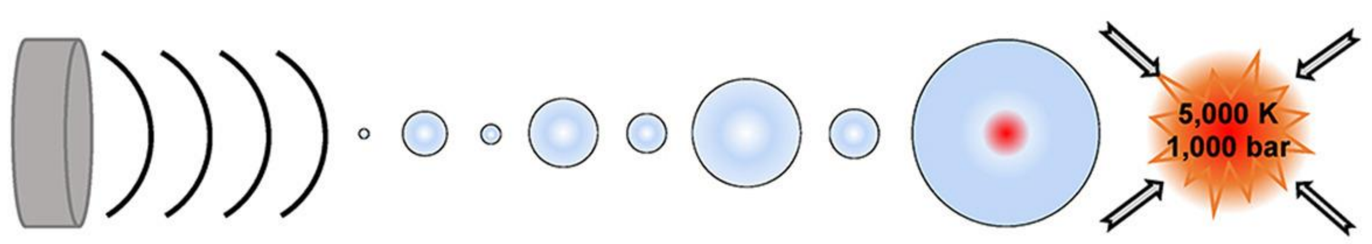
Sonochemistry (Latin *sonus* 'sound') is an emerging branch of chemistry which uses ultrasonic waves (ultrasound) as the activation mode instead of conventional thermal energy, often using a piezoelectric material to perform **(ultra)sonication**.[1]

Sonicating a liquid forms microscopic bubbles through **cavitation**. These bubbles collapse when unstable, reaching high temperatures (~5000 K) and pressures (~1000 bar) locally,[2] creating highly reactive environments that form intermediates not typically accessible in bulk without harsh reagents.[3]



Acoustic cavitation in sonochemical systems.

Curr. Opin. Green Sust. Chem. **2019**, *18*, 84–89.

Relation to Green Chemistry

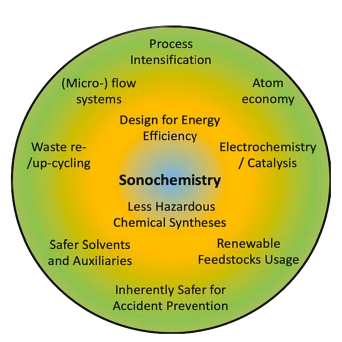
25–31

Conventional Organic Synthesis

- Raw materials (reagents)
- Use of catalysts
- Inefficient synthetic routes
- Chemical waste
- Air pollution
- Solid toxic waste
- Energy-intensive
- Side reactions
- Byproducts

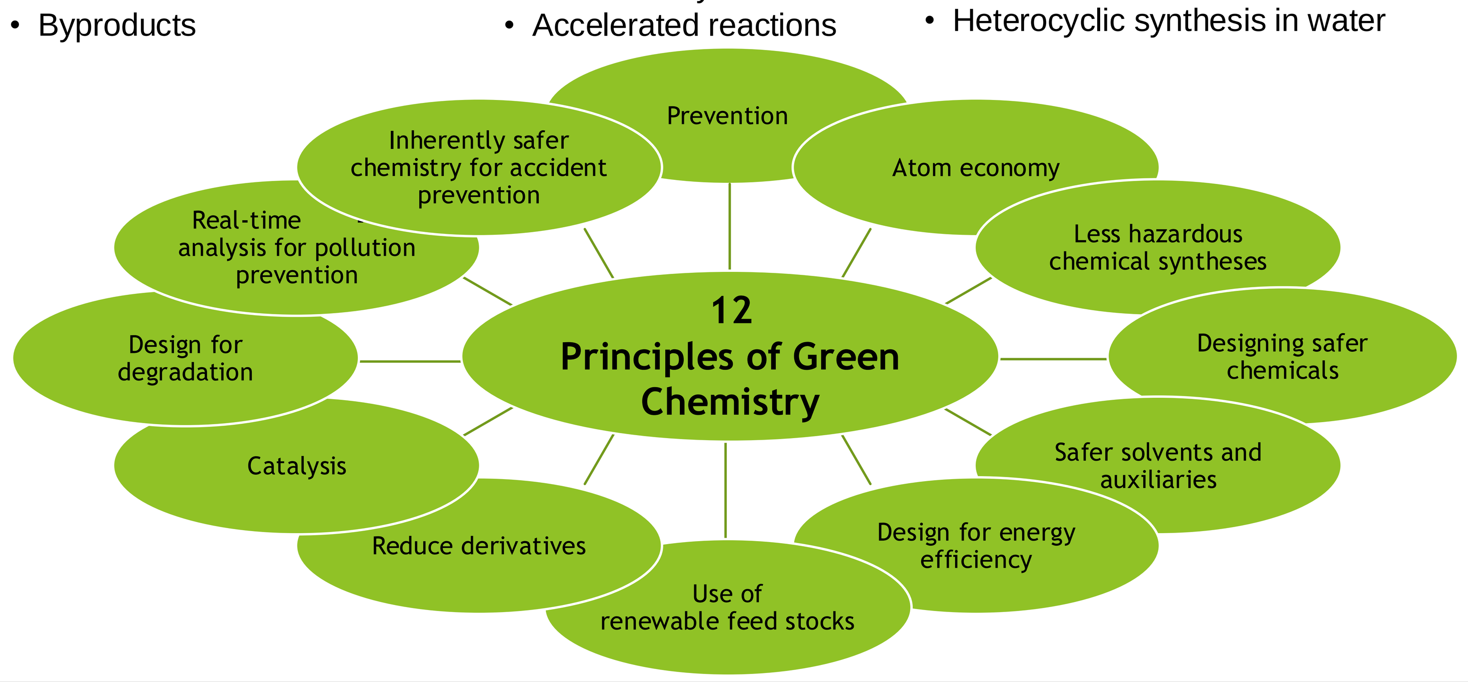
Green Organic Synthesis

- Renewable raw materials
- Minimum chemical waste
- Energy-efficient
- Higher yields
- Benign solvents
- No side reactions
- Green solvents
- Green catalysis
- Accelerated reactions



Sonochemical Organic Synthesis

- Improved reaction rates
- Energy-efficient
- Higher reaction yields
- Reduced waste
- Safer reagents
- Recyclable and reusable catalysts
- Safer solvents or solvent-free sonochemical reactions
- Heterocyclic synthesis in water



About the Authors — Dan Reddy, Giovanni, Jawad, Vijay Shah

References

History and Development

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- **1754** — Euler postulates acoustic cavitation[4]
- **1894–1895** — Thornycroft and Barnaby first experimentally show cavitation on propeller blades[5]
- **1917** — Rayleigh publishes model of cavitation and determines bubble pressures[6]
- **1927** — Wood and Loomis report influence of external sonic waves on water behavior[7]
- **1930s** — Moriguchi, Schmid, Ehert, *et al.*: ultrasound affects electrolysis reactions[8]
- **1950s–1960s** — Kolb, Nyborg, Penn, & Bard: ultrasound impacts electrochemical mass transfer[9]
- **1980s–1990s** — Piezoelectrics become widely available: greater access to sonochemistry[10]
- **2000s–2010s** — Sonochemistry for organic synthesis and wastewater treatment gain popularity[11]
- **2020s** — Microdroplet sonochemistry evolves[12]

Advantages and Drawbacks

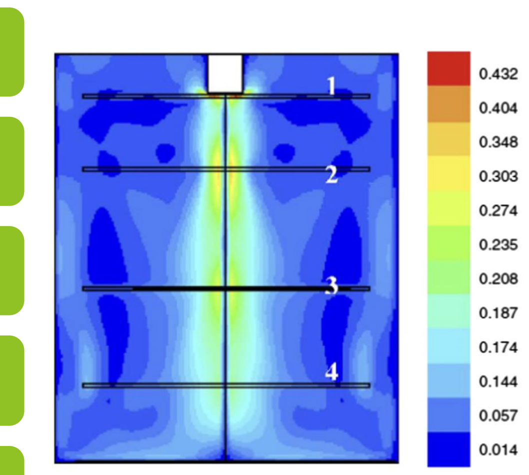
13–15

Advantages

- **Versatility of applications** — *chemical synthesis, biotechnology, wastewater treatment, polymer degradation, extraction, textile processing*
- **Access to unorthodox reactions** — *aqueous/solventless*
- **Improved yields and selectivities** — *easier activation of catalysts*
- **Enhanced kinetics** — *shortened reaction times*
- **Wide range of frequencies** — *10 kHz – 100 kHz: physical changes; 100 kHz – 2 MHz: chemical changes*

Current Challenges

- Scalability
- Lack of homogeneity
- Limited to liquid media
- Erosion of probe/transducer
- Temperature control/reproducibility
- Sensitivity to operational parameters



Focused cavitation in an ultrasonic horn. The contours represent the mean velocity magnitude (m/s).

Renew. Sust. Energy Rev. **2016**, *63*, 302–314.

Successful and Emerging Applications

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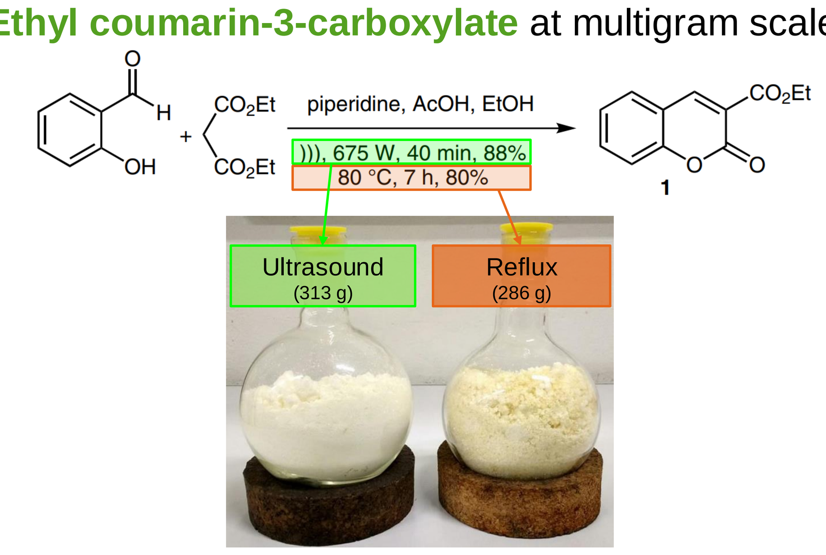
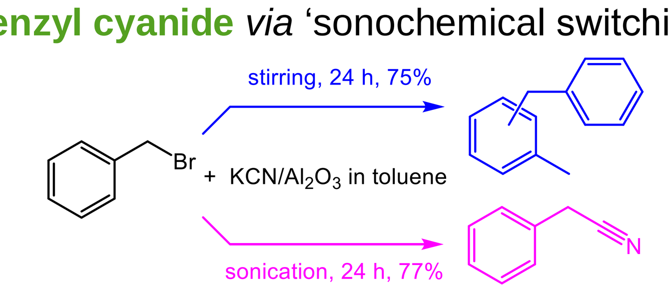
Batch Processes

Ethyl coumarin-3-carboxylate at multigram scale[16]



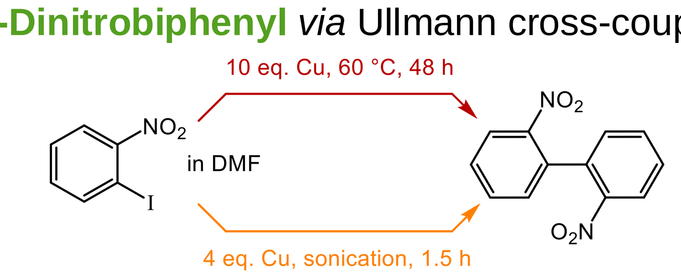
Synthesis **2017**, *49*, 2677–2682.

Benzyl cyanide *via* 'sonochemical switching'[17]



Advances in Sonochemistry, JAI Press (London), **1991**, vol. 2, p. 211.

2,2'-Dinitrobiphenyl *via* Ullmann cross-coupling[18]



Practical Sonochemistry, Ellis Horwood (Chichester), **1991**.

Continuous Processes

Dichloromethane and Trichloroethylene Degradation (pilot-scale water treatment)[19]

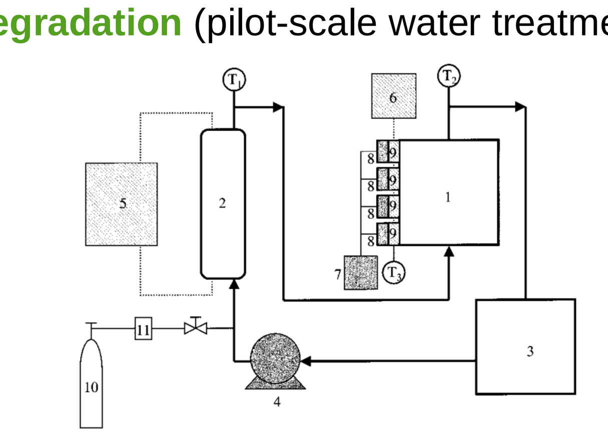


Figure 1. Experimental setup: 1, reaction vessel; 2, heat exchanger; 3, recirculating tank; 4, peristaltic pump; 5, chiller; 6, thermostat; 7, sonochemical power supply; 8, piezoelectrical transducers; 9, transducers cooling jacket; 10, background gas supply; 11, flow meter; T_1, thermometer at the exit of the heat exchanger; T_2, thermometer at the exit of the ultrasonic vessel; T_3, thermometer at the transducer cooling jacket.

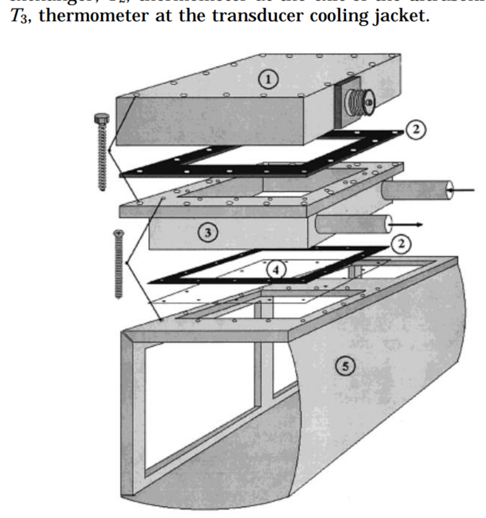
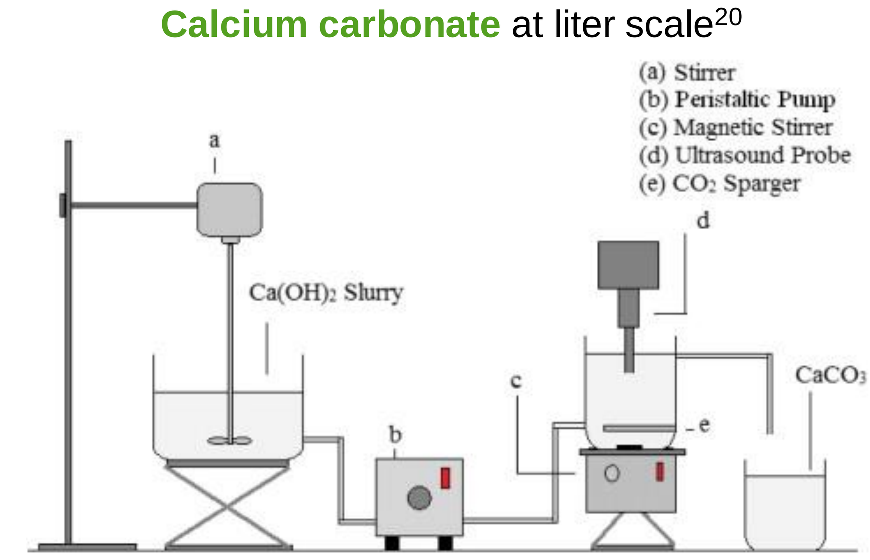


Figure 2. Pilotstation reactor vessel: 1, transducer housing (17.5 cm × 17.5 cm); 2, gasket; 3, transducer cooling water jacket; 4, PTFE acoustic window (11.5 cm × 11.5 cm); 5, reactor vessel body. Vessel is shown with one of four transducers and with end-closures removed.

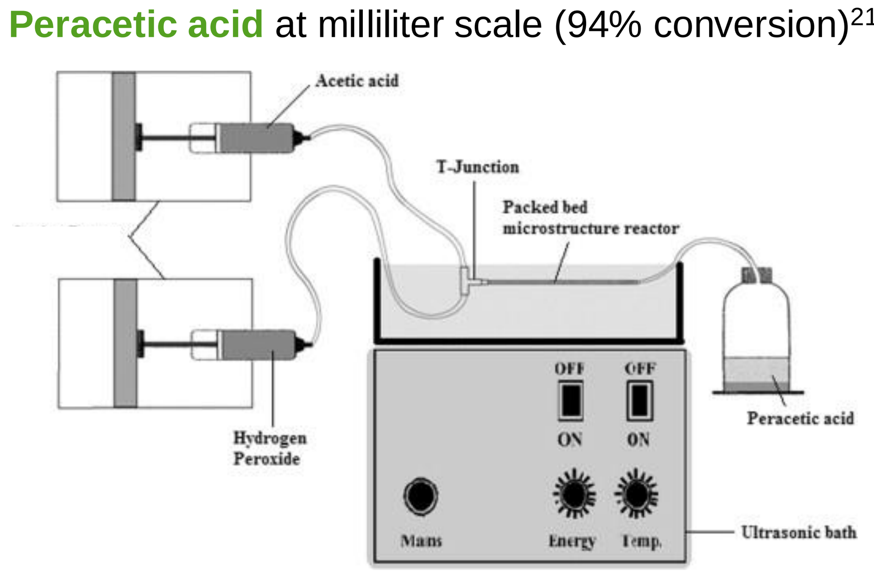
Ind. Eng. Chem. Res. **2001**, *40*, 3855–3860.

Calcium carbonate at liter scale[20]



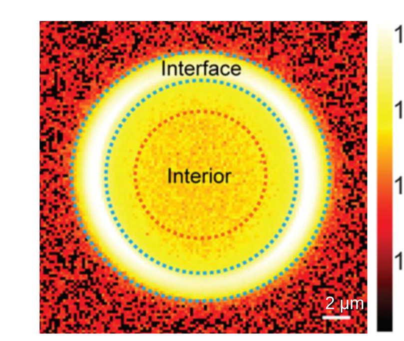
Ultrasonics Sonochem. **2015**, *24*, 132–139.

Peracetic acid at milliliter scale (94% conversion)[21]



Chem. Eng. J. **2015**, *276*, 91–96.

Assorted Topics



Megavolt-per-Centimeter Electric Fields at Water Microdroplet Interface[22]

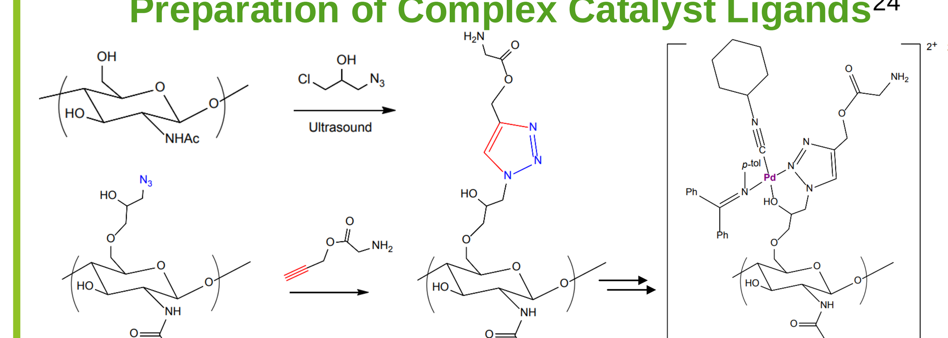
Stimulated Raman excited fluorescence intensity in sonicated emulsion of hexadecane and aqueous Rhodamine 800

J. Phys. Chem. Lett. **2020**, *11*, 7423–7428.

Synthesis of Inorganic Semiconductors[23]

Ultrasonics Sonochem. **2021**, *75*, 105594. *Ultrasonics Sonochem.* **2023**, *101*, 106691.

Preparation of Complex Catalyst Ligands[24]



Carbohydrate Polymers **2021**, *252*, 117167.