Continuous Process Intensification

Mechanochemistry: The Oldest Real Chemistry

Anil Kumar

Types of Chemistry

Thermochemistry	Heating/Cooling
Photochemistry	Light
Electrochemistry	Electric Field
Sonochemistry	Sound
Mechanochemistry	Mechanical Force
Magnetochemistry	Magnetic Field

Mechanochemistry

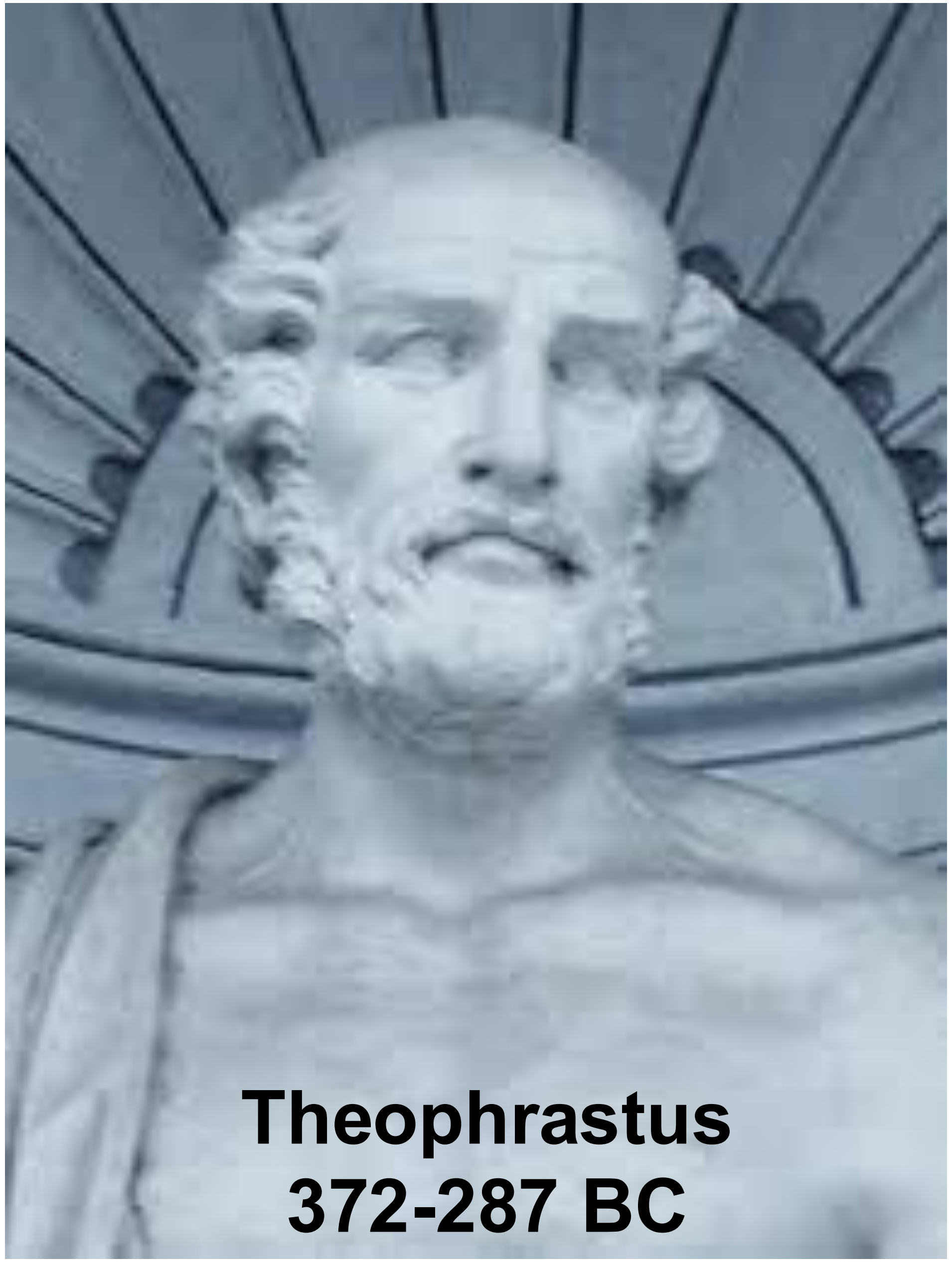
The Most Ancient Chemistry

Mechanochemistry

313 BC


THEOPHRASTI
DE LAPIDIBVS
LIBER,
Ab ADRIANO TVRNEBO
Latinitate donatus.

LVTETIÆ,
Ex Officina Federici Morelli Typographi Regij,
in vico Iacobęo, ad insigne Fontis.
M. D. LXXVIII.
CVM PRIVILEGIO REGIS.



Theophrastus
372-287 BC

Mechanochemistry

Possibly the first documented extraction of a metal from its compound

$$HgS(s) + Cu(s) \Rightarrow Hg(l) + CuS(s)$$

Described byTheophrastus in 4^{th} century B.C.
Reaction proceeds despite extremely low solubility of HgS ($K_{sp} = 10^{-54}$), by grinding in the presence of acetic acid (vinegar)

Avoids heating or aggressive reagents!

Mechanochemistry

The “Dutch Method”: Synthesis of lead white pigment

Theophrastus in his book On Stones
Plinius in *Naturalis Historia* (AD 77-79).

Mild temperatures (heated by horse dung) and readily scalable

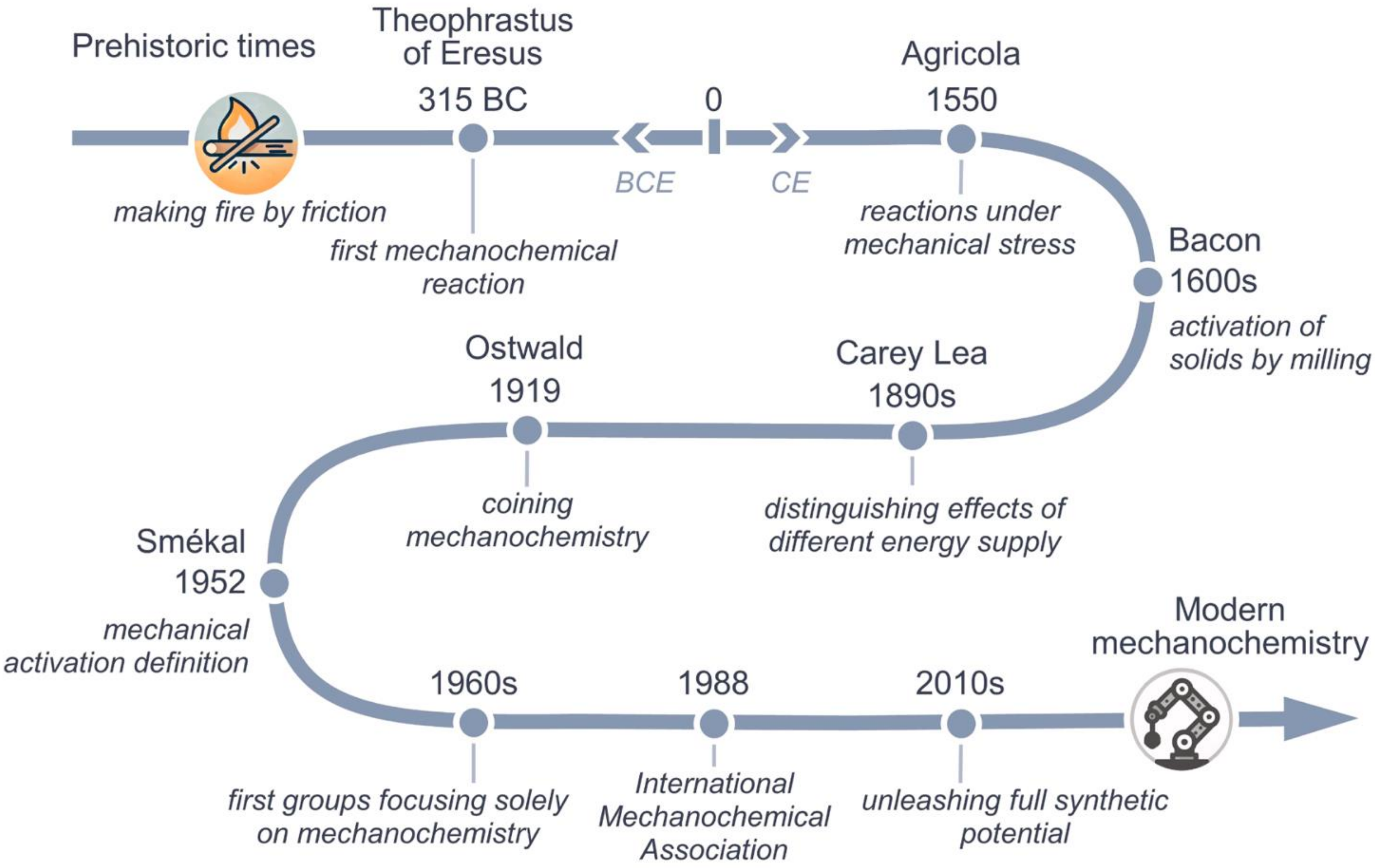
Mild temperatures (heated by horse dung) and readily scalable

https://www.youtube.com/watch?v=rZQQAsphqBc&list=PLdesNkcRuf70shzcrbWS8dwixJdnSVYWD&index=3

Mechanochemistry

https://www.youtube.com/watch?v=rZQQAsphqBc&list=PLdesNkcRuf70shzcrbWS8dwixJdnSVYWD&index=3

Mechanochemistry: Historical Perspective



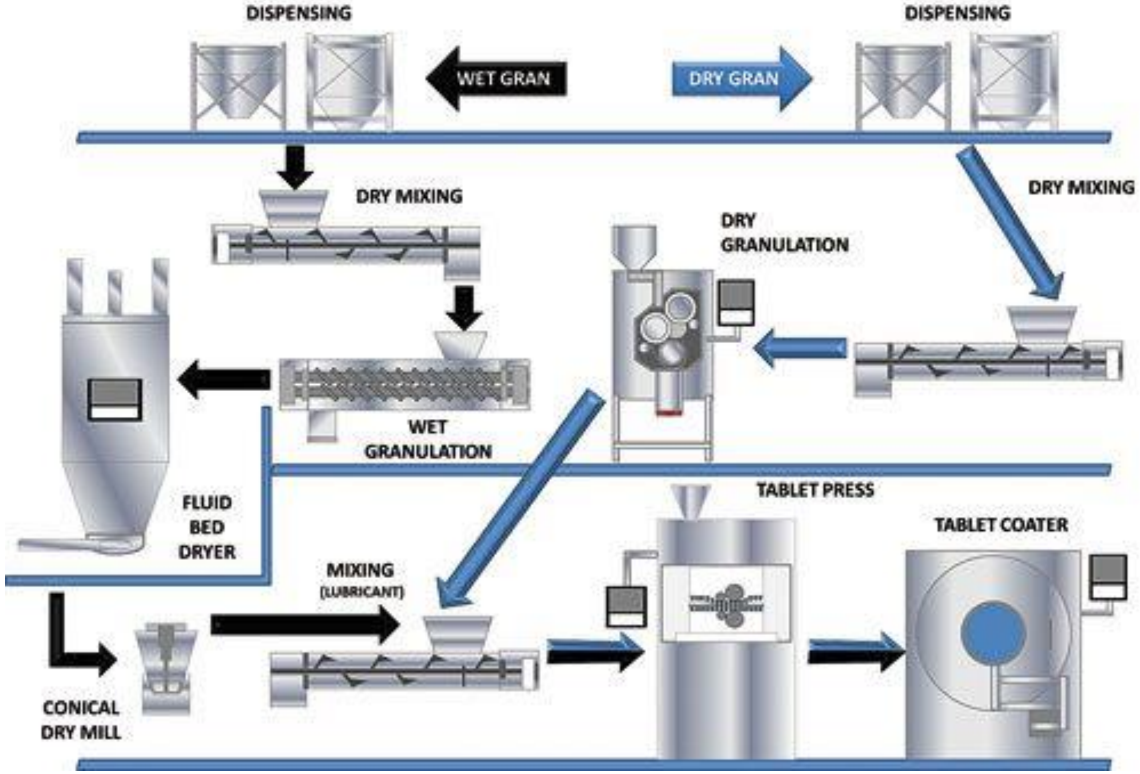
Stolar, T.; Emmerling, F. et al. Mechanochemistry: Looking Back and Ahead, Chem 2026, 12, 102880

Mechanochemistry

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY

IUPAC Top Ten Emerging Technologies in Chemistry 2019

Mechanochemistry

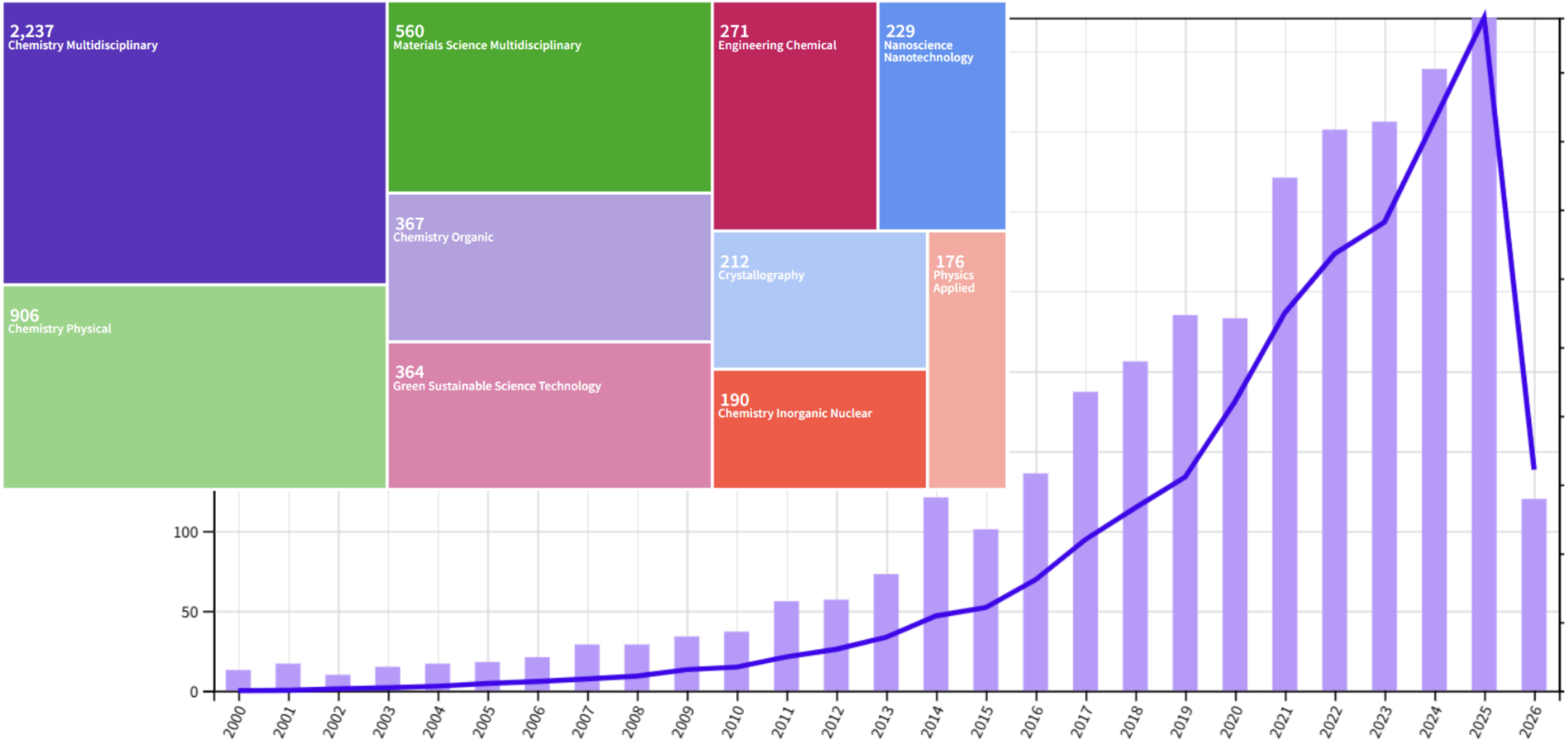


Food Industry

Tablet Formulations

Bulk Chemical/Materials Synthesis ?????

Mechanochemistry – Number of Publications 2000-2026 (ca. 3600)



Web of Science Search May 4 2026: Topic “Mechanochemistry“ / Research Area: “Chemistry”
cf. https://www.cas.org/resources/cas-insights/mechanochemistry

Slide: Prof. Kappe

Mechanochemistry

Mechanochemistry

Mechanochemistry – Sustainability as Driver (Minimizing Solvent Usage)

Green metrics in mechanochemistry

Nicolas Fantozzi,[a] Jean-Noël Volle,[a] Andrea Porcheddu,[b] David Virieux,[a] Felipe García*[cd] and Evelina Colacino*[a]

Chem. Soc. Rev. **2023**, *52*, 6680

Angew. Chem. Int. Ed. **2024**, *63*, e202414745

Meeting the UN Sustainable Development Goals with Mechanochemistry

Jasna Alić, Moritz-Caspar Schlegel, Franziska Emmerling,* and Tomislav Stolar**

Comparison of traditional and mechanochemical production processes for nine active pharmaceutical ingredients (APIs)

Emília P. T. Leitão*

RSC Sustainability **2024**, *2*, 3655

Linking mechanochemistry with the green chemistry principles: Review article

Sergi Arfelis[a,b,c], Ana I. Martín-Perales[b,d], Remy Nguyen[e], Antonio Pérez[b], Igor Cherubin[b,f], Christophe Len[e,g], Irene Malpartida[b,h], Alba Bala[a,c], Pere Fullana-i-Palmer

Heliyon **2024**, *10*, e34655

LCA as a Tool to Detect Environmental "Hot Spots" in Early-Stage Mechanochemical Synthesis of Organic Dyes

Or Galant, Aseel Aborome, Aaron S. McCalmont, Stuart L. James, Michael Patrascu, and Sabrina Spatari*

ACS Sustainable Chem. Eng. **2023**, *11*, 12155

Mechanochemistry Can Reduce Life Cycle Environmental Impacts of Manufacturing Active Pharmaceutical Ingredients

Or Galant, Giacomo Cerfeda, Aaron S. McCalmont, Stuart L. James, Andrea Porcheddu, Francesco Delogu, Deborah E. Crawford, Evelina Colacino, and Sabrina Spatari*

ACS Sustainable Chem. Eng. **2022**, *10*, 1430

Slide: Prof. Kappe

Mechanochemistry

Mechanochemistry – A Rediscovered Branch of Chemistry

Books

- Margetić, D. *Organic Mechanochemistry - A New Tool for Sustainable Synthesis*; Elsevier, **2025**

Special Issues

- *ACS Sust. Chem. Eng.* **2021** (virtual SI)
- *Chem. Commun.* **2012/13** (themed collection)
- *Chem. Eur. J.* **2025** (virtual hot topic)

Reviews - Synthetic Organic Mechanochemistry

- James, S. et al. *Chem. Soc. Rev.* **2012**, *41*, 413
- Friščić, T. et al. *ACS Cent. Sci.* **2017**, *3*, 13
- Browne, D. L. et al. *Chem. Sci.* **2018**, *9*, 3080
- Lamaty, F. et al. *Eur. J. Org. Chem.* **2022**, e202101516
- Borchardt, L. et al. *Chem. Commun.* **2022**, *58*, 1661
- Porcheddu, A. et al. *ChemSusChem* **2022**, *15*, e202200362
- Colacino, E. et al. *Chem. Soc. Rev.* **2023**, *52*, 6680
- Stolar, T.; Emmerling, F. et al. *Chem* **2026**, *12*, 102880

Slide: Prof. Kappe

Mechanochemistry

ADVANTAGES OF MECHANOCHEMICAL PROCESSES *vs.* SOLUTION METHODS

No need of extra reagents (activation by milling) or in excess.
Reactants economy, Waste economy

Higher yields and better selectivity compared to solution syntheses
Better green chemistry metrics

Allows process intensification and « *higher throughput* »
Energy economy

Access to new compounds and 'impossible' molecules to obtain in solution (mechanistic phenomena observed in solid-state chemistry can be different)
New reactivities = Innovation in the chemical space

Dramatic increase of kinetics
(better contact of the reactants)
Time economy

MECHANOCHEMISTRY

Use of (benign) insoluble reactants without drawbacks linked to solubility and/or steric hindrance

To reduce or avoid quantity of organic solvents (including in the work-up) then limiting environmental impact in facilities (waste reduction / solvent recycling).
Reduced waste disposal costs and worker exposure to harmful VOS.

Ambient temperature, no heating required - Simplicity of the experimental set-up

Nicolas Fantozzi et al. Chem. Soc. Rev., 2023, 52, 6680

Mechanochemistry

CMCC Mechanochemistry Discussions

@cmcc-mechanochemistry · 654 subscribers · 51 videos

Welcome to the Mechanochemistry Discussions! This seminar series is hosted by the NSF ...

chem.tamu.edu/cmcc/online_seminars.php and 1 more link

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Mechanochemistry with an Atomic Force Microscope
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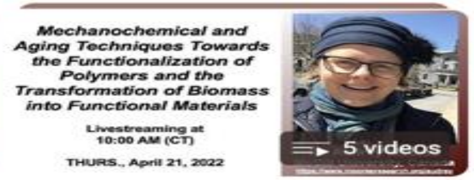

Green Chemistry & Mechanochemical Treatments...
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Organic Synthesis in Mechanochemistry
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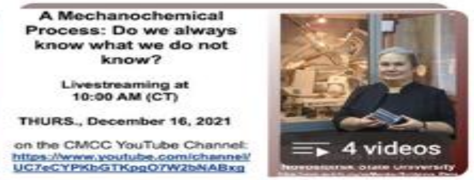

Overviews of Mechanochemistry
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All Mechanochemistry Discussions Seminars
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Seminarios mecanoquímicos en español
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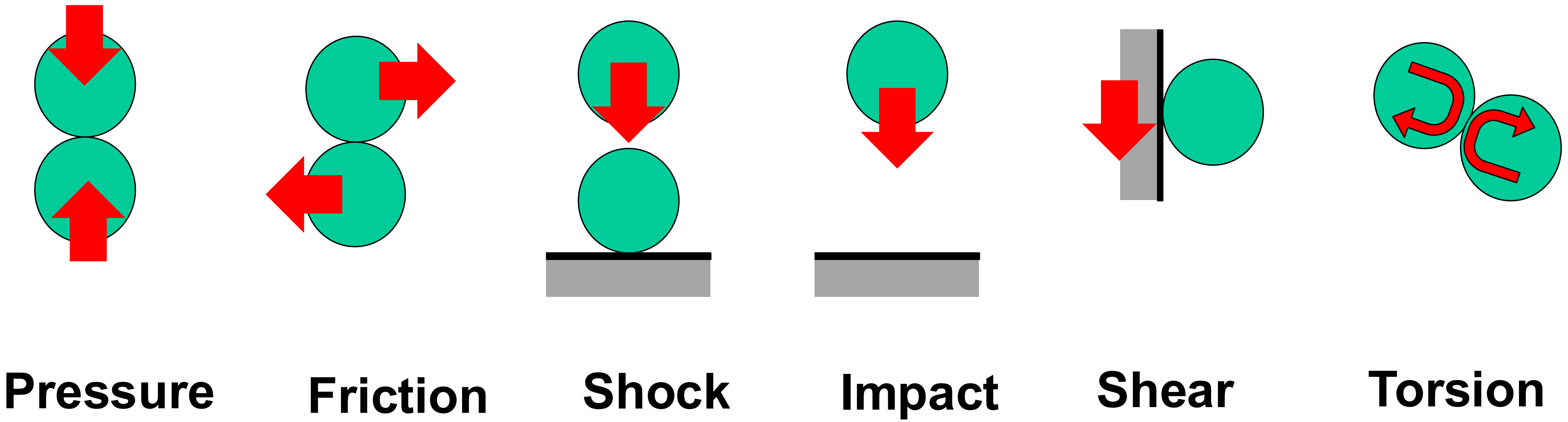
https://www.youtube.com/@cmcc-mechanochemistry/playlists

Mechanochemistry

A mechanochemical reaction is defined as “a chemical reaction that is induced by the direct absorption of mechanical energy” (IUPAC Compendium of Chemical Terminology 2009)



https://www.wab-group.com/flow-chemistry/

Dong, L. et al. Mechanochemistry: Fundamental Principles and Applications, Adv. Sci. 2024, 12, 2403949
Stolar, T.; Emmerling, F. et al. Mechanochemistry: Looking Back and Ahead, Chem 2026, 12, 102880
Stauch, T. et al. Advances in Quantum Mechanochemistry: Electronic Structure Methods and Force Analysis, Chem. Rev. 2016, 116, 14137

Mechanochemistry

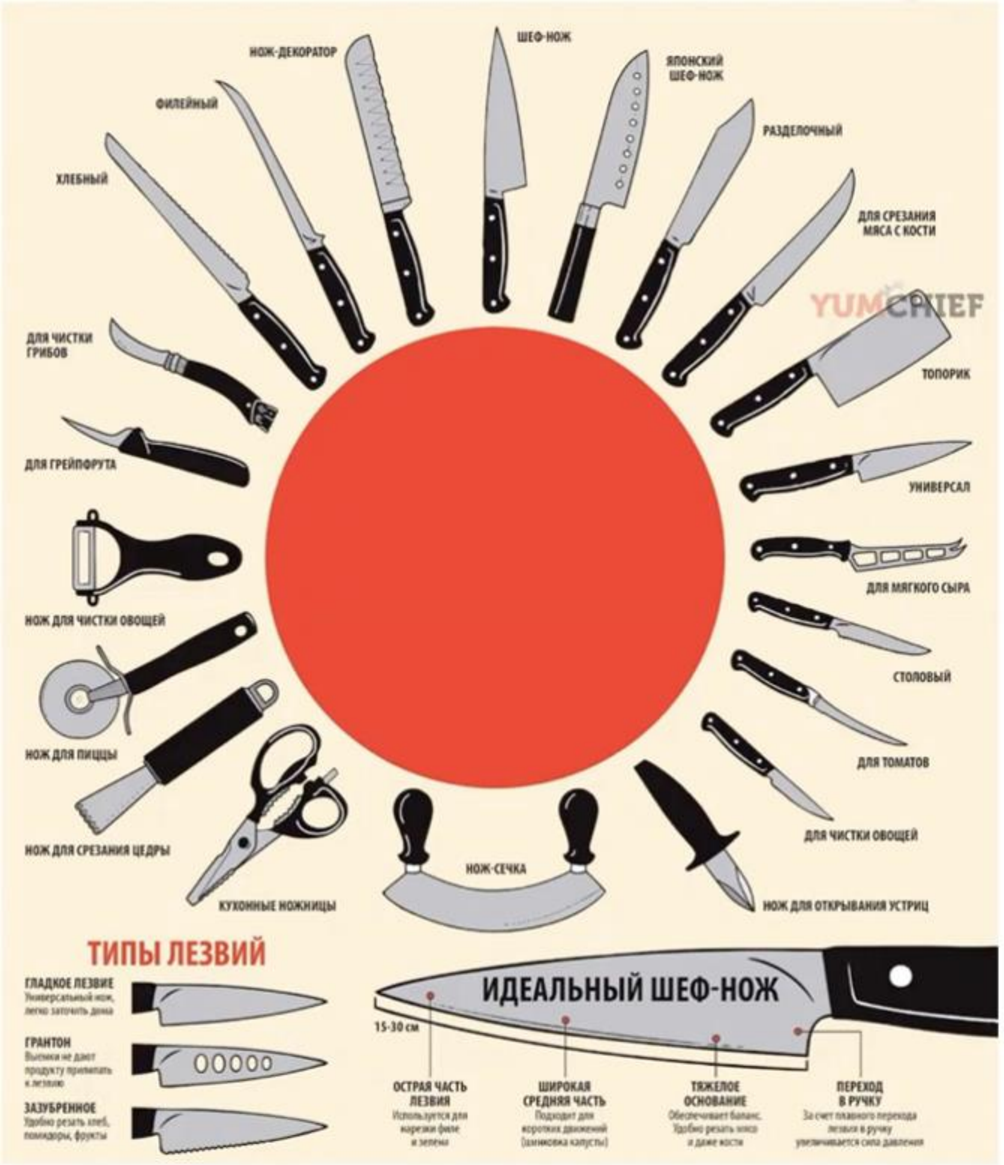
What happens **DURING** impacts?

- Vibrational and electronic excitation
- Generation of defects
- Heating
- Mixing
- Comminution (generation of surfaces, size decrease)
- **Reaction itself**

What happens **BETWEEN** impacts?

- Annealing or re-grouping of defects,
- Cooling (heating for exothermic reactions)
- Relaxation of stresses
- **Reaction itself**

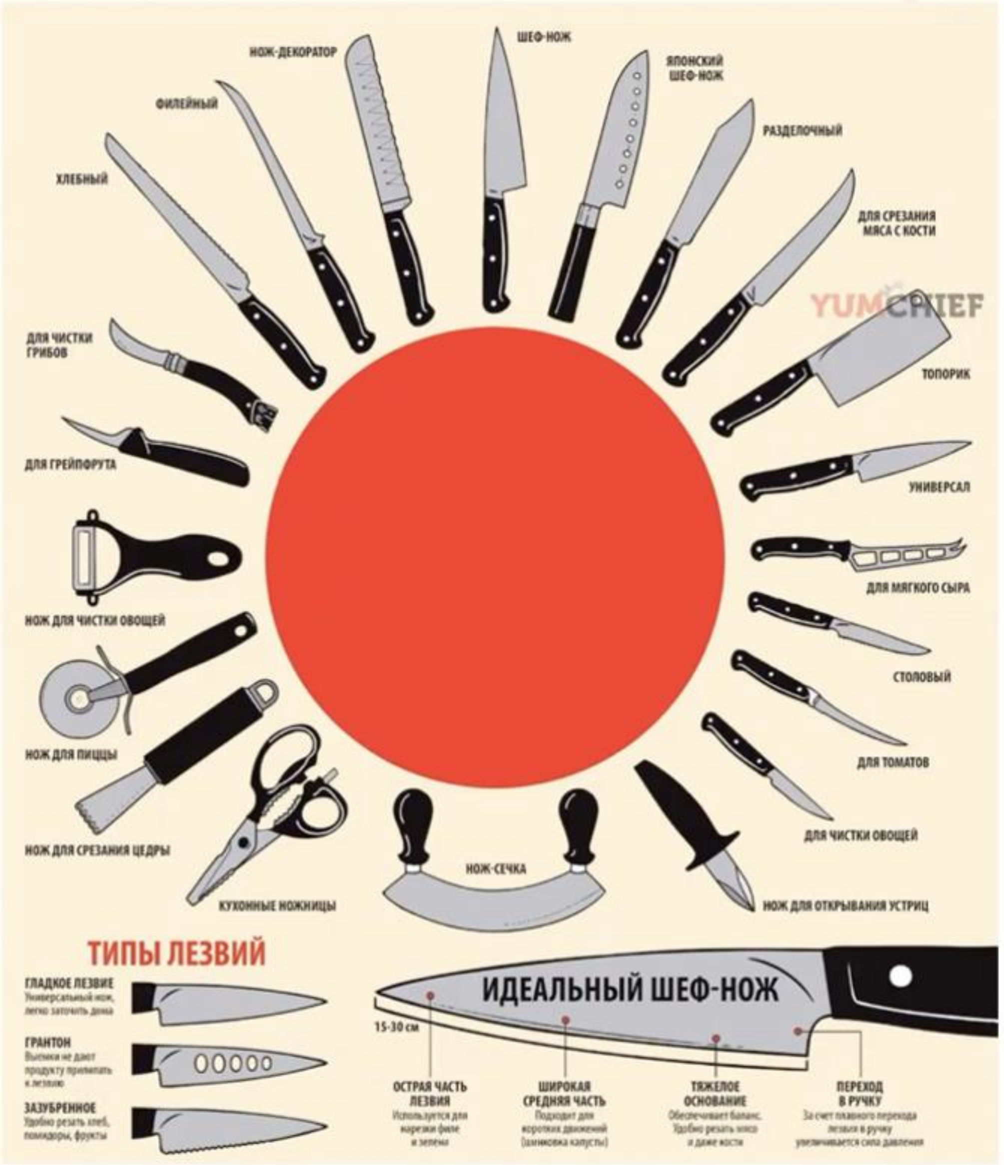
Mechanochemistry



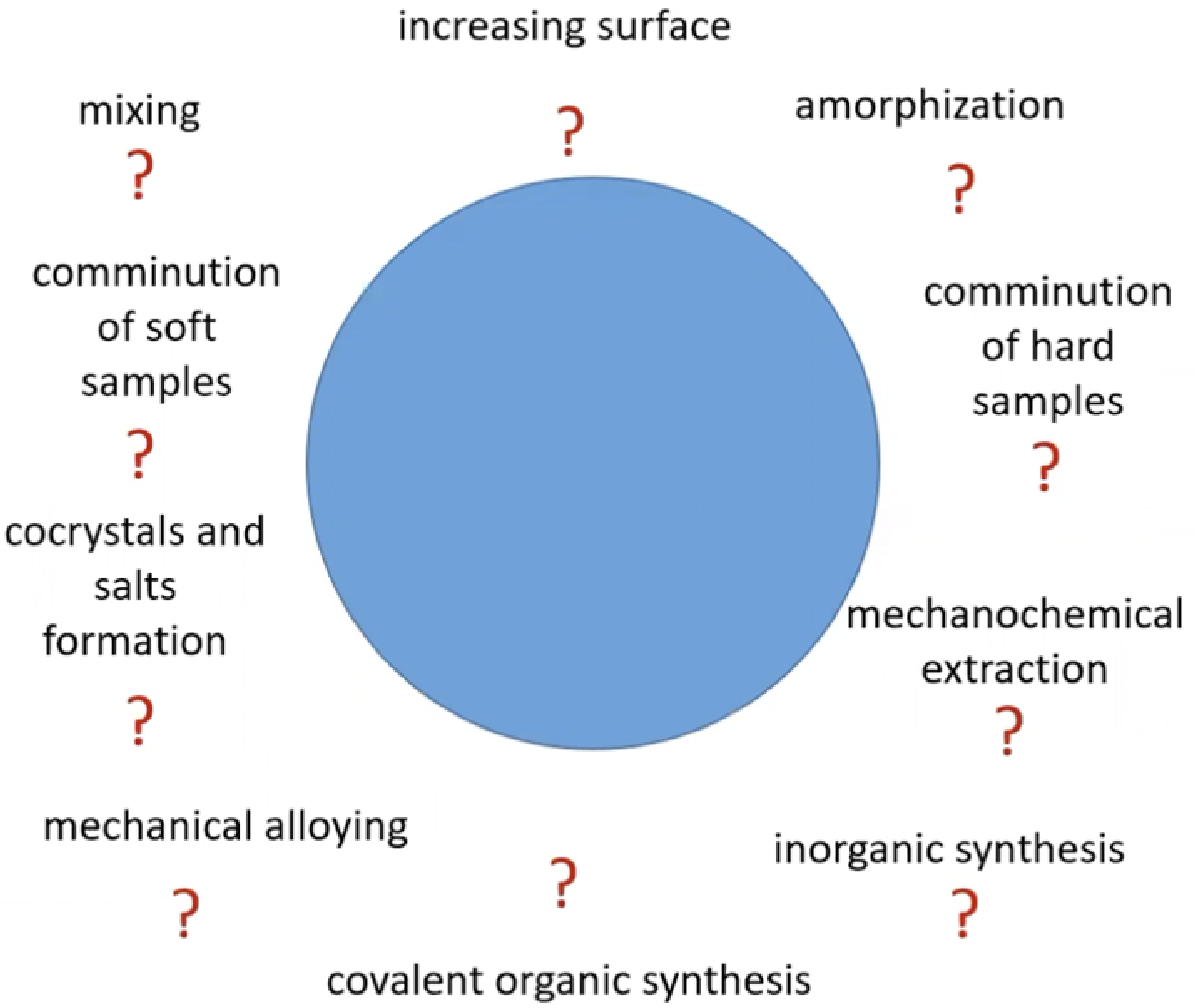
https://www.pinterest.ru/pin/675821487817105608/

https://www.youtube.com/watch?v=WPyzykk79K0&list=PLdesNkcRuf70shzcrbWS8dwixJdnSVYWD

Mechanochemistry



https://www.pinterest.ru/pin/675821487817105608/



https://www.youtube.com/watch?v=WPyzykk79K0&list=PLdesNkcRuf70shzcrbWS8dwixJdnSVYWD

Mechanochemistry

Types of Mechanochemical Reactions

Organic Chemistry | Hot Paper

Angewandte International Edition Chemie

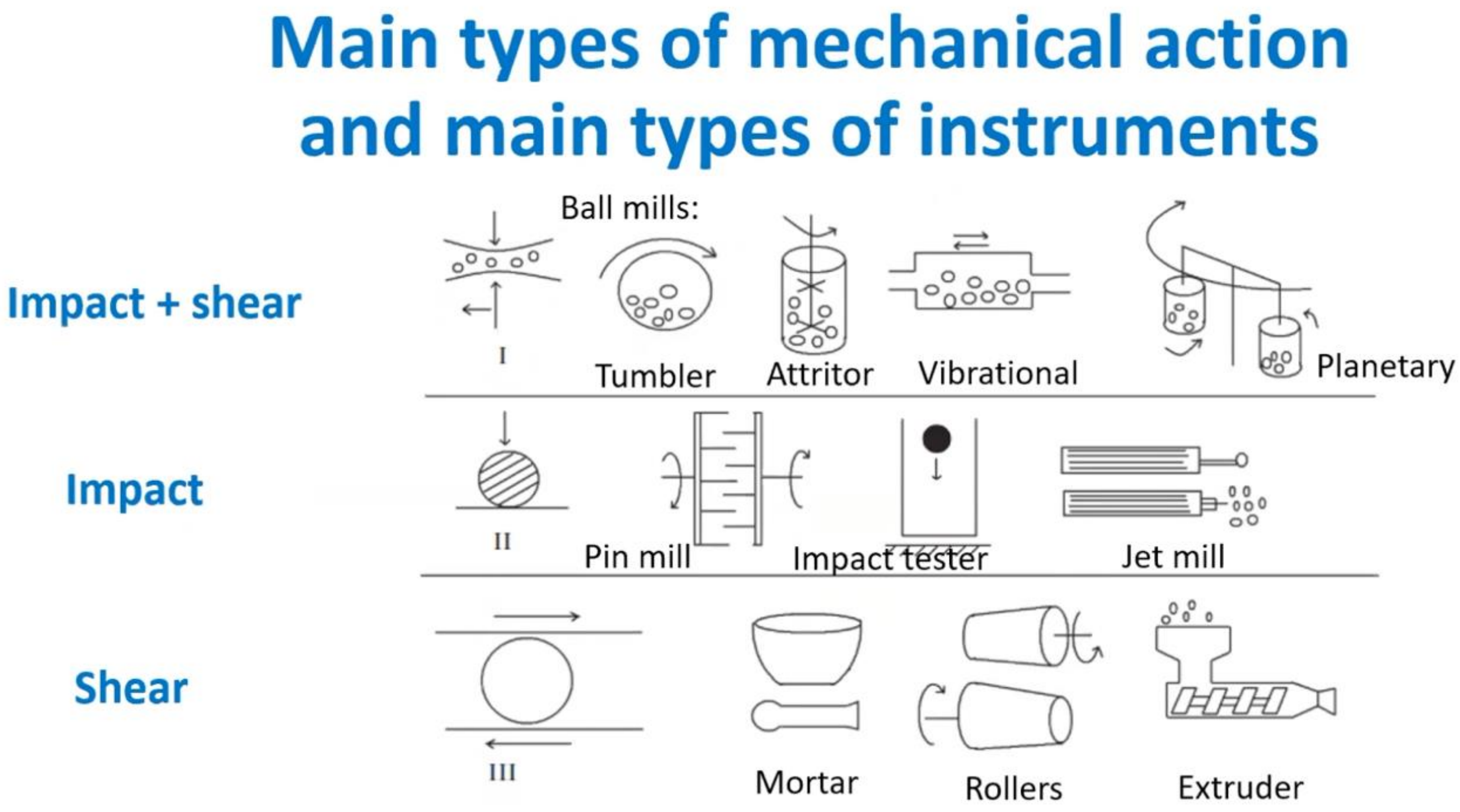
Experimental Isolation of Single Impact, Cumulative Energy, Aging, and Liquid-Assisted Grinding Effects in Mechanochemical Reactions

- Type I: reactions completed under mechanical impact
  - conversion occurs exclusively during active milling
  - scales linearly with the cumulative energy (E_{total})
- Type II: reactions that continue via aging after mechanical activation
  - impact triggers transformations that progress in the absence of further mechanical input
  - post-impact reactivity correlates with imparted single-impact energy
- LAG reactions remain firmly impact-driven
  - product yields continue to scale linearly with E_{impact} for both reaction types

horizontal mixer mill (MM500)
14 mL PFA jar, 1 × ø 15 mm ball

Templ, J.; Borchardt, L. *Angew. Chem. Int. Ed.* **2026**, *65*, e23191

Mechanochemistry



Electro, Photo, Acoustic, Thermal, Magentic…
coupled with mechano

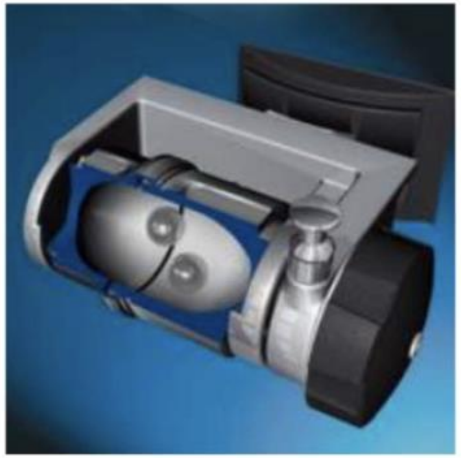
Stolar, T.; Emmerling, F. et al. Mechanochemistry: Looking Back and Ahead, Chem 2026, 12, 102880

Mechanochemistry

Mechanochemistry – Critical Operational Parameters (Milling)

General Parameters

- Type of mill (e.g. mixer of planetary)
- Material of mill and balls
- Grinding agents (liquids or solids)
- Temperature


Specific (Numerical) Milling Parameters

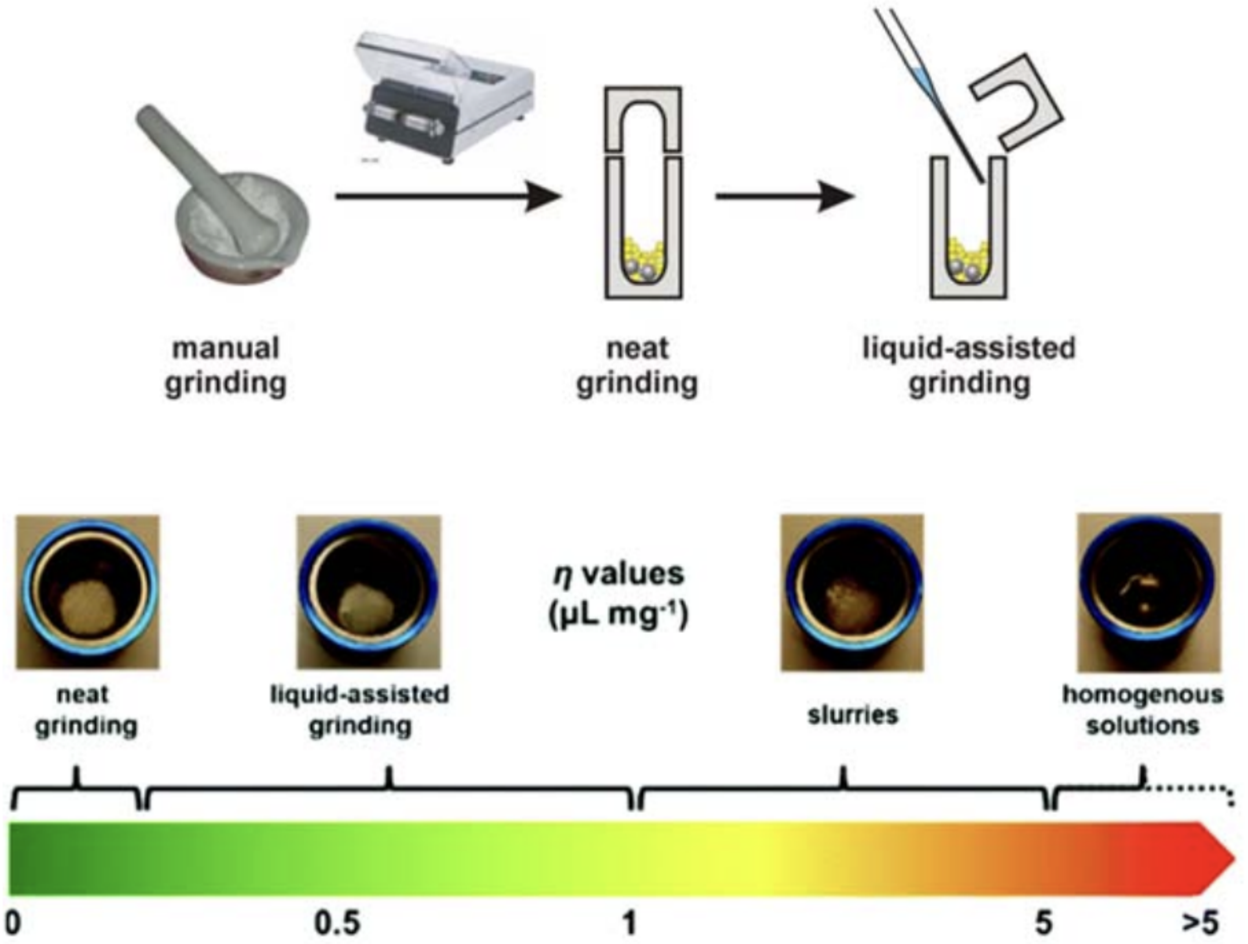
- Cavity or jar volume
- Ball diameter
- Number of balls
- Volume of reactants
- Volume ratio of balls : sample : free space
- Milling oscillating frequency (or rpm)
- Milling time




Howard, J. L.; Cao, Q.; Browne, D. L. *Chem. Sci.* **2018**, *9*, 3080

Slide: Prof. Kappe

Mechanochemistry – Liquid-Assisted Grinding (LAG)



LAG uses a small amount of a liquid to accelerate reactions, as well as to enable and direct transformations that do not take place by neat grinding.

*A value of η = 0 corresponds to neat grinding, η > 10 μL/mg corresponds to a typical solution reaction, while **LAG lies in the range of ≈0–1 μL/mg.** In that range, reactivity appears independent of reactant solubility, distinguishing LAG from slurry reactions (η > 1 μL/mg) in which low solubility does hinder reactivity.*

$$\eta = \frac{V\,(\text{LAG liquid, }\mu\text{L})}{m\,(\text{reagents, mg})}$$

Friščić,T.; Childs, S. L.; Rizvic, S. A. A.; Jones, W. *CrystEngComm* **2009**, *11*, 418
Friščić, T. et al. *ACS Cent. Sci.* **2017**, *3*, 13; Wenger, L. E.; Hanusa, T. P. *Chem. Commun.* **2023**, *59*, 14210
Breinsperger, J. et al. *Chem. Eur. J.* **2026**, *32,* e03536; Fang, Y. et al *Adv. Synth. Catal.* **2026**, *368*, e70372

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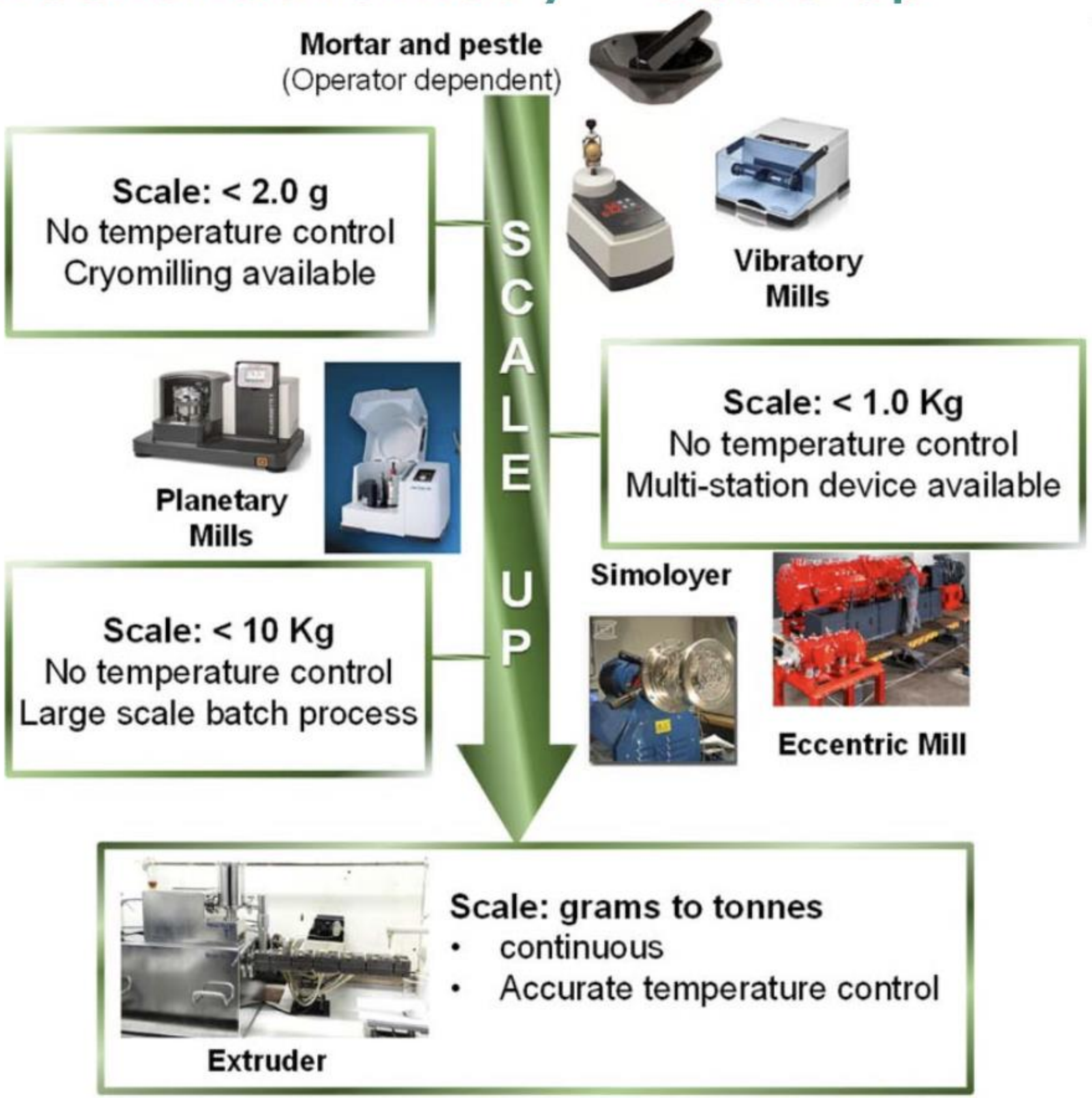
Mechanochemistry – Scale-up



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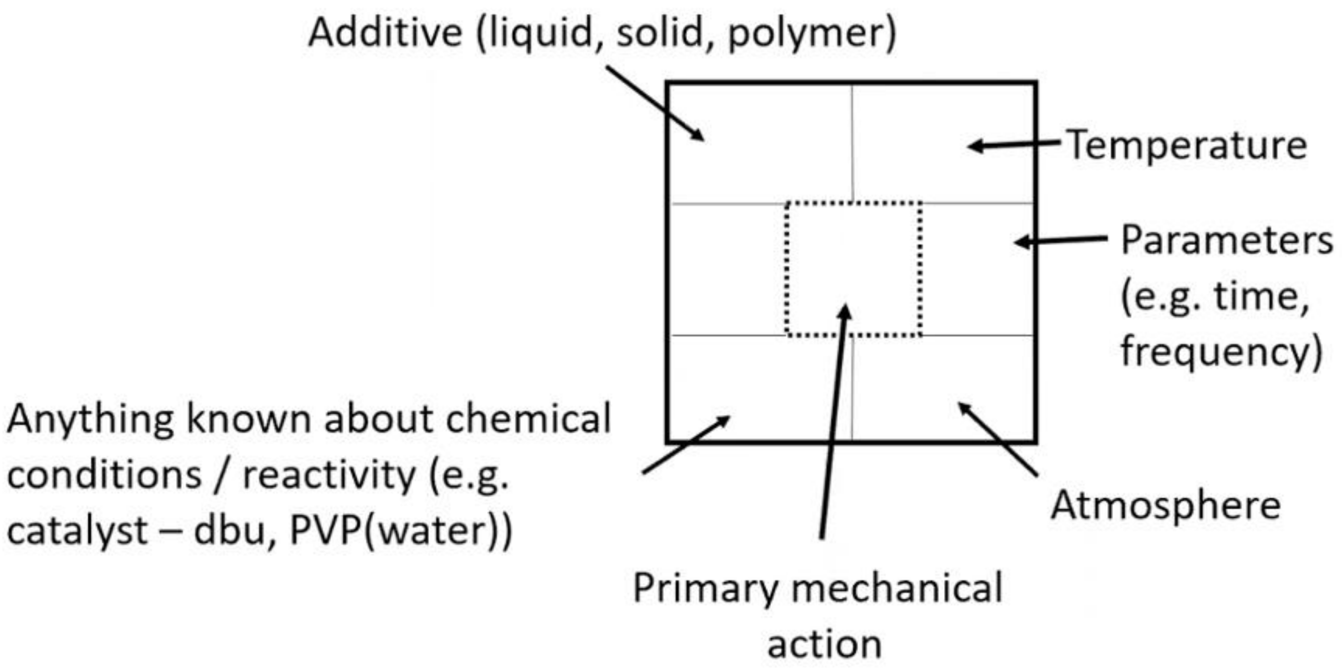
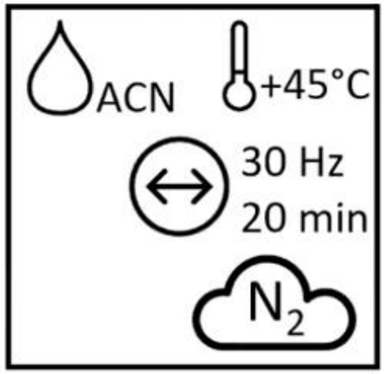
Mechanochemistry

Mechanochemical Notations





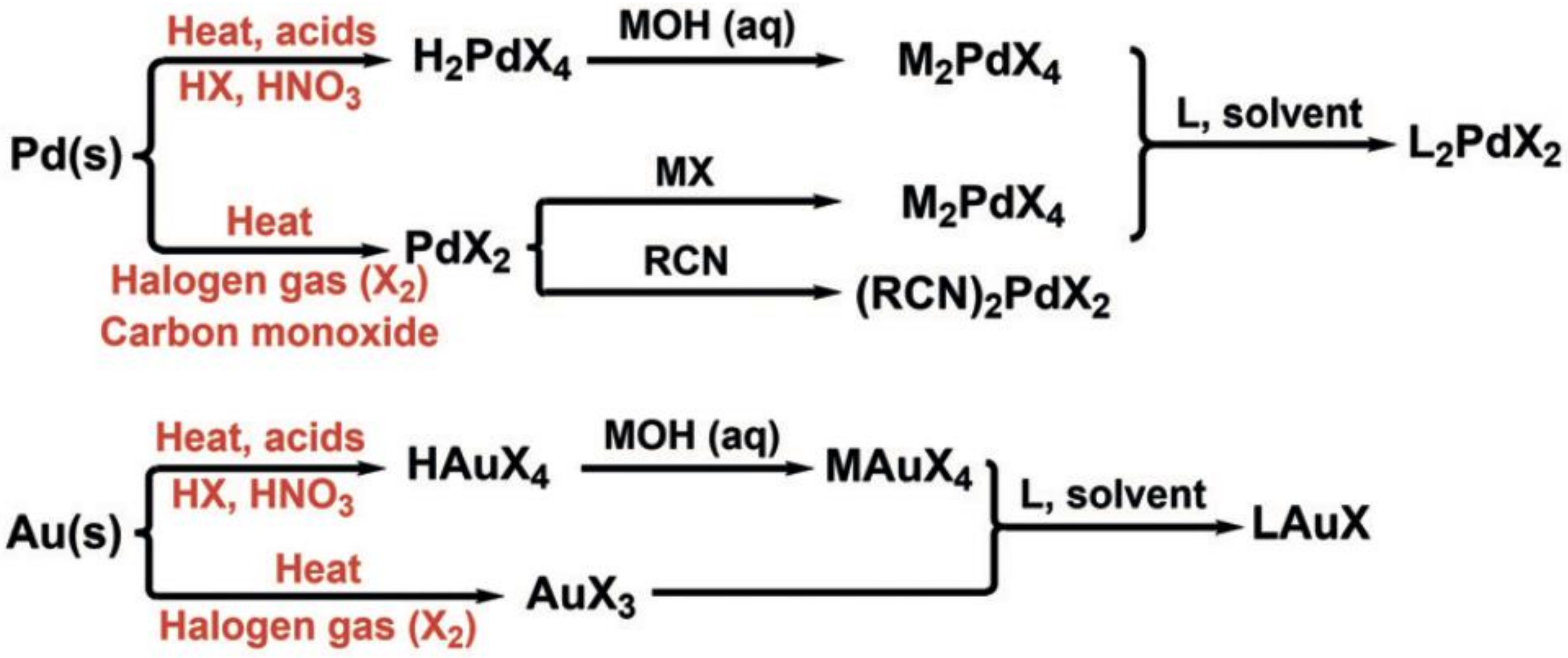
Michalchuk, A. A., Boldyreva, E. V., Belenguer, A. M., Emmerling, F., & Boldyrev, V. V. (2021). Tribochemistry, mechanical alloying, mechanochemistry: what is in a name?. Frontiers in Chemistry, 9, 359

Nicolas Fantozzi et al. Chem. Soc. Rev., 2023, 52, 6680

Mechanochemistry

Metal Recycling and Processing:

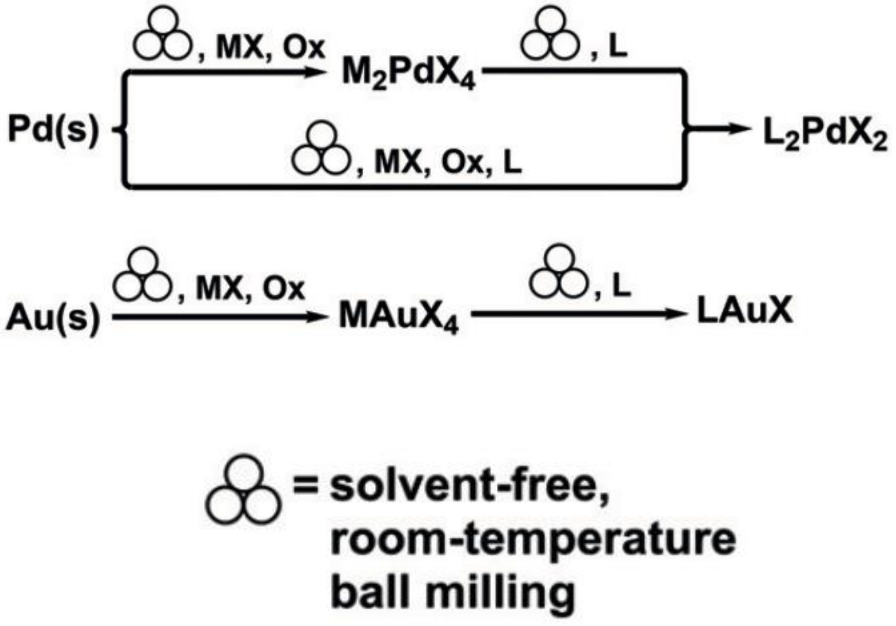
Traditional Method Aqua Regia: Extremely Polluting



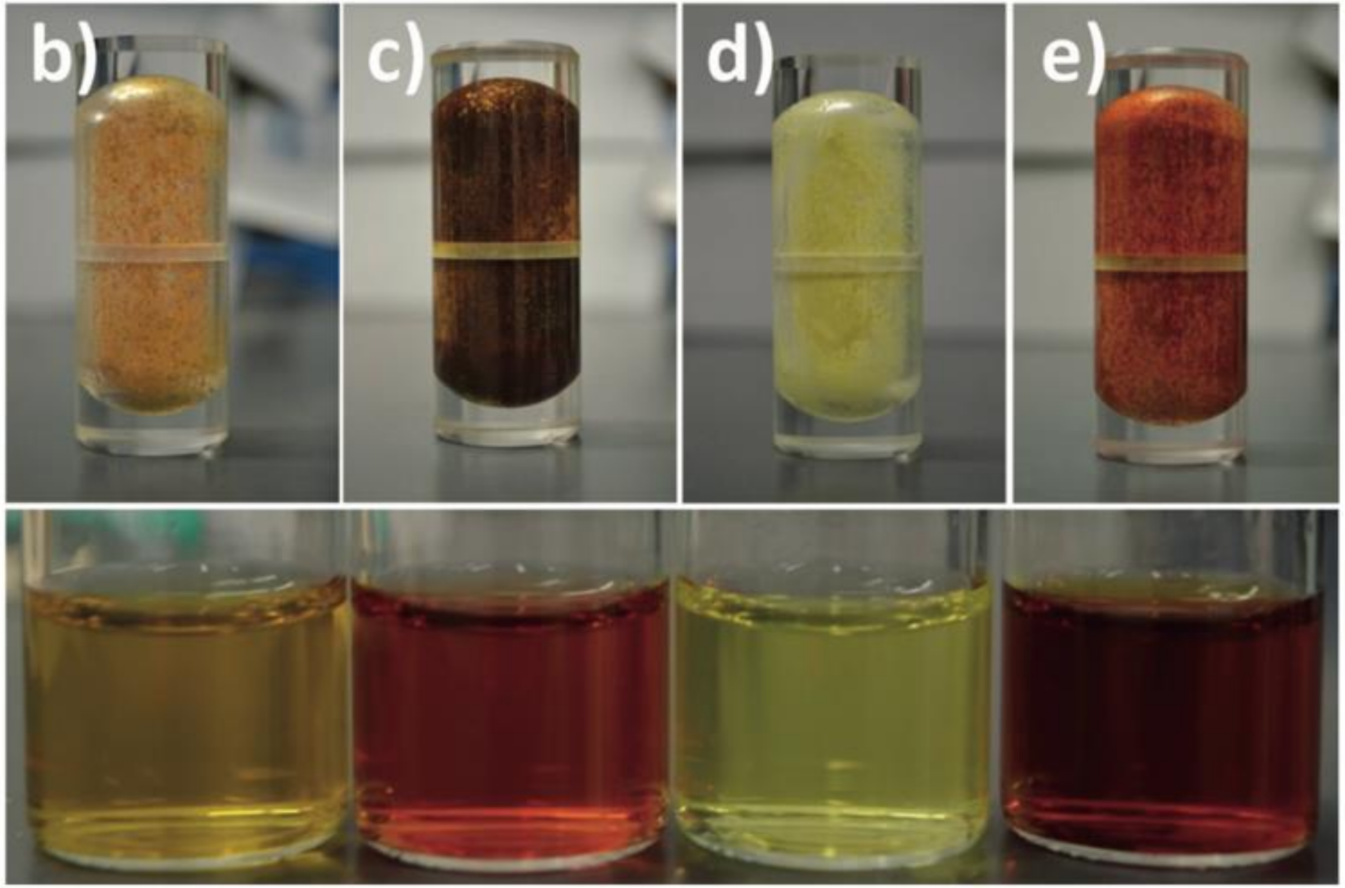
Tomislav Friščić and co workers, Angew Chem, Int Ed Eng, 2018, 57, 2667

Mechanochemistry

Metal Recycling and Processing:



X= Cl, Br, I
M= K, NH_4
Ox = oxidant
L= ligand



b) $(NH_4)_2PdCl_4$; c) $(NH_4)_2PdBr_4$; d) NH_4AuCl_4; e) NH_4AuBr_4.

Tomislav Friščić and co workers, Angew Chem, Int Ed Eng, 2018, 57, 2667

Mechanochemistry

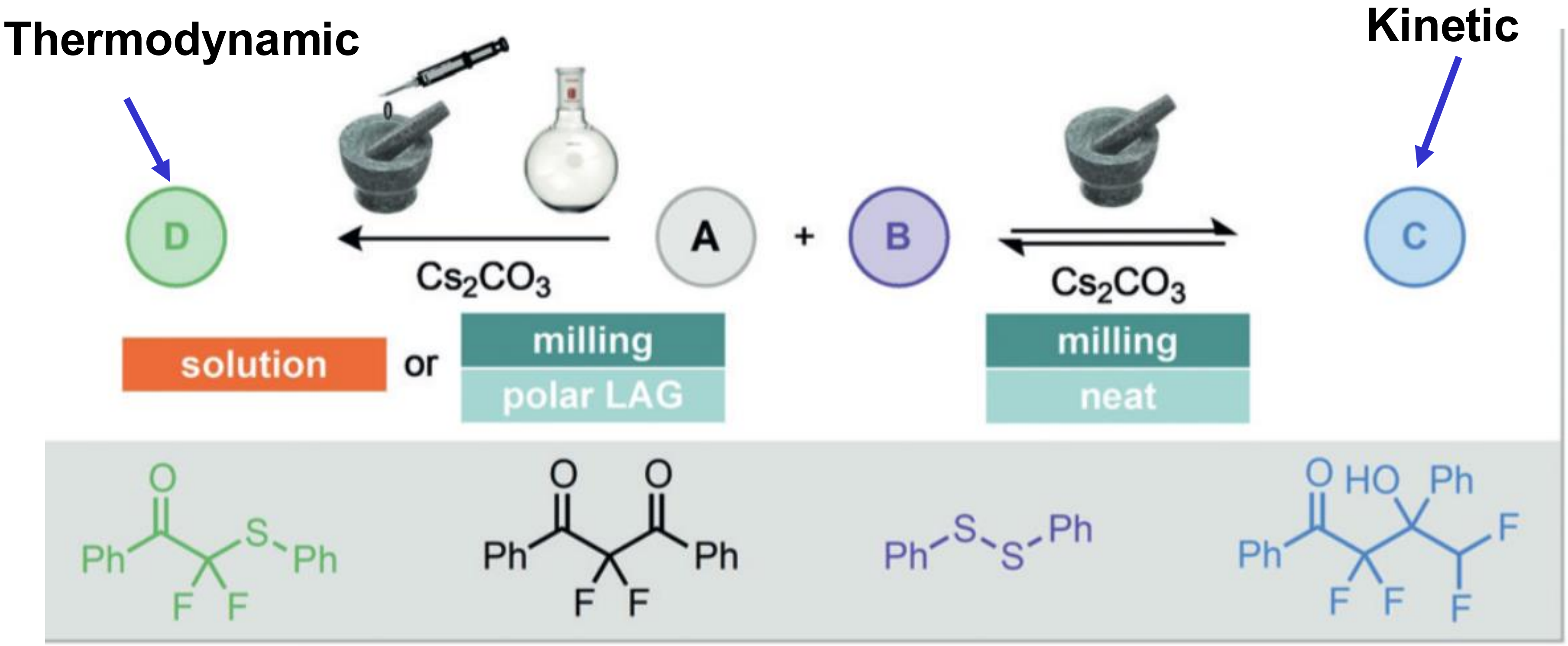
GDCh Communications Angewandte Chemie International Edition

Mechanochemistry

International Edition: DOI: 10.1002/anie.201810141
German Edition: DOI: 10.1002/ange.201810141

Switching Chemoselectivity: Using Mechanochemistry to Alter Reaction Kinetics

*Joseph L. Howard, Michael C. Brand, and Duncan L. Browne**



Angew. Chem. Int. Ed. 2018, 57, 16104

Mechanochemistry

Angewandte Chemie International Edition

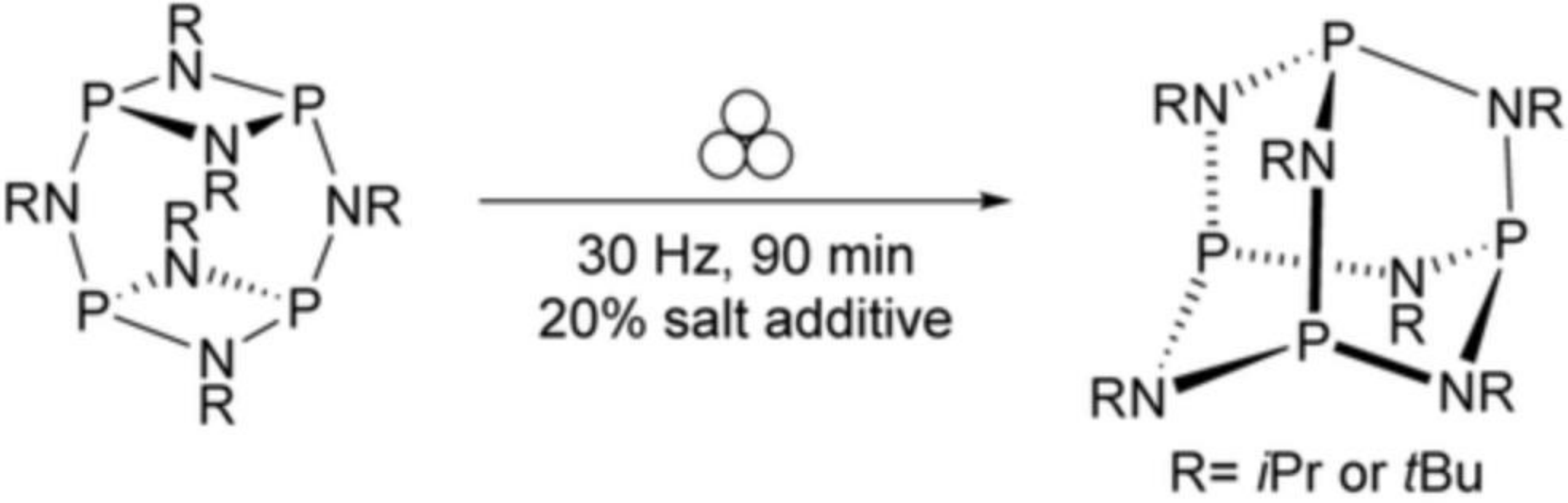
GDCh A Journal of the German Chemical Society

Communication | Full Access

The First Synthesis of the Sterically Encumbered Adamantoid Phosphazane $P_4(N^tBu)_6$: Enabled by Mechanochemistry

Yan X. Shi, Dr. Kai Xu, Dr. Jack K. Clegg, Dr. Rakesh Ganguly, Dr. Hajime Hirao, Prof. Dr. Tomislav Friščić, Prof. Dr. Felipe García

First published: 19 August 2016 | https://doi.org/10.1002/anie.201605936 | Citations: 99



Angew. Chem. Int. Ed. 2016, 55, 12736-40

Mechanochemistry

nature nanotechnology

ARTICLES

https://doi.org/10.1038/s41565-020-00809-9

Check for updates

Mechanochemistry for ammonia synthesis under mild conditions

Gao-Feng Han[1], Feng Li[1], Zhi-Wen Chen[2,3]✉, Claude Coppex[4], Seok-Jin Kim[1], Hyuk-Jun Noh[1], Zhengping Fu[5,6], Yalin Lu[5,6], Chandra Veer Singh[3], Samira Siahrostami[4]✉, Qing Jiang[2]✉ and Jong-Beom Baek[1]✉

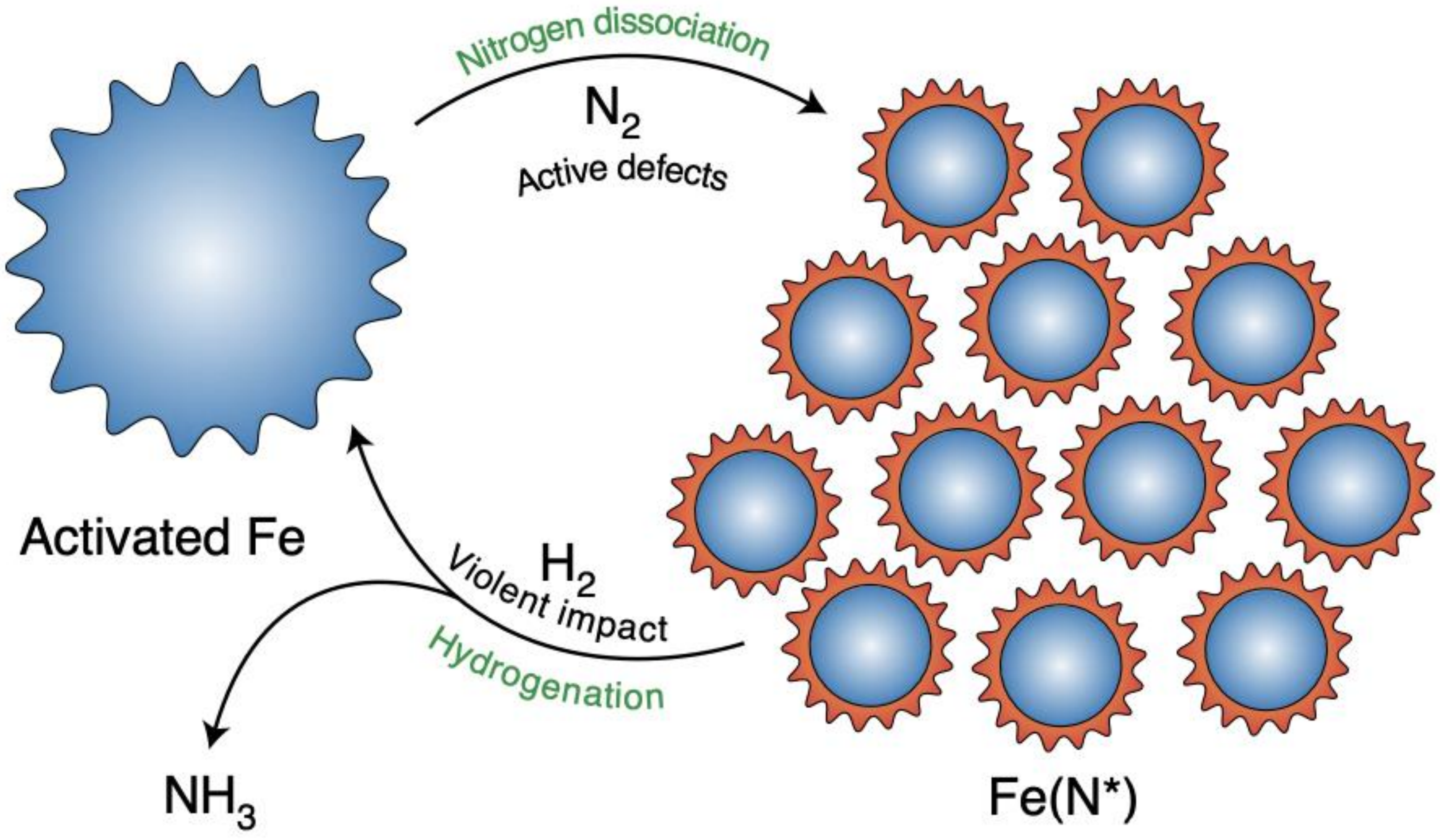
Haber–Bosch process at 400–500 °C and above 100 bar.

Mechanochemical method at 45 °C and 1 bar using Iron-based catalyst

Haber–Bosch process : 25 vol%, 450 °C, 200 bar

Mechanochemical method: 82.5 vol%,

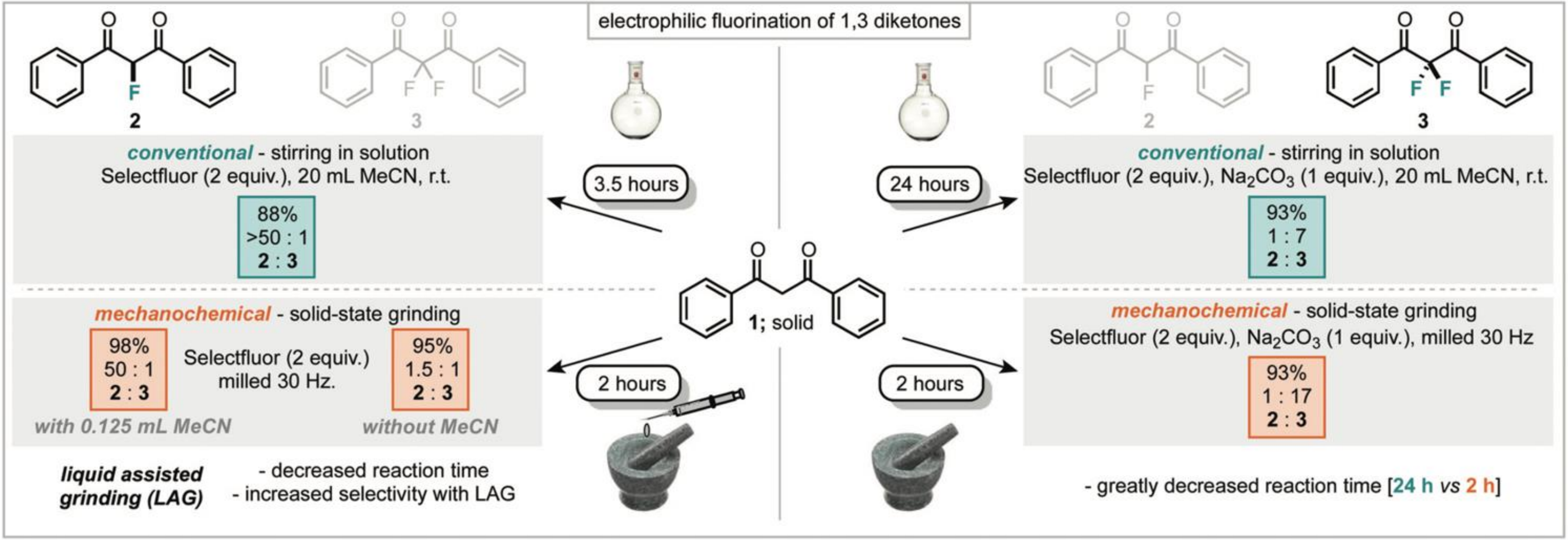
Mechanochemistry



High defect density and violent impact at the iron catalyst

Mechanochemistry

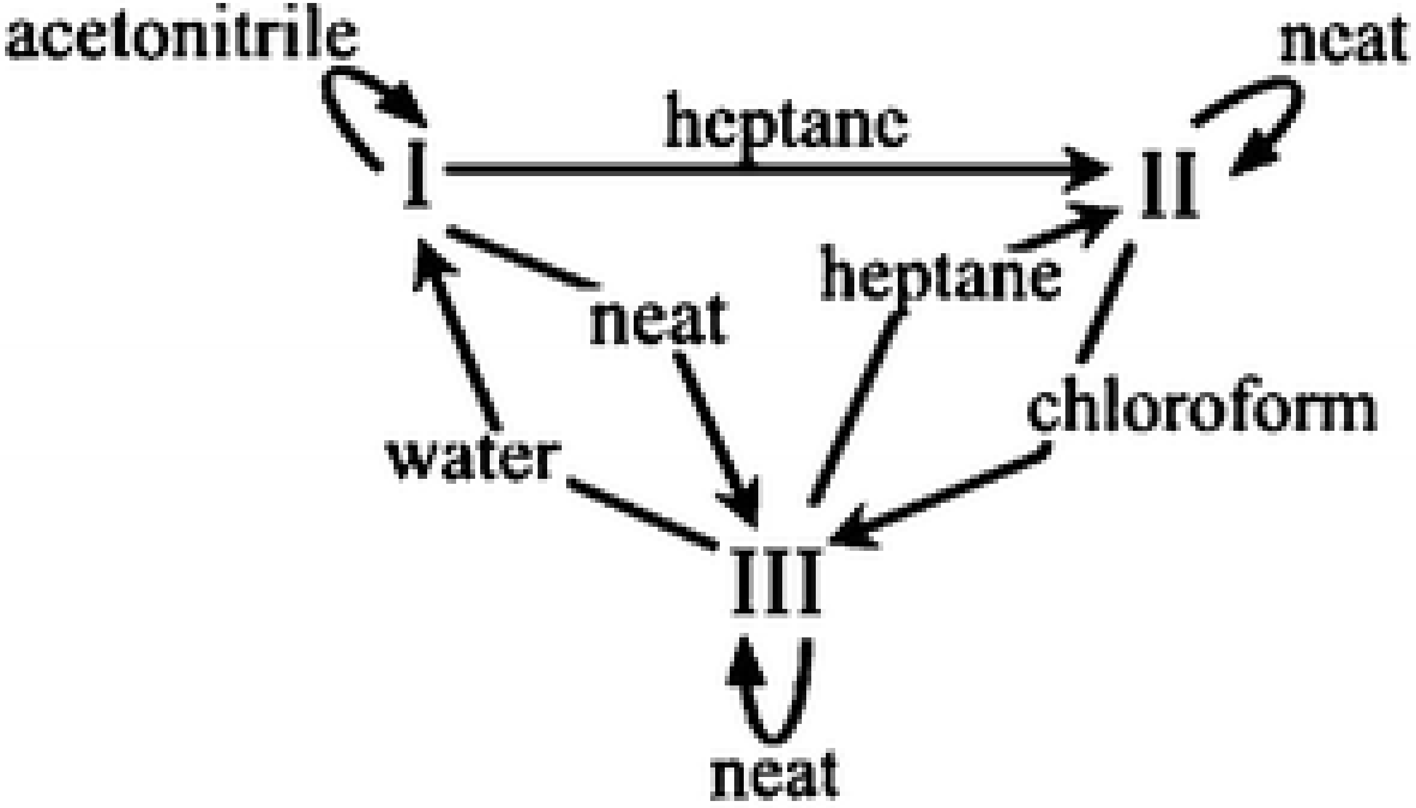
Reactivity Control via LAG



Green Chem., 2017, 19, 2798

Mechanochemistry

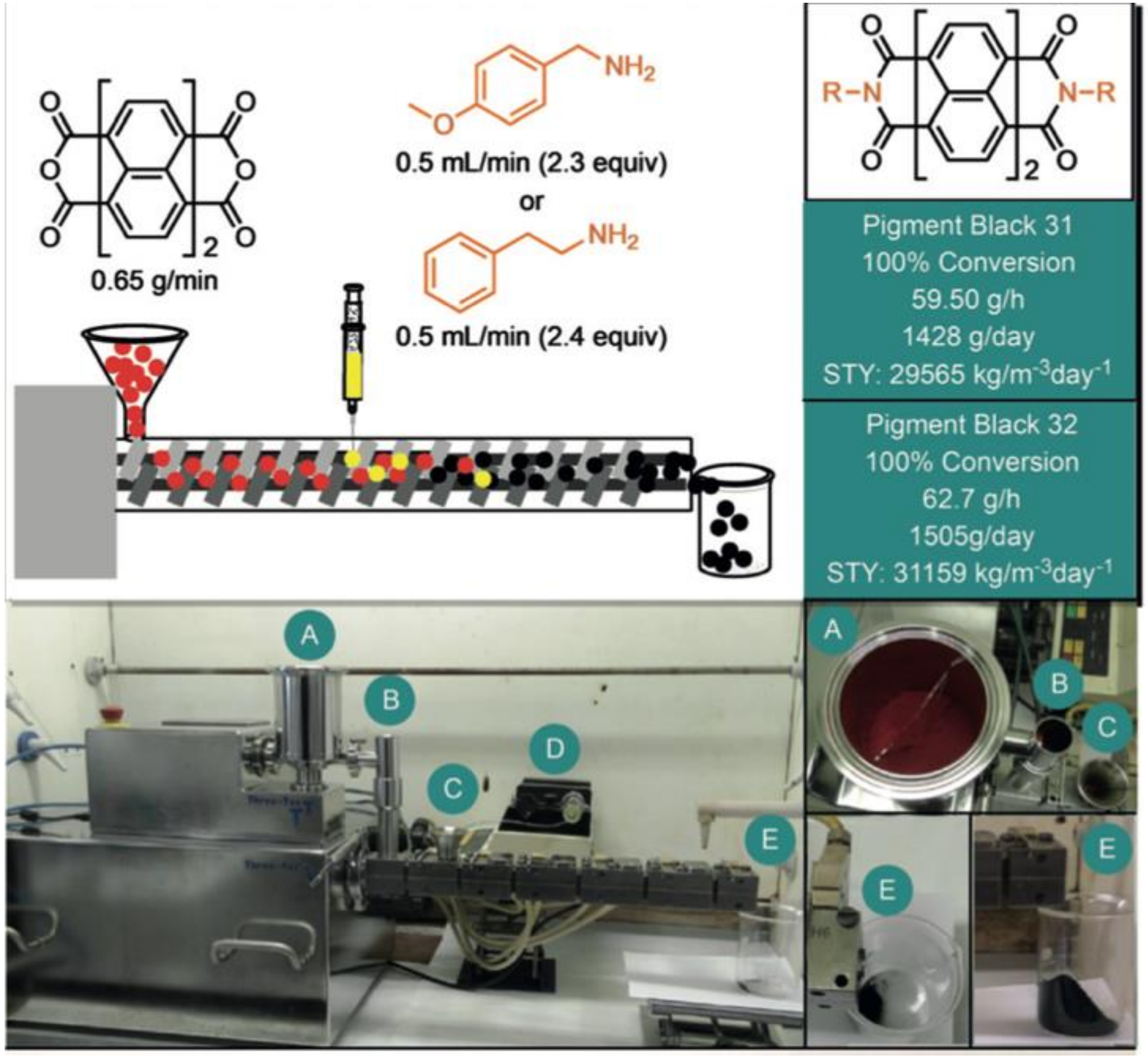
Solvent-Assisted Polymorph Transformation Anthranilic Acid



Chem Commun 2005, 7, 880

Mechanochemistry

Greener Dye Production via TSE



Angew. Chem. Int. Ed. 2020, 59, 4478 – 4483

Mechanochemistry

Mechanoredox Catalysis

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HOME > SCIENCE > VOL. 366, NO. 6472 > REDOX REACTIONS OF SMALL ORGANIC MOLECULES USING BALL MILLING AND PIEZOELECTRIC MATERIALS

REPORT

Redox reactions of small organic molecules using ball milling and piezoelectric materials

KOJI KUBOTA, YADONG PANG, AKIRA MIURA, AND HAJIME ITO   Authors Info & Affiliations

SCIENCE • 20 Dec 2019 • Vol 366, Issue 6472 • pp. 1500-1504 • DOI: 10.1126/science.aay8224

Redox catalysis in a ball mill

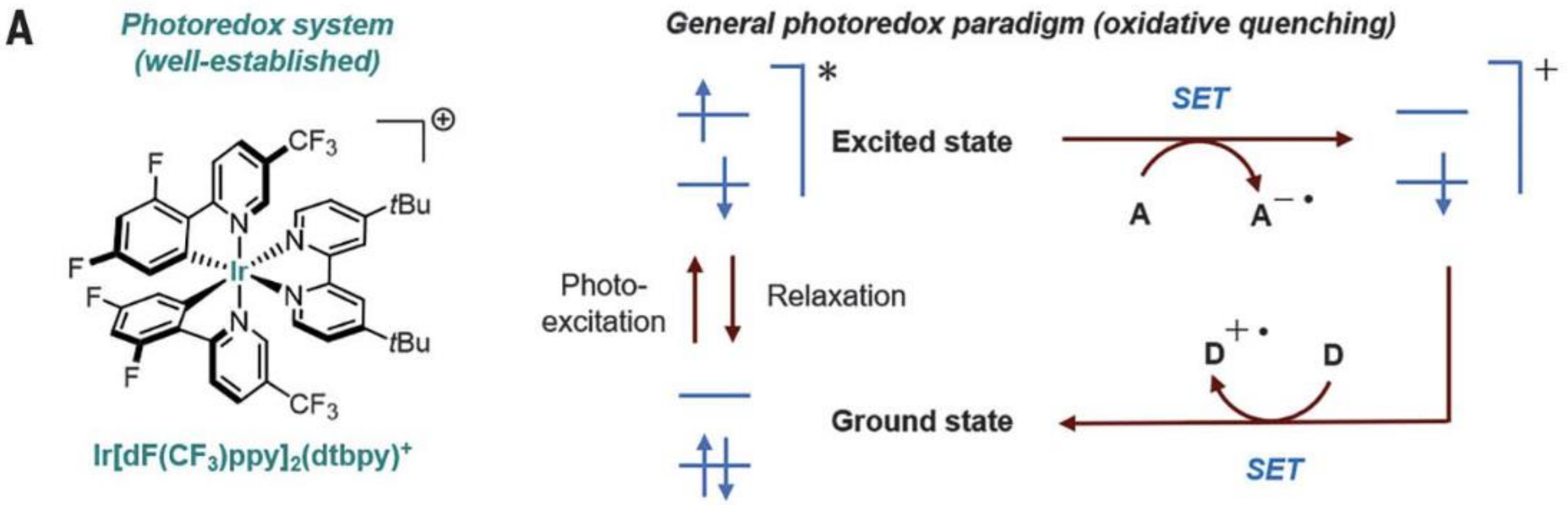
Mixing solid reactants in a ball mill is a promising means of avoiding the copious solvent waste associated with most chemical syntheses. Kubota *et al.* now report that adding a piezoelectric catalyst to the mix can promote bond formation through apparent electron transfer cycles (see the Perspective by Xia and Wang). Specifically, barium titanate activates aryl diazonium salts toward borylation and

CURRENT ISSUE

Kubota et al., Science 2019, 366, 1500–1504)

Mechanochemistry

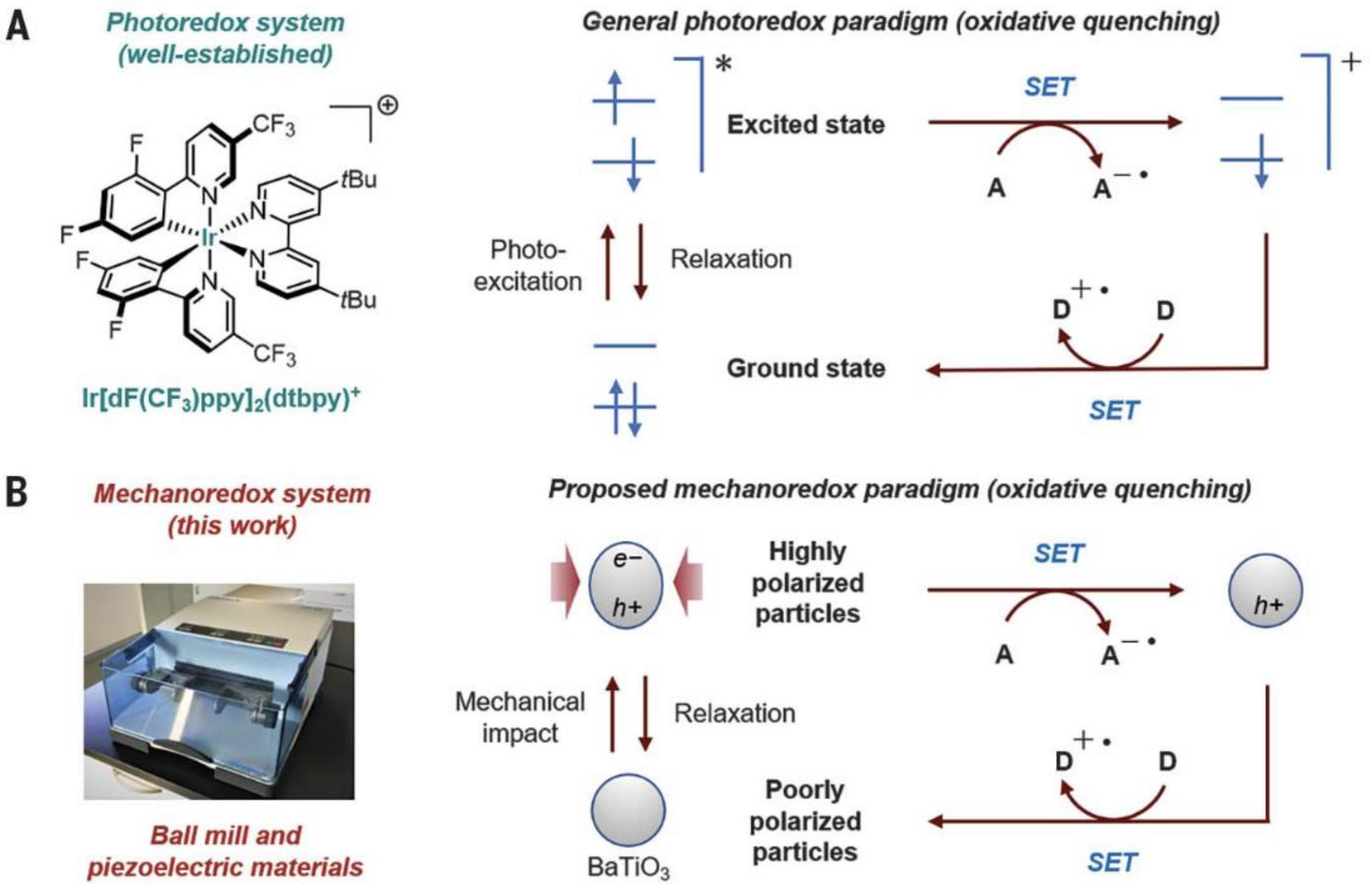
Mechanoredox Catalysis



Kubota et al., Science 2019, 366, 1500–1504)

Mechanochemistry

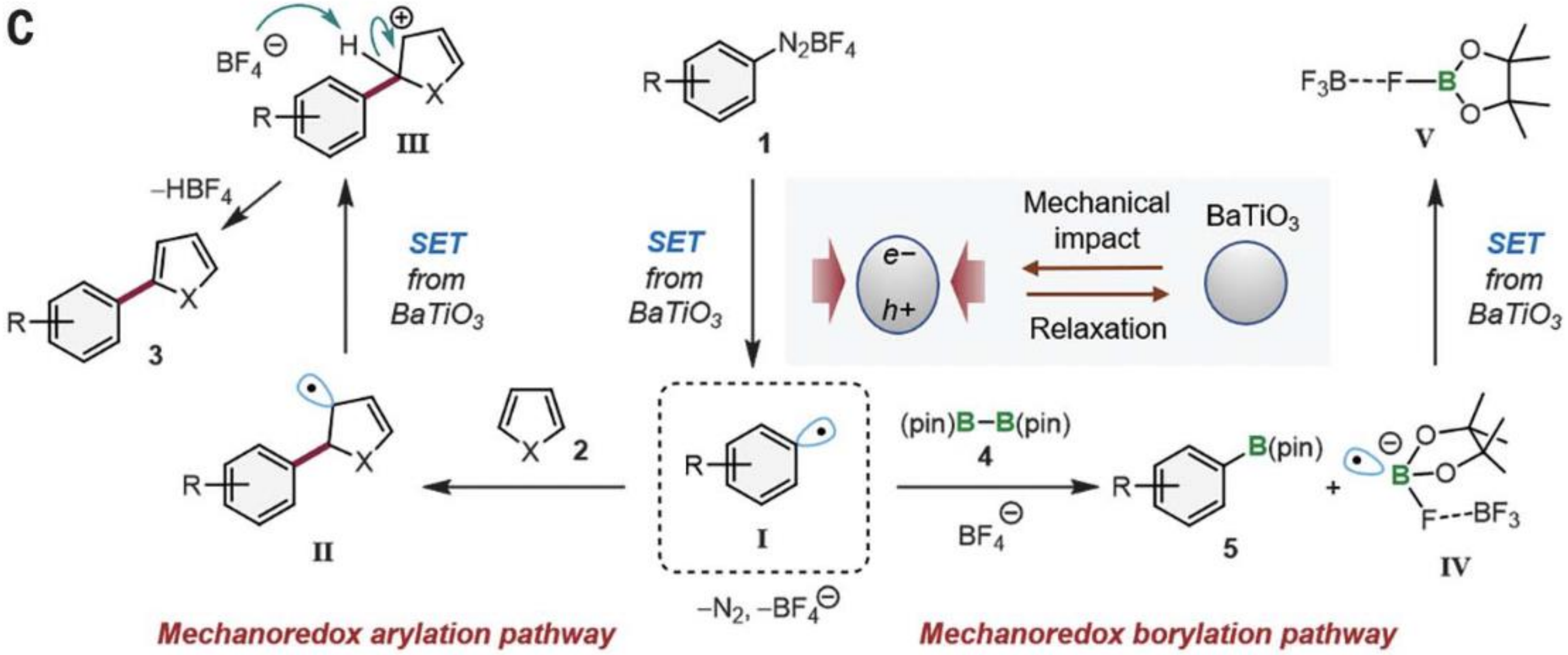
Mechanoredox Catalysis



Kubota et al., Science 2019, 366, 1500–1504)

Mechanochemistry

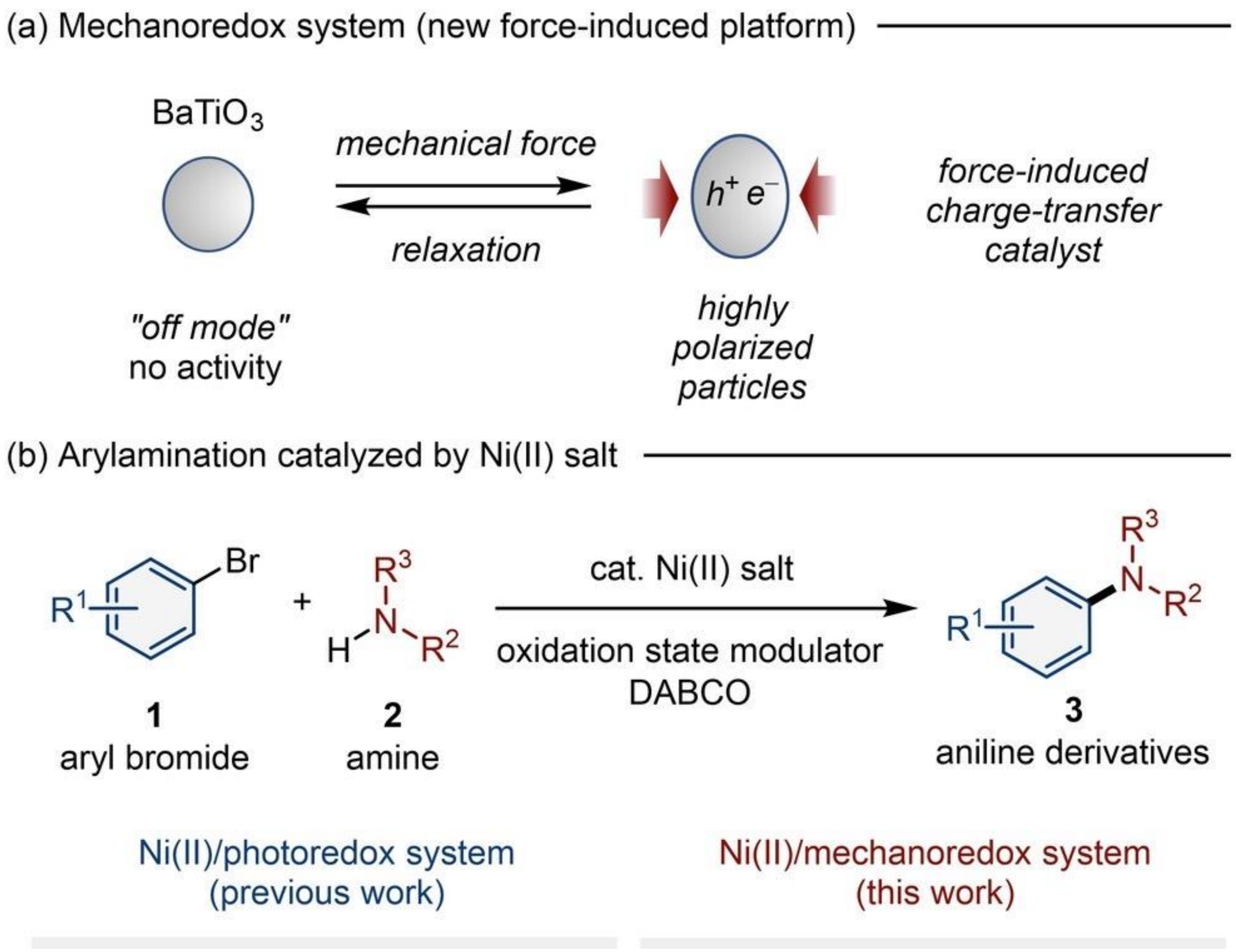
Mechanoredox Catalysis



Kubota et al., Science 2019, 366, 1500–1504)

Mechanochemistry

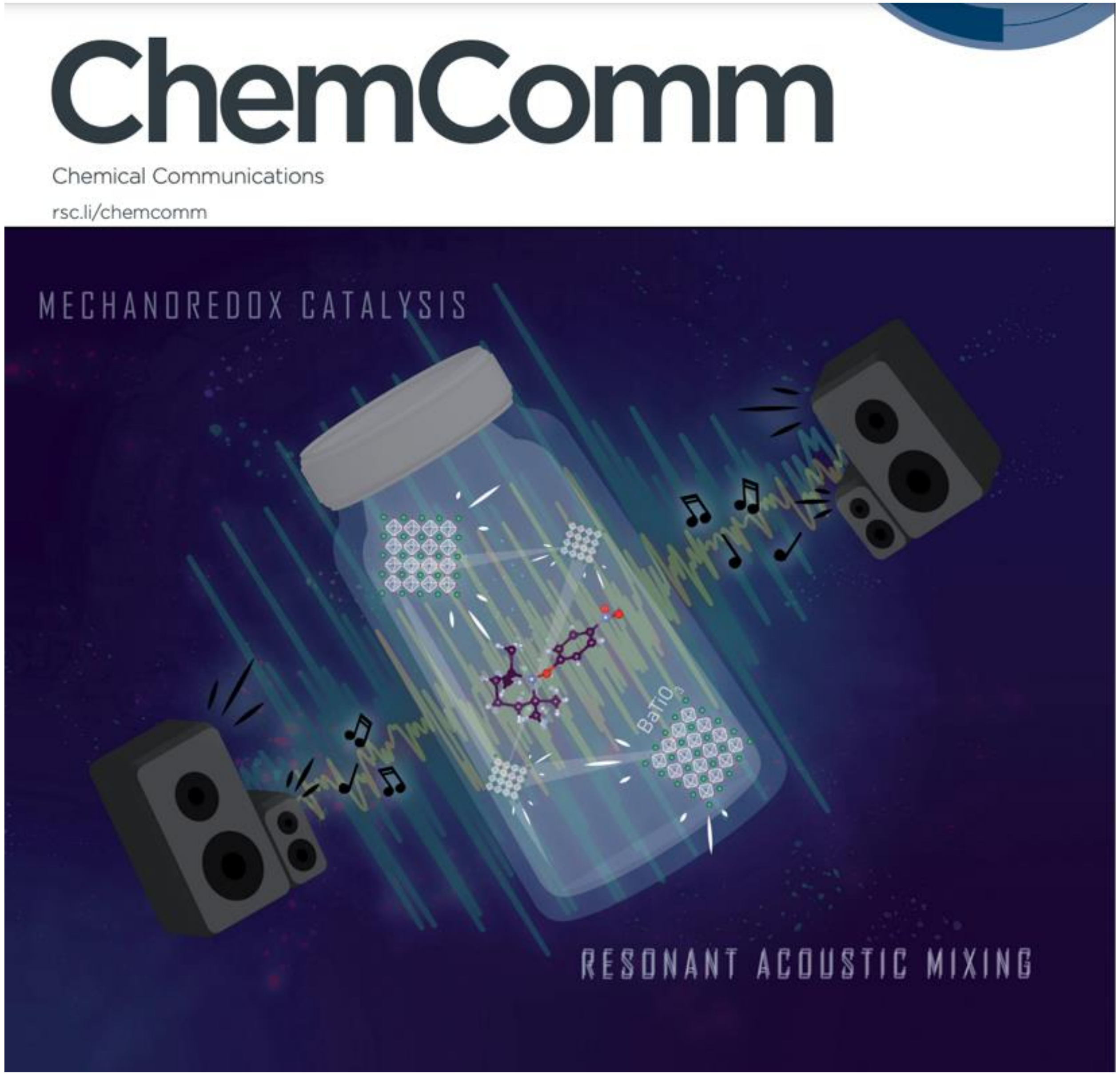
Mechanoredox Catalysis



Angew Chem, Int Ed, 2023, e202311531

Mechanochemistry

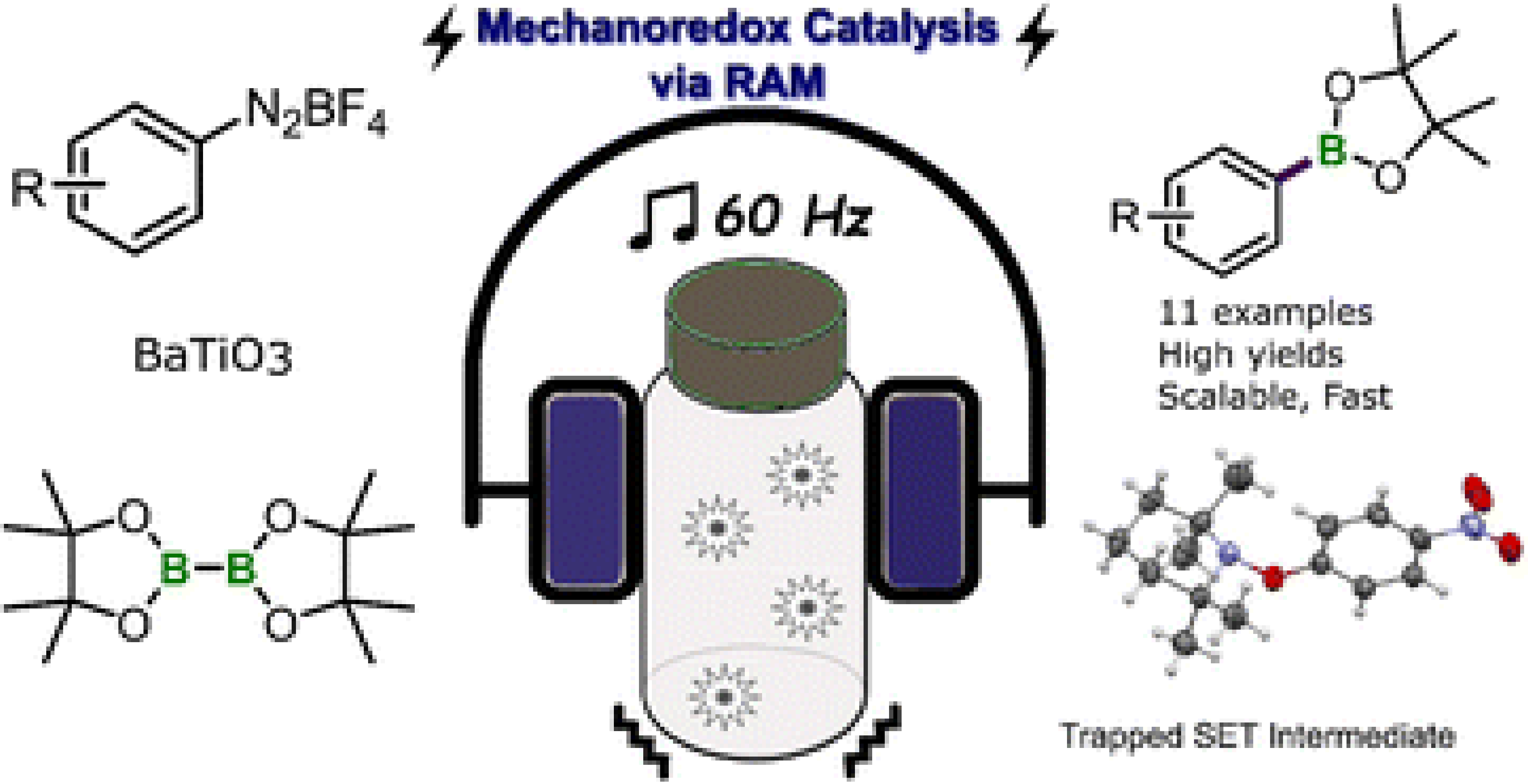
Mechanoredox Catalysis



Chem. Commun. 2023, 59, 1010–1013.

Mechanochemistry

Mechanoredox Catalysis



Chem. Commun. 2023, 59, 1010–1013.

Mechanochemistry

Asymmetric Organocatalysis

Is Solvent Critical: Solvation-Desolvation?

Chemistry A European Journal

Chemistry Europe
European Chemical Societies Publishing

Full Paper | Full Access

A Highly Efficient Asymmetric Organocatalytic Aldol Reaction in a Ball Mill

Belén Rodríguez Dr., Angelika Bruckmann, Carsten Bolm Prof. Dr.

First published: 22 May 2007 | https://doi.org/10.1002/chem.200700188 | Citations: 227

Mechanochemistry

CHEMISTRY
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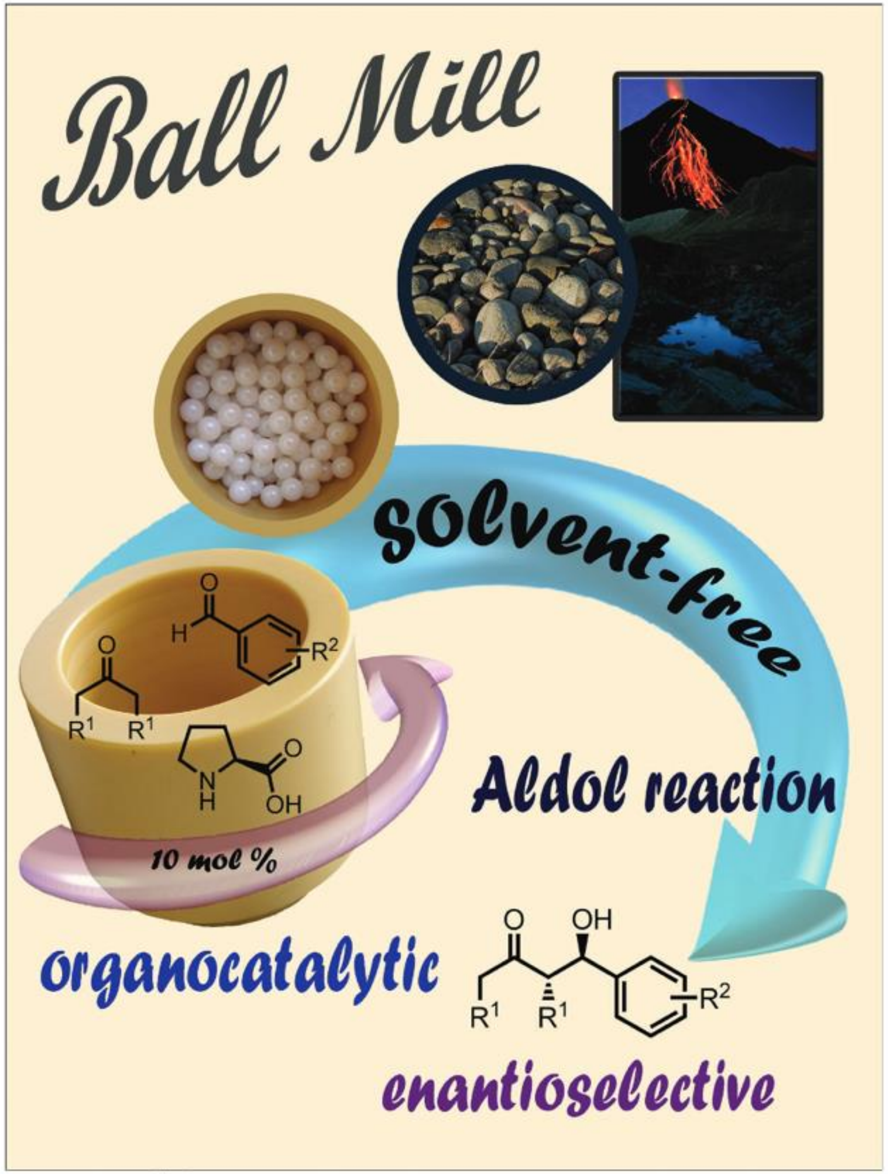
FULL PAPER

DOI: 10.1002/chem.200700188

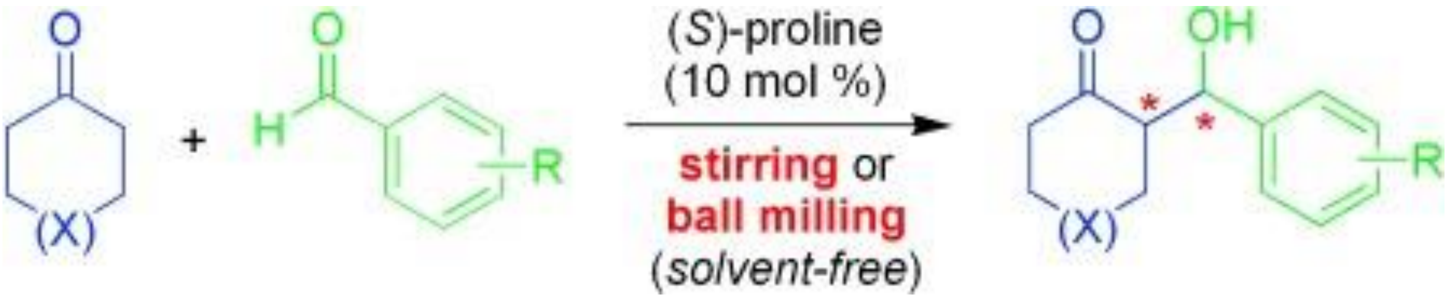


4710 interScience

Chem. Eur. J. **2007**, *13*, 4710 – 4722

Mechanochemistry

Asymmetric Organocatalysis



Anti-aldol products with up to >99 % enantiomeric excess (_ee_)

method	time (h)	yield (%)	*anti:syn*	*ee* (%)
ball milling	5.5	99	89:11	94
stirring in a flask	96	98	87:13	94

Mechanochemistry

C-H Bond formation

Angewandte Chemie International Edition
GDCh A Journal of the German Chemical Society

Communication | Full Access

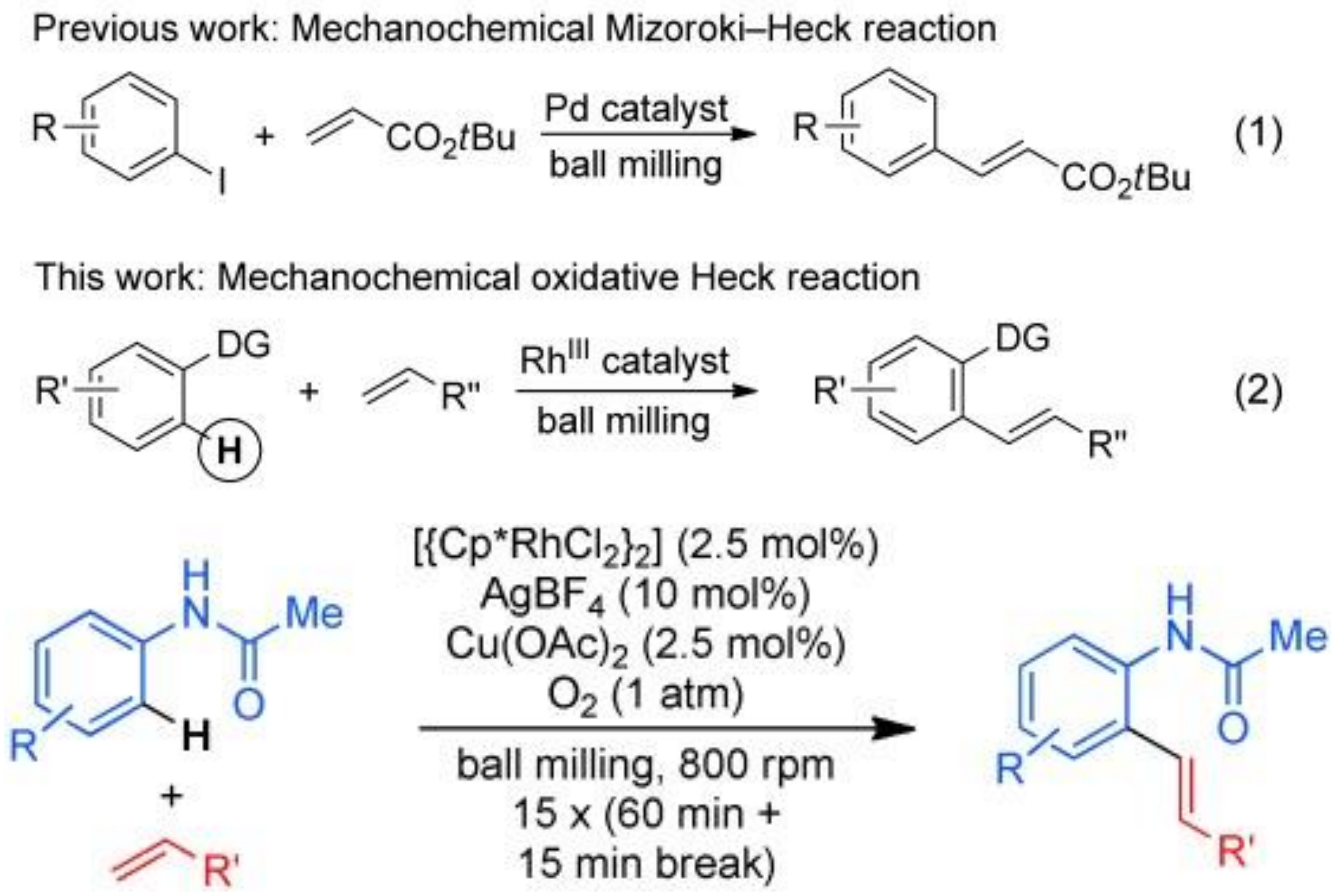
Mechanochemical Rhodium(III)-Catalyzed C—H Bond Functionalization of Acetanilides under Solventless Conditions in a Ball Mill†

Gary N. Hermann, Peter Becker, Prof. Dr. Carsten Bolm

First published: 07 May 2015 | https://doi.org/10.1002/anie.201502536 | Citations: 103

Mechanochemistry

C-H Bond formation



Mechanochemistry

Grignard formation and reaction with Gaseous CO_2

Angewandte Chemie International Edition
GDCh
A Journal of the German Chemical Society

Communication | Open Access

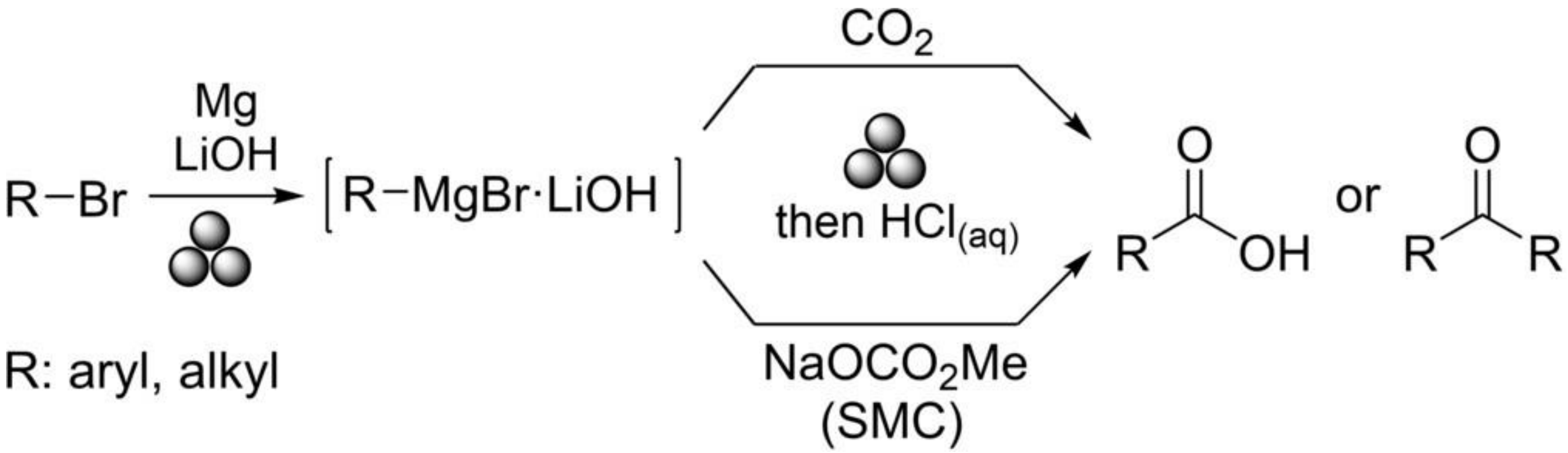
Mechanochemical Grignard Reactions with Gaseous CO_2 and Sodium Methyl Carbonate**

Victoria S. Pfennig, Romina C. Villella, Julia Nikodemus, Prof. Dr. Carsten Bolm

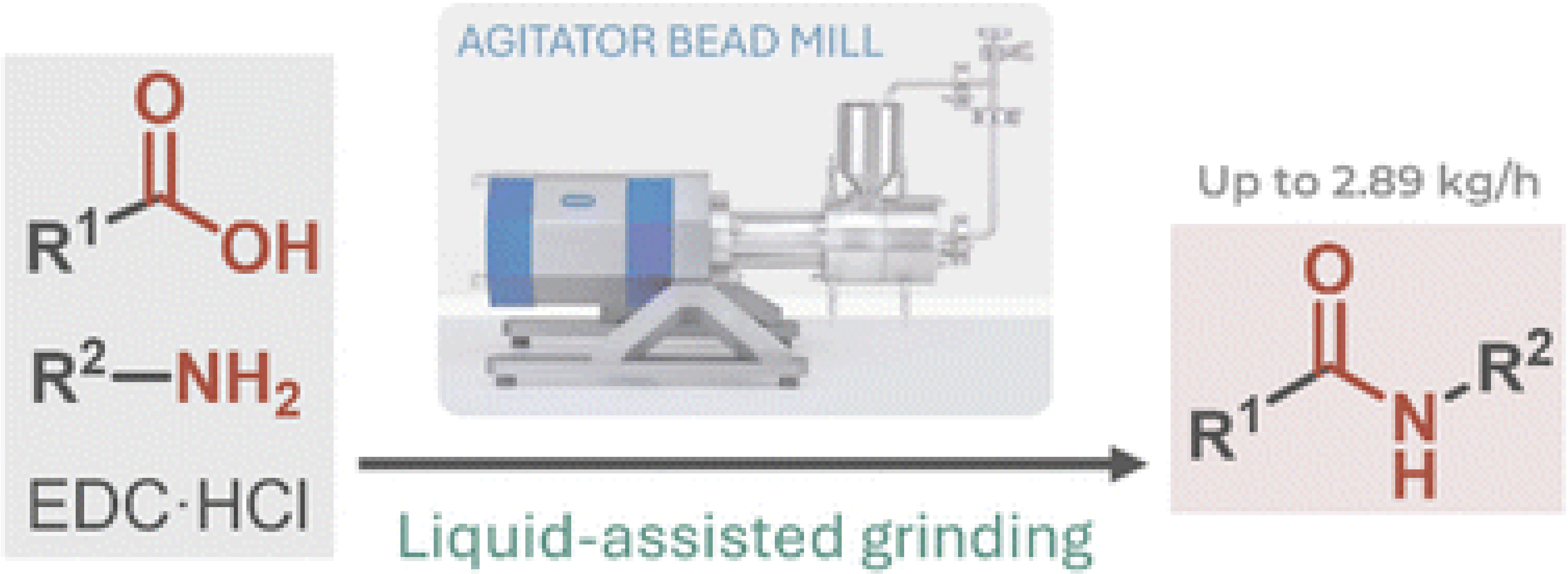
First published: 23 December 2021 | https://doi.org/10.1002/anie.202116514 | Citations: 64

Mechanochemistry

Grignard formation and reaction with Gaseous CO_2



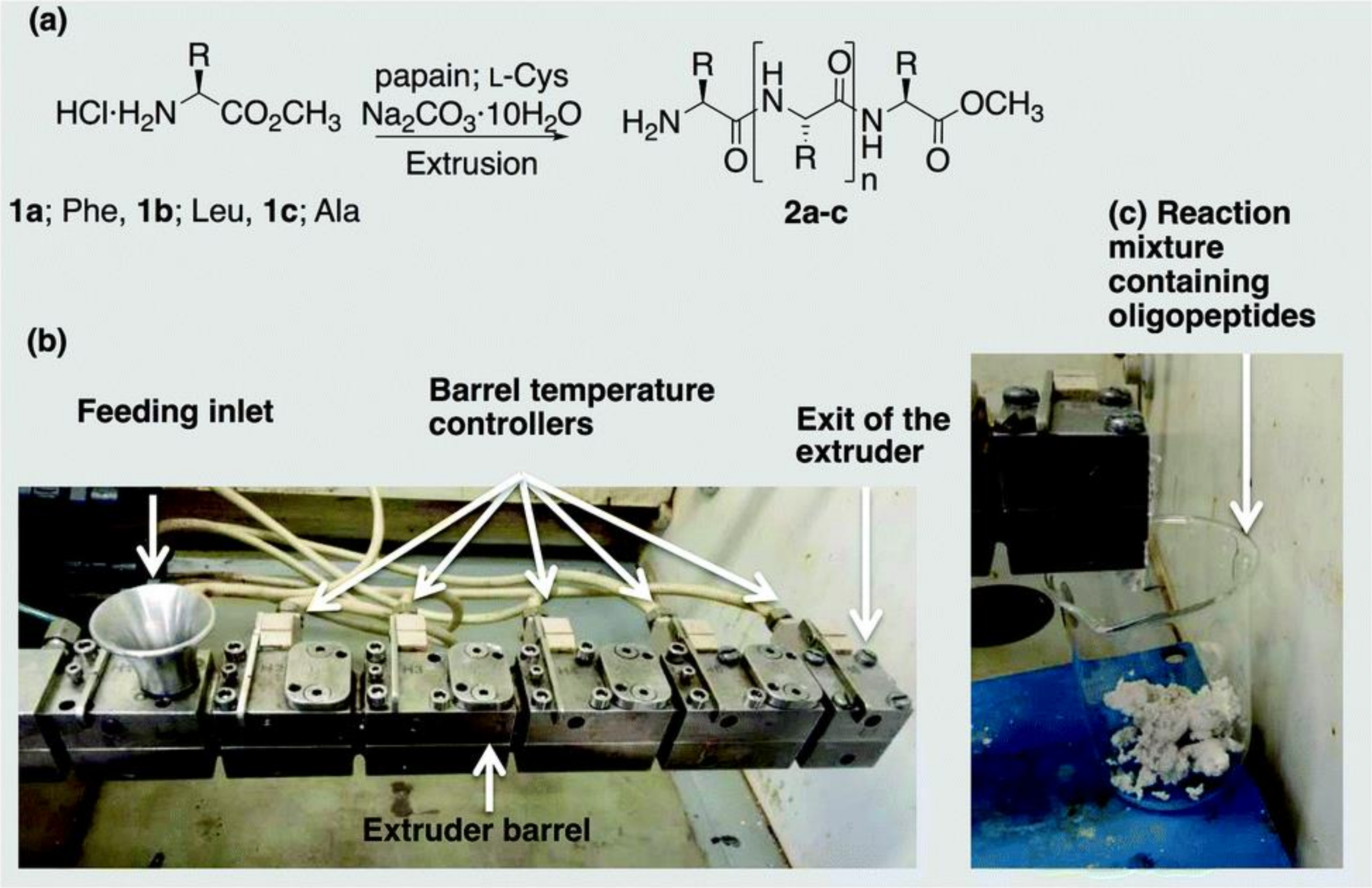
Amide Synthesis



Kappe and coworkers, Green Chen. 2026, DOI https://doi.org/10.1039/D5GC04764A

Mechanochemistry

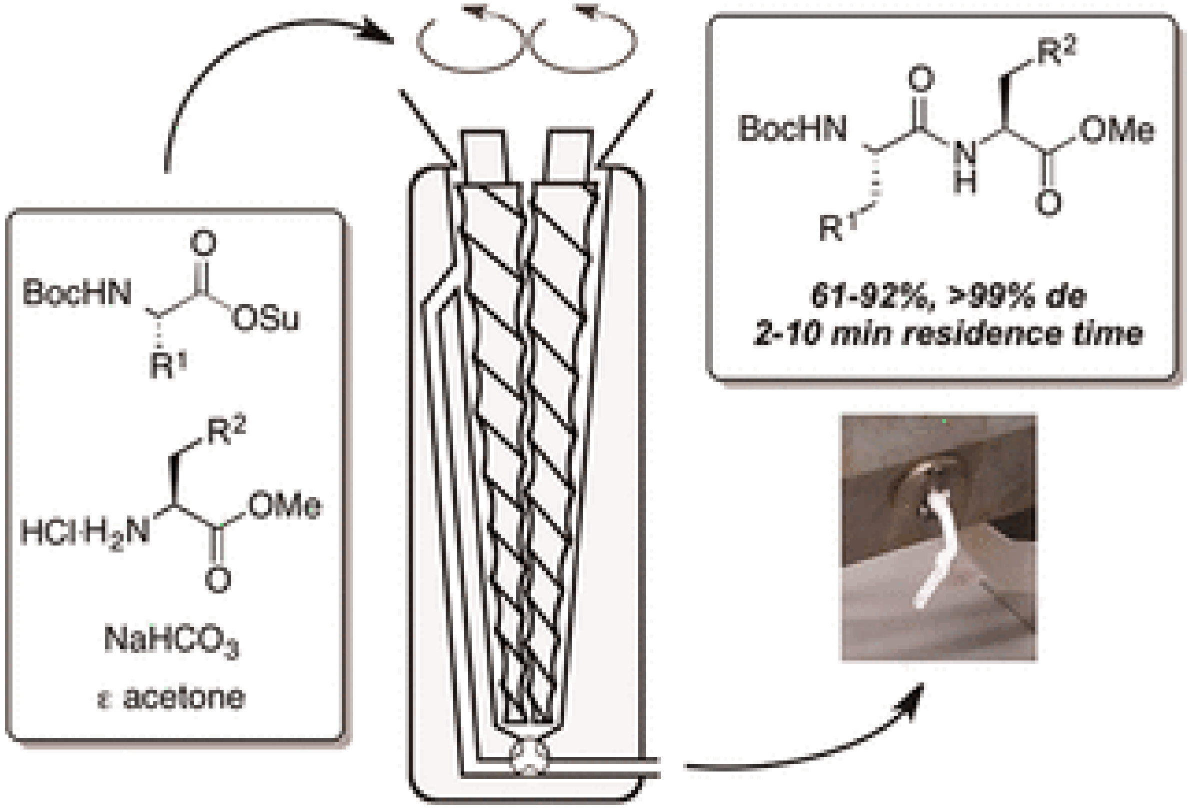
Peptide Chemistry



Green Chem., 2018,20, 1262-1269

Mechanochemistry

Peptide Chemistry



Peptide Couplings by Reactive Extrusion

CMR-free
Solid-tolerant
Efficient
Fast
Versatile
Continuous

ACS Sustainable Chem. Eng. 2018, 6, 12, 16001–16004

N-Alkylation

Angewandte Chemie International Edition

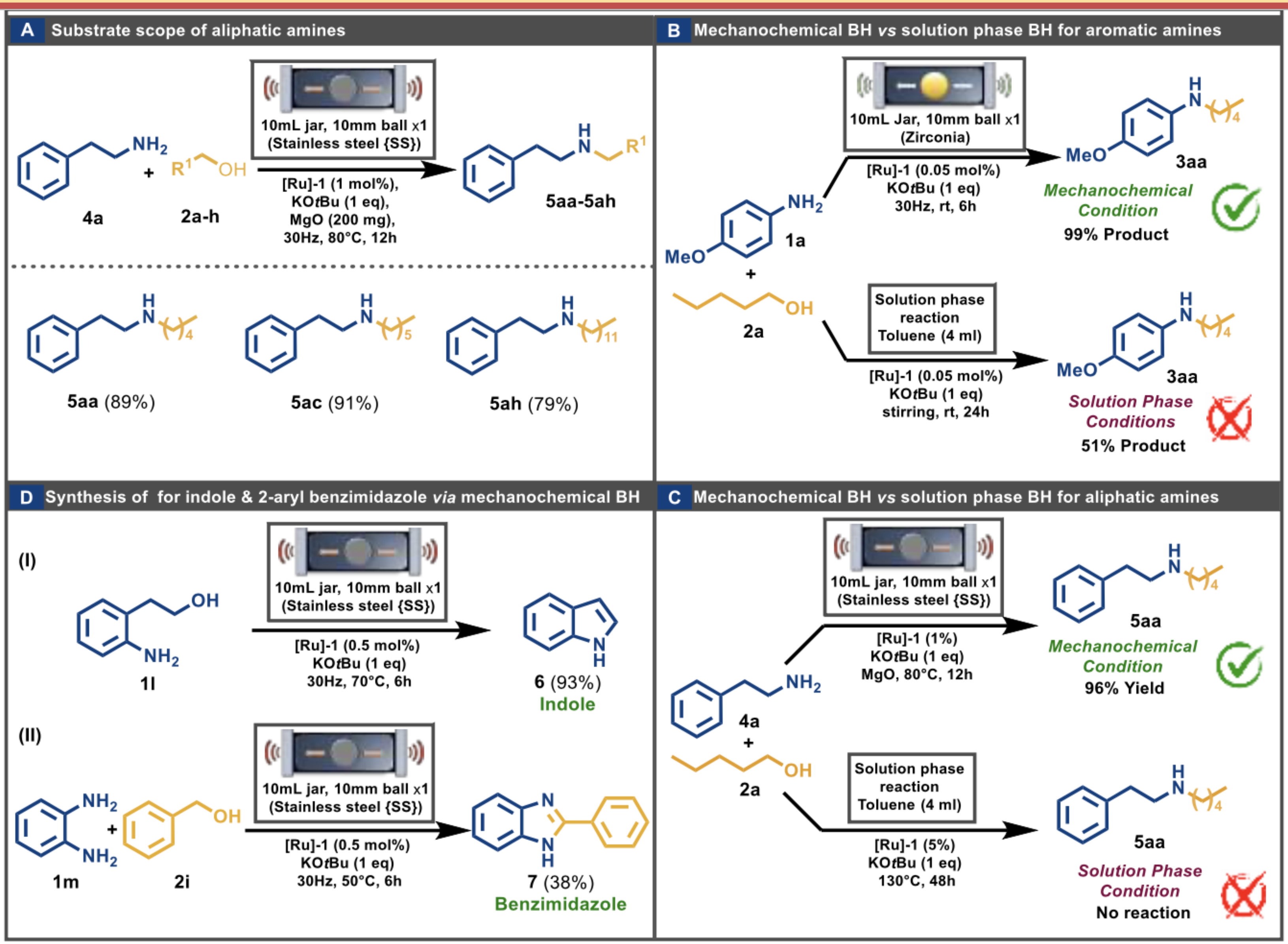
GDCh German Chemical Society

Research Article | Open Access

Mechanochemistry-Driven Borrowing Hydrogen Processes for Ru-Catalyzed *N*-Alkylation: A Pathway to Enhanced Sustainability and Efficiency

Sourav Behera, Dr. Dipak J. Fartade, Dr. Rita Mocci, Michela Matta, Prof. Lidia De Luca, Prof. Andrea Porcheddu

Amide Synthesis



Kappe and coworkers, Green Chen. 2026, DOI https://doi.org/10.1039/D5GC04764A

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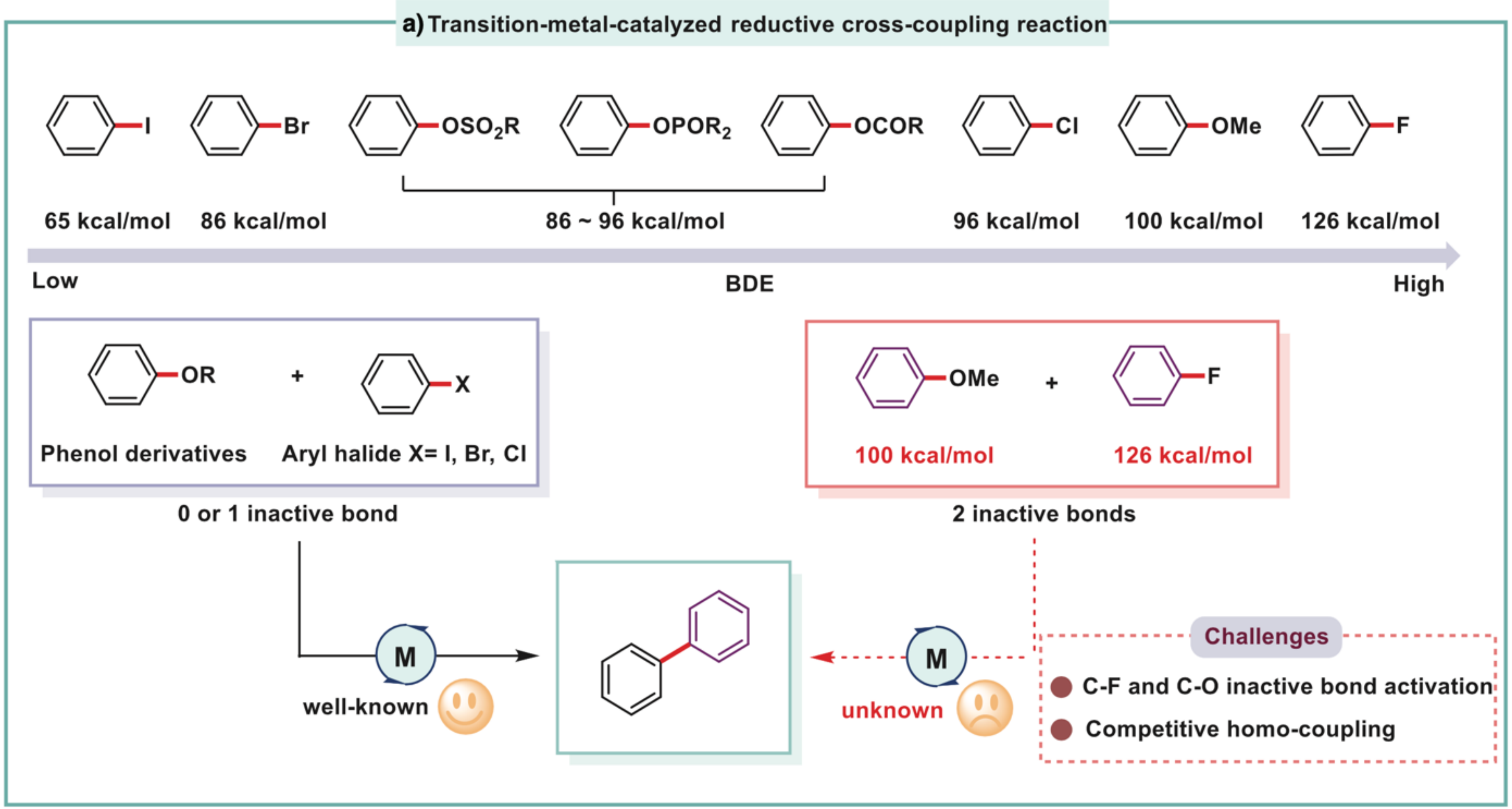
How to cite: *Angew. Chem. Int. Ed.* **2025**, *64*, e202424186
doi.org/10.1002/anie.202424186

Mechanochemistry

Mechanochemically Enabled Formal Reductive Cross-Coupling Reaction Between Aryl Ethers and Aryl Fluorides

*Tianfen Liu, Xuemei Zhang, Qingqing Wang, and Zhong Lian**



Research Article

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How to cite: *Angew. Chem. Int. Ed.* **2025**, *64*, e202424186
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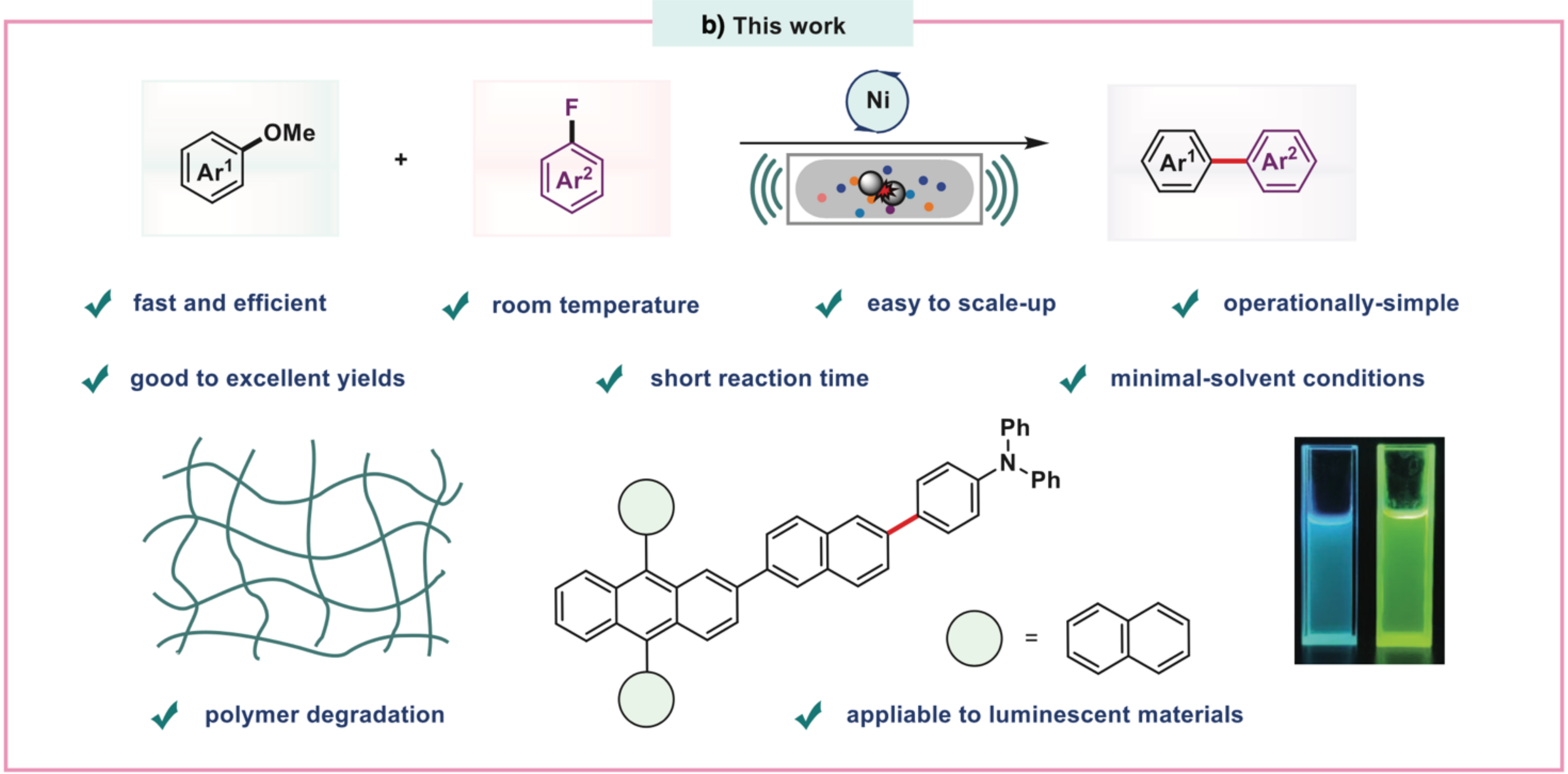
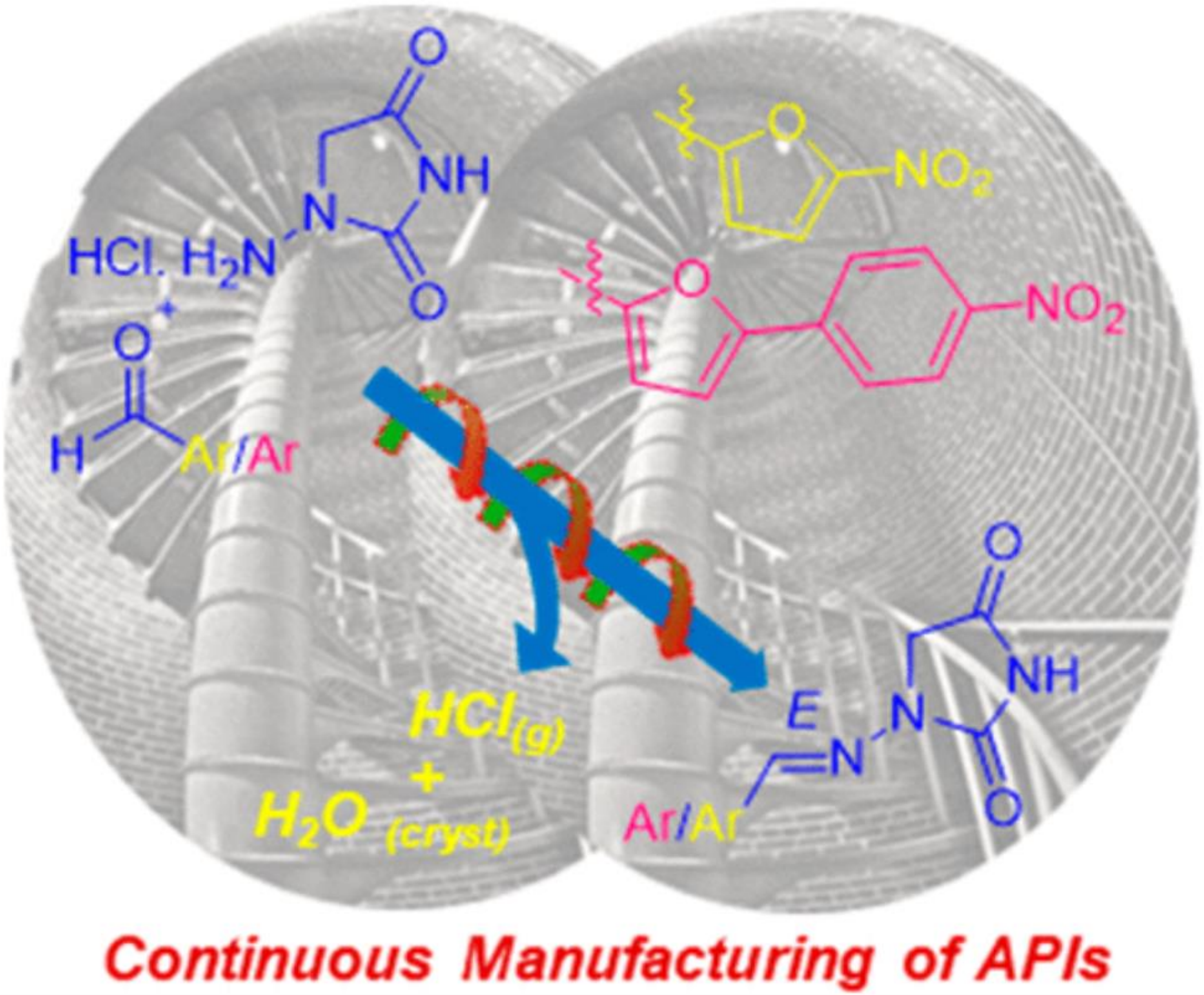


Mechanochemistry

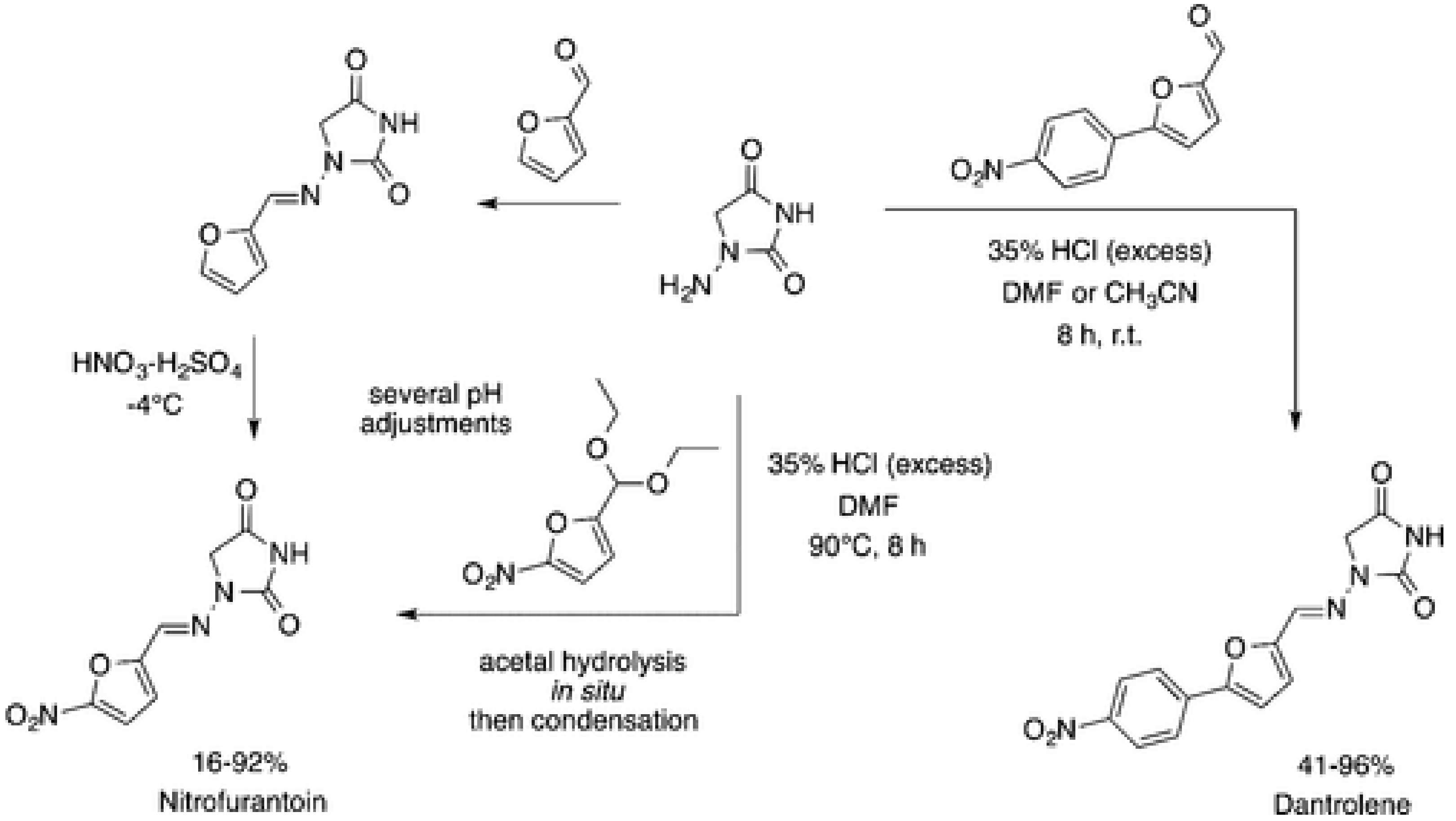
Mechanochemistry API Synthesis via TSE



ACS Sustainable Chem. Eng. 2020, 8, 32, 12230–12238

Mechanochemistry

Hydrazone-Based API Synthesis via TSE



Conventional Industrial Production

ACS Sustainable Chem. Eng. 2020, 8, 32, 12230–12238

Mechanochemistry

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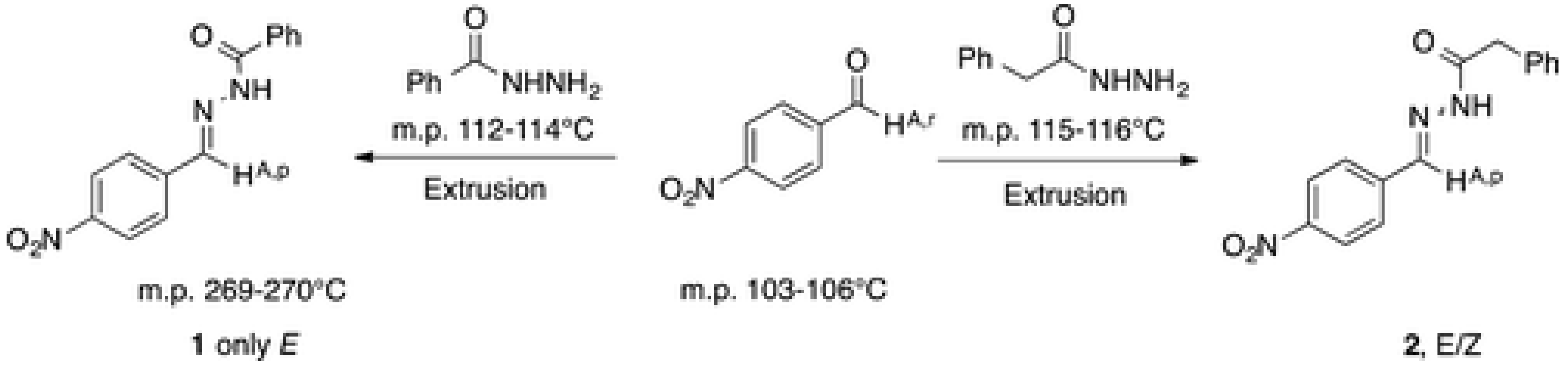
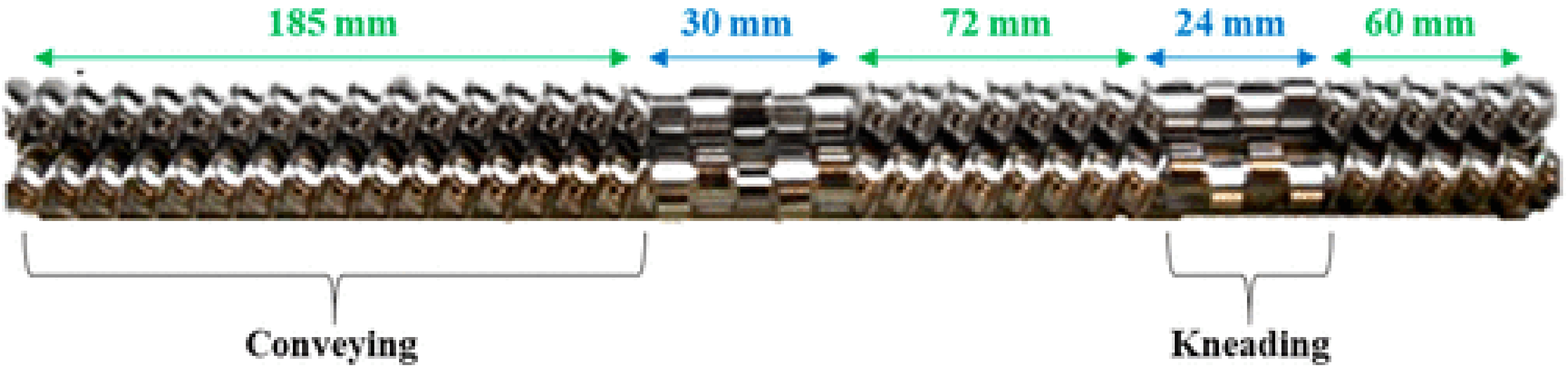


Model Reactions



ACS Sustainable Chem. Eng. 2020, 8, 32, 12230–12238

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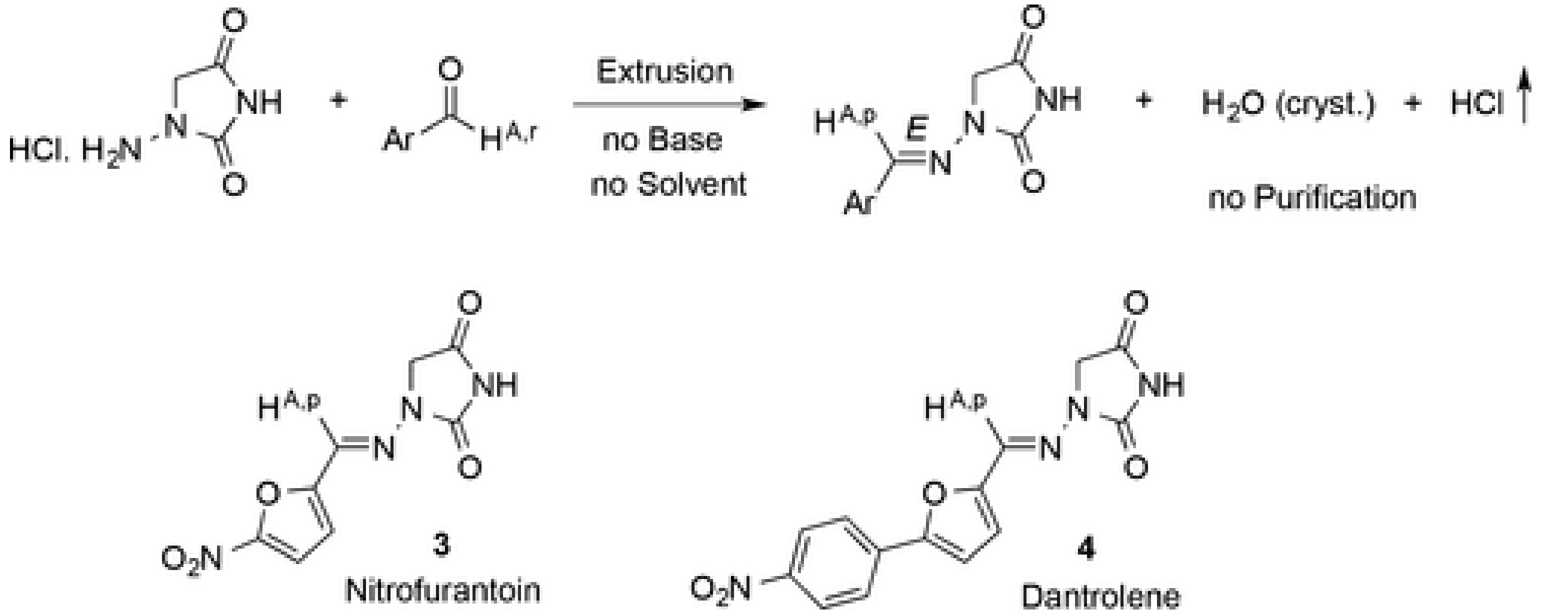

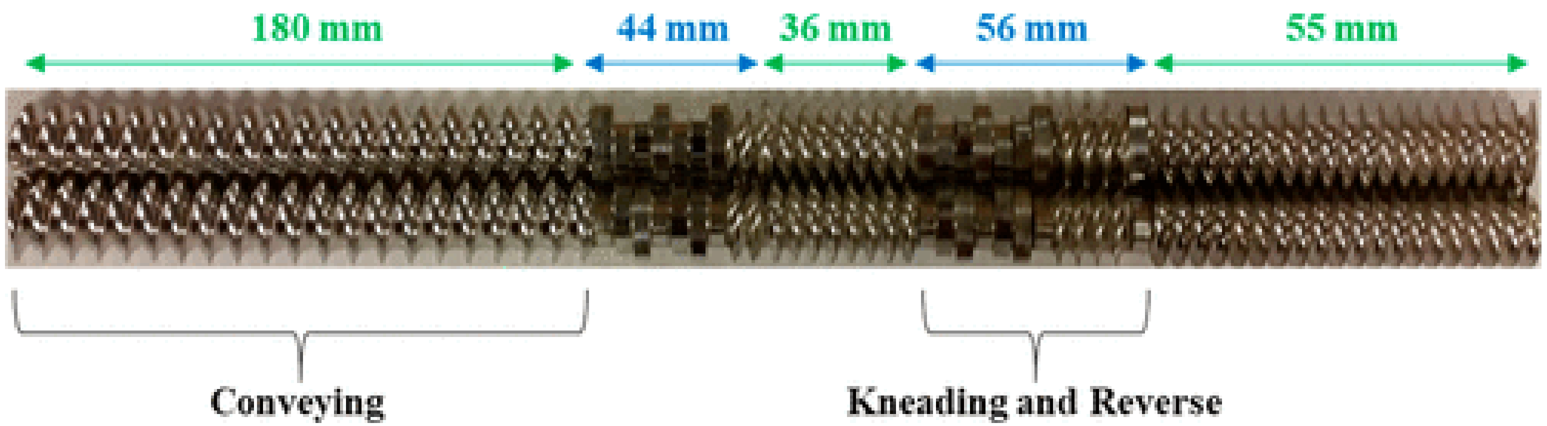

ACS Sustainable Chem. Eng. 2020, 8, 32, 12230–12238

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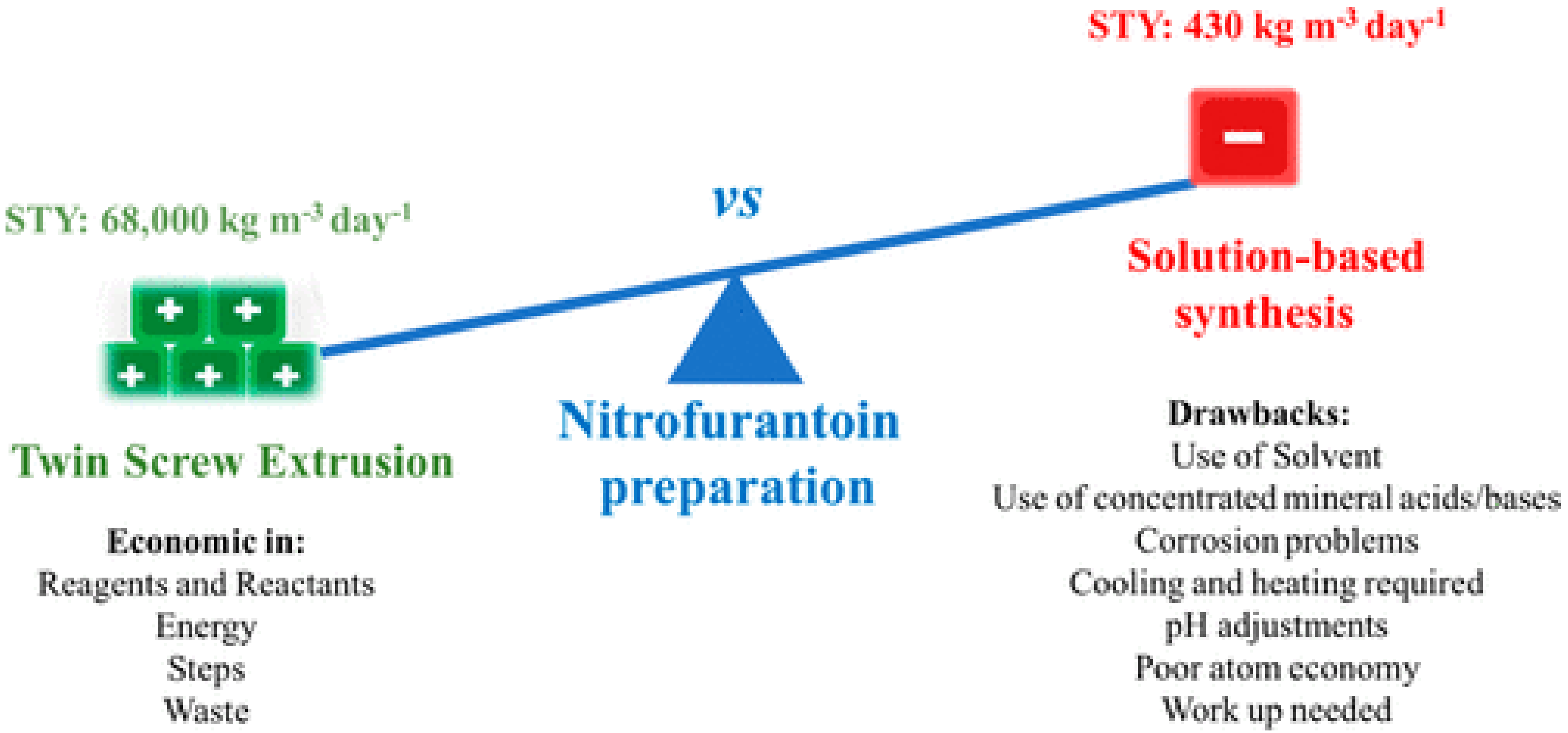
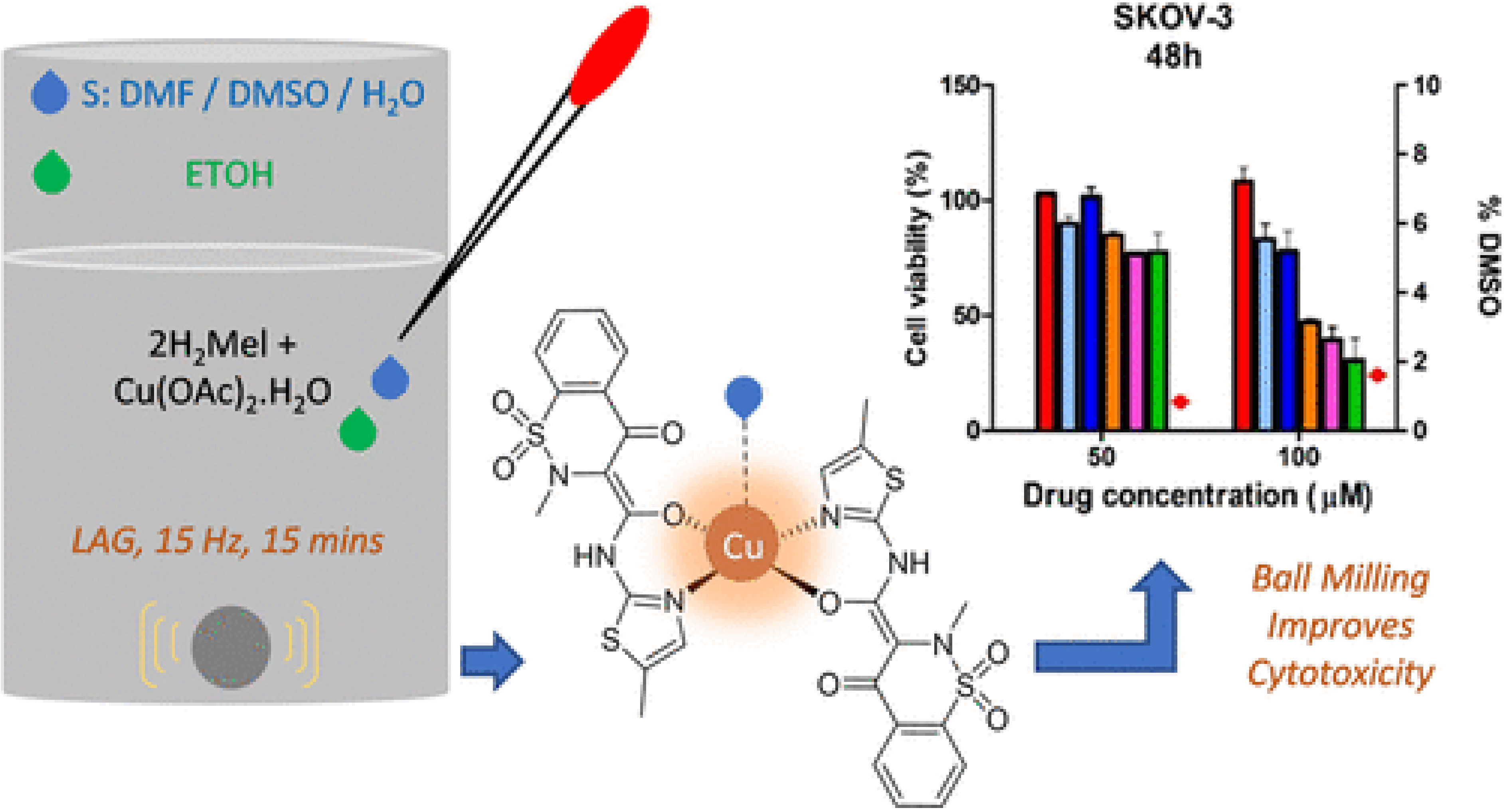


ACS Sustainable Chem. Eng. 2020, 8, 32, 12230–12238

Mechanochemistry

Cytotoxicity of Mechanochemically Prepared Cu(II) Complexes



ACS Sustainable Chem. Eng. 2020, 8, 40, 15243–15249

Mechanochemistry

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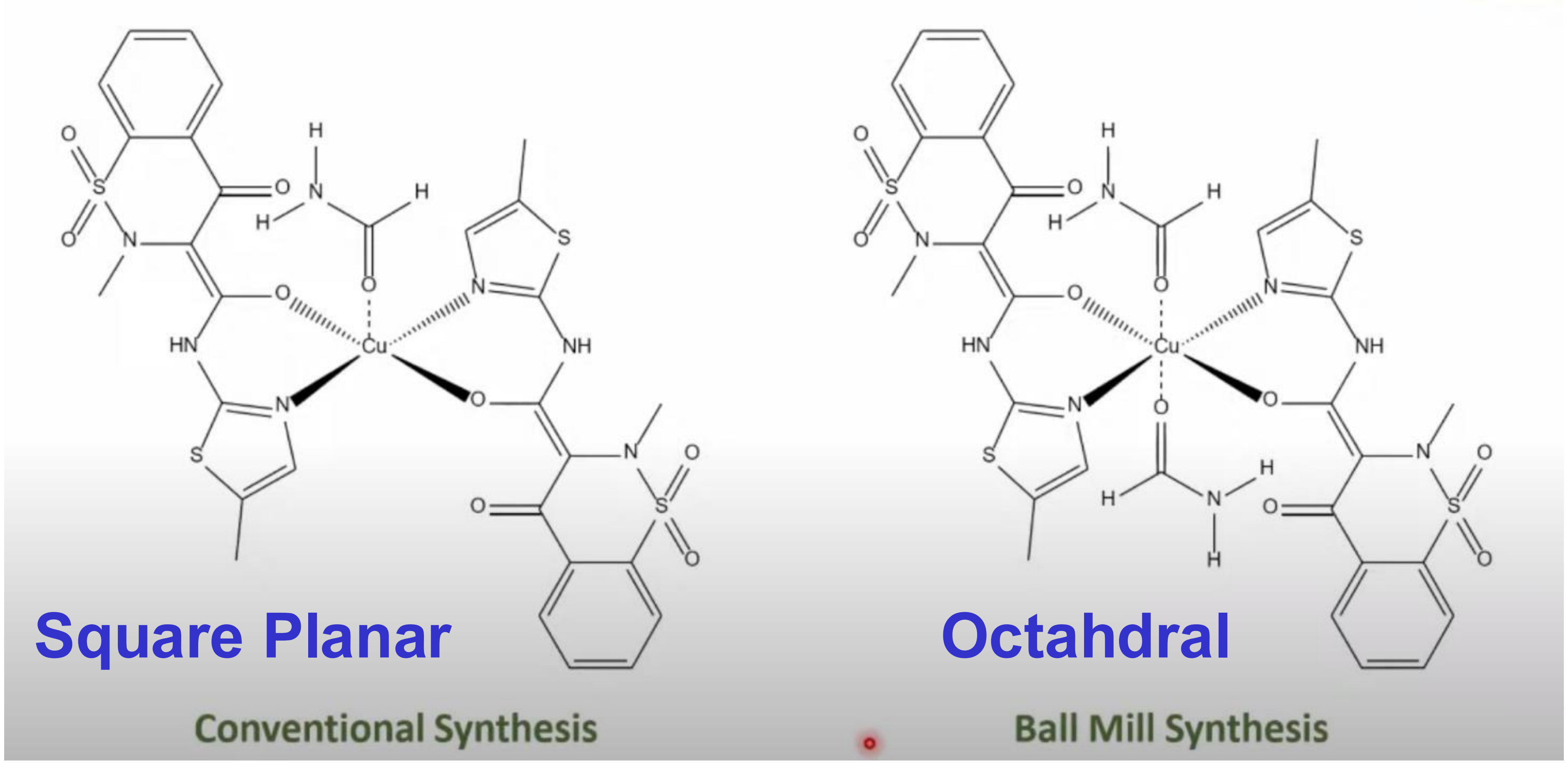
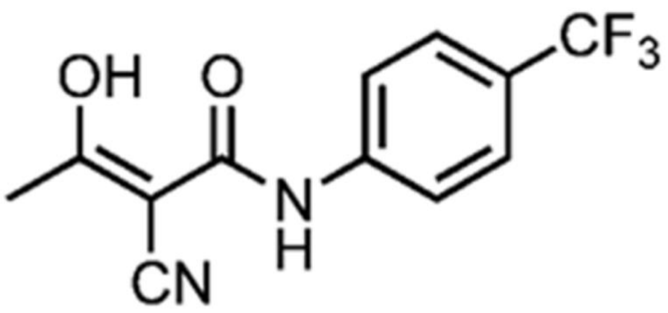


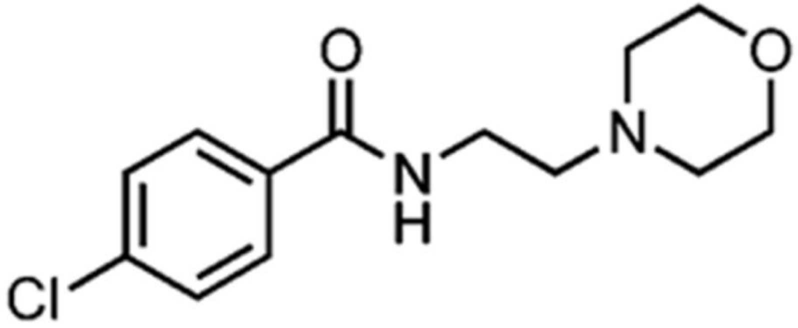
ACS Sustainable Chem. Eng. 2020, 8, 40, 15243–15249

Mechanochemistry

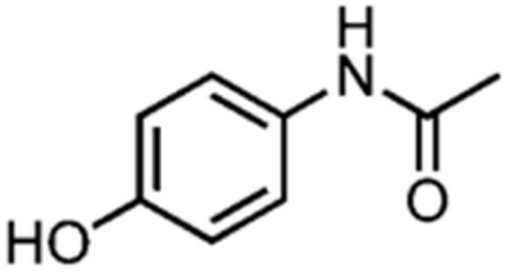
API via TSE



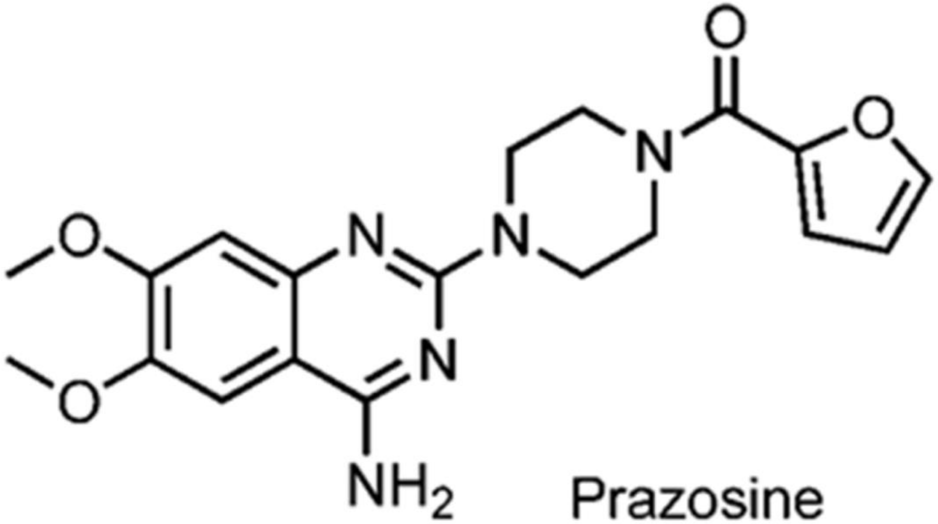
Teriflunomide



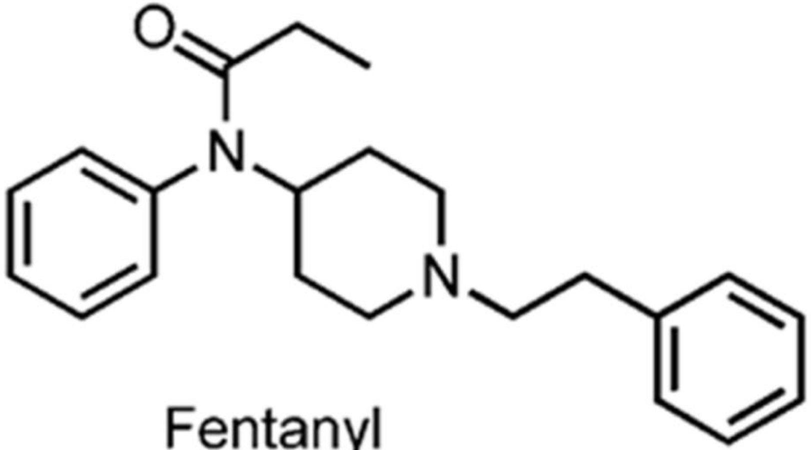
Moclobemide



Paracetamol



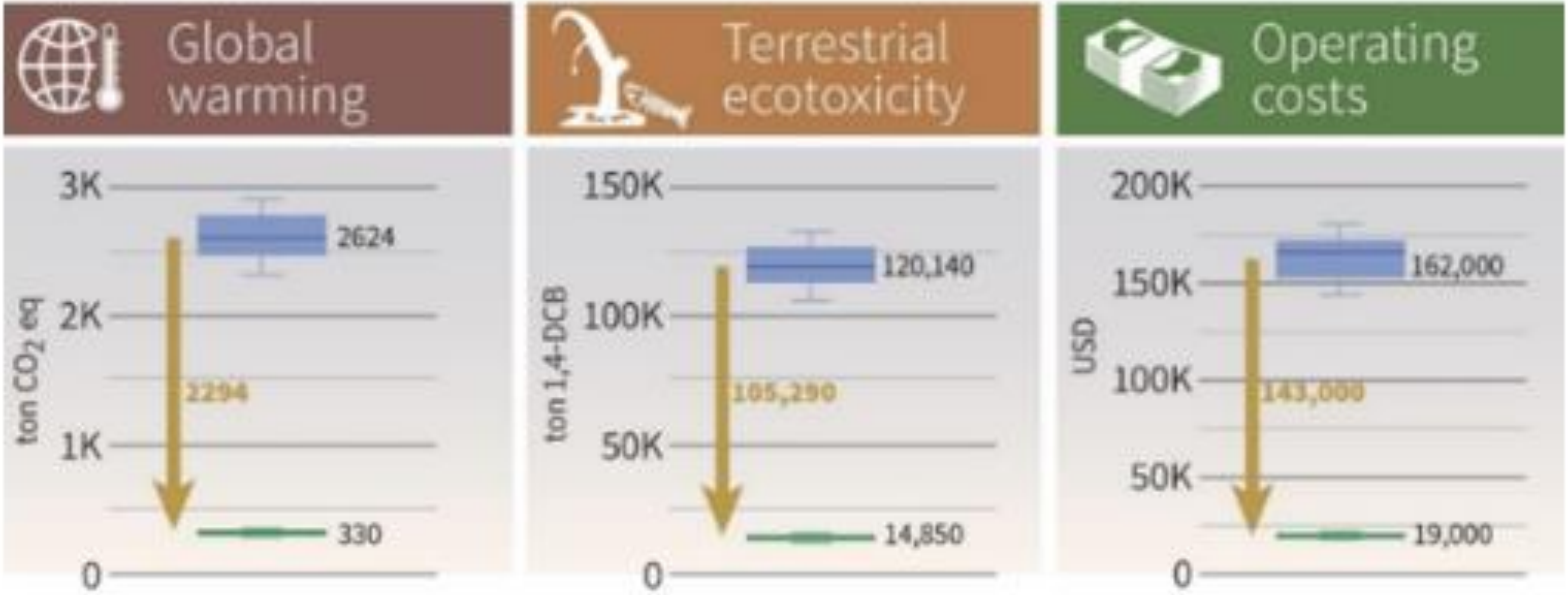
Prazosine



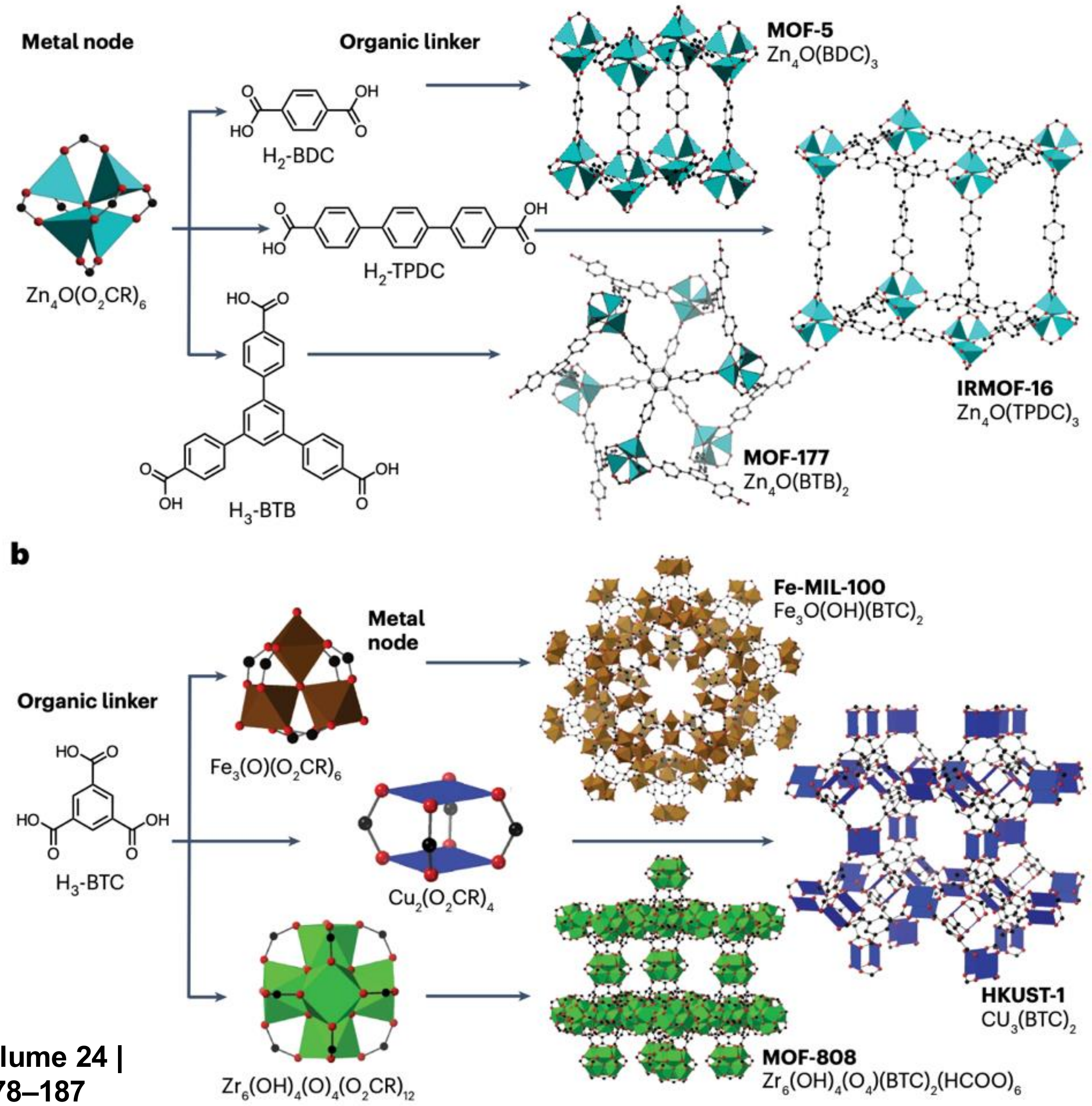
Fentanyl

Crawford, D. E.; James, S. L. A Reflection on Synthesis by Extrusion Ten Years on: Achievements, Challenges and Opportunities for Solvent-free, Sustainable, Continuous Chemical Manufacturing (Commentary), Chem. Sci. 2026, 17 (18), 8823 [DOI: 10.1039/D6SC90085B]

Mechanochemistry



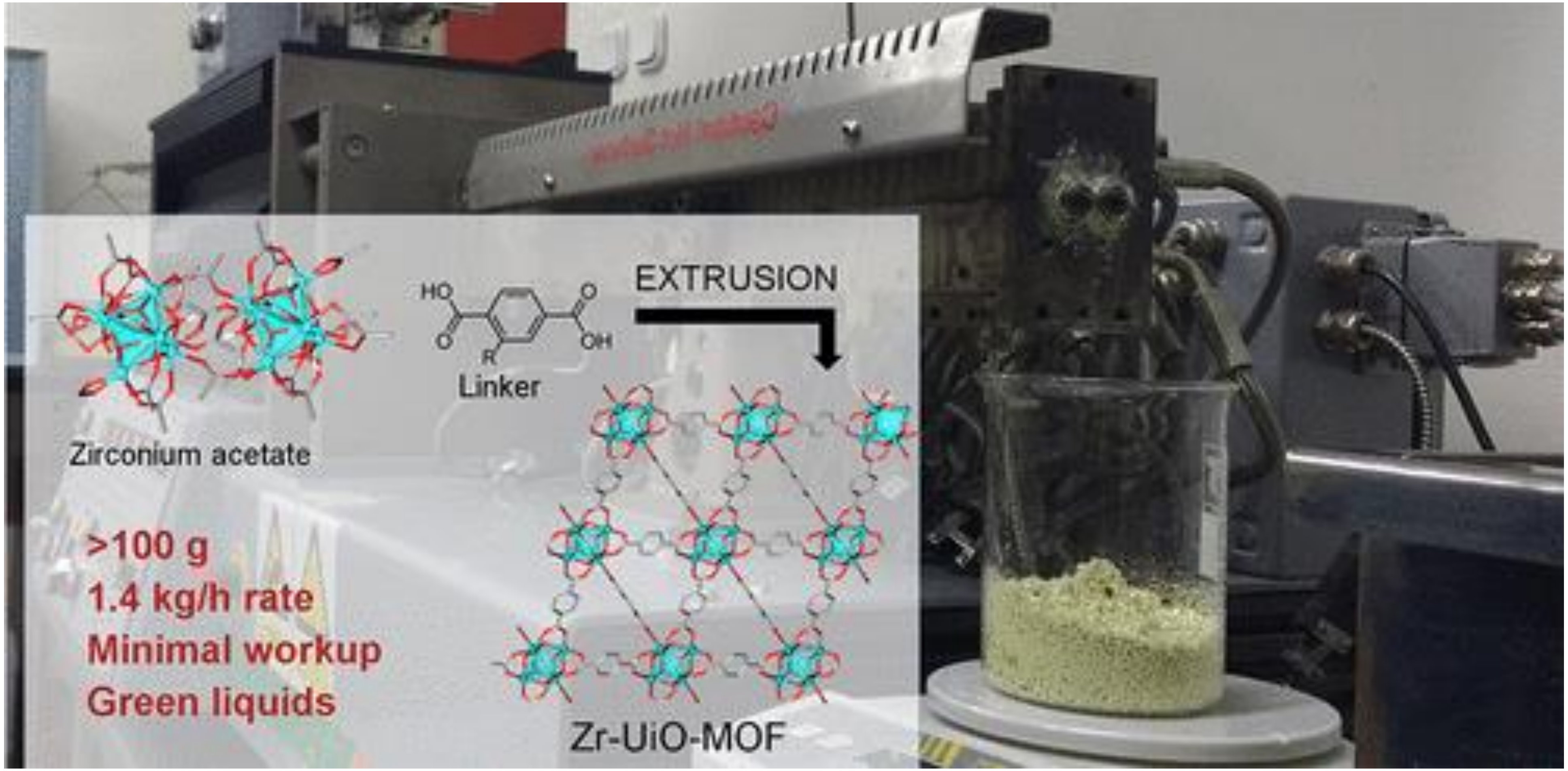
PCP/MOF in the world



Nature Materials | Volume 24 | February 2025 | 178–187

Mechanochemistry

MOF: Water Assisted



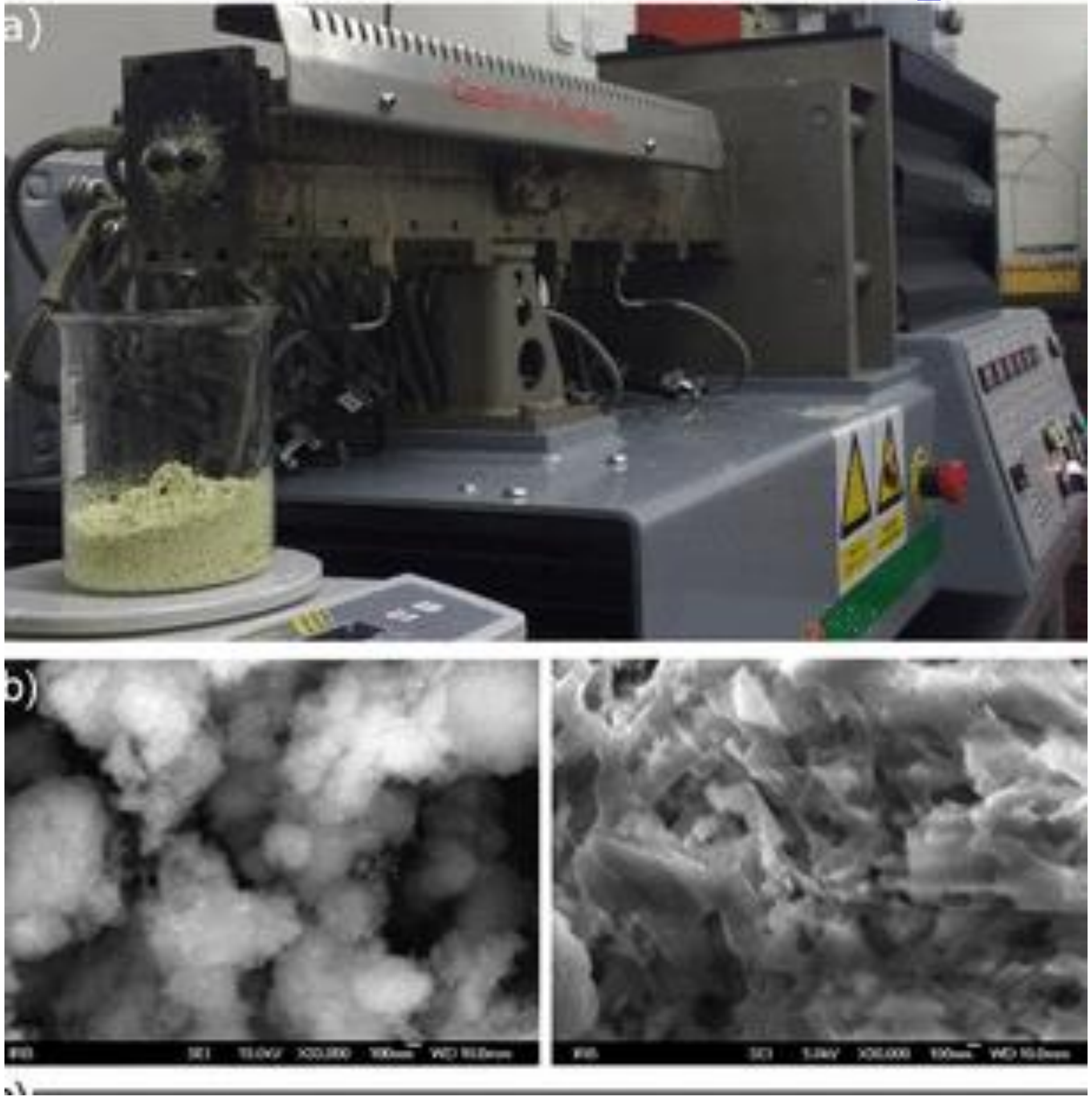
ACS Sustainable Chem. Eng. 2018, 6, 11, 15841–15849

Mechanochemistry

MOF Production via TSE

Chem. Sci., 2015,6, 1645-1649

Mechanochemistry



ACS Sustainable Chem. Eng. 2018, 6, 11, 15841–15849

Mechanochemistry

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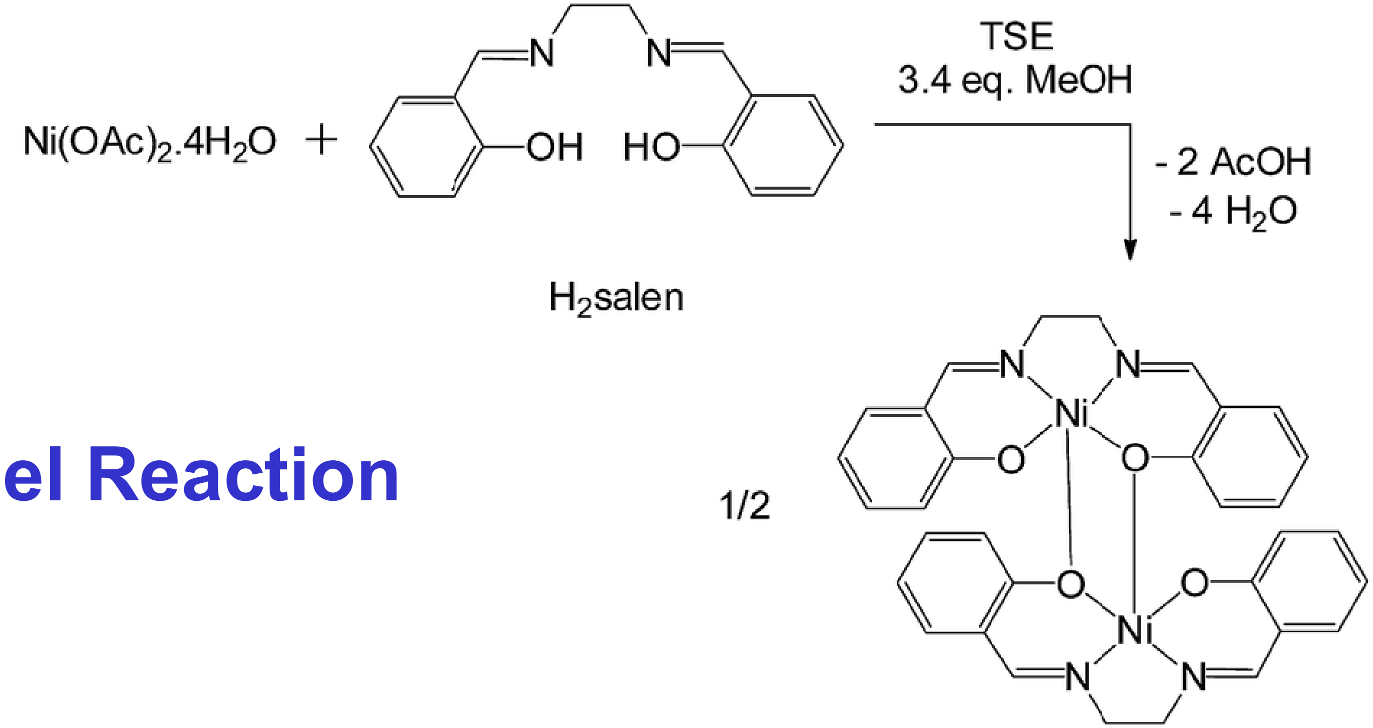
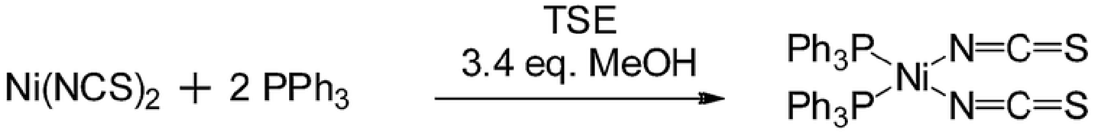


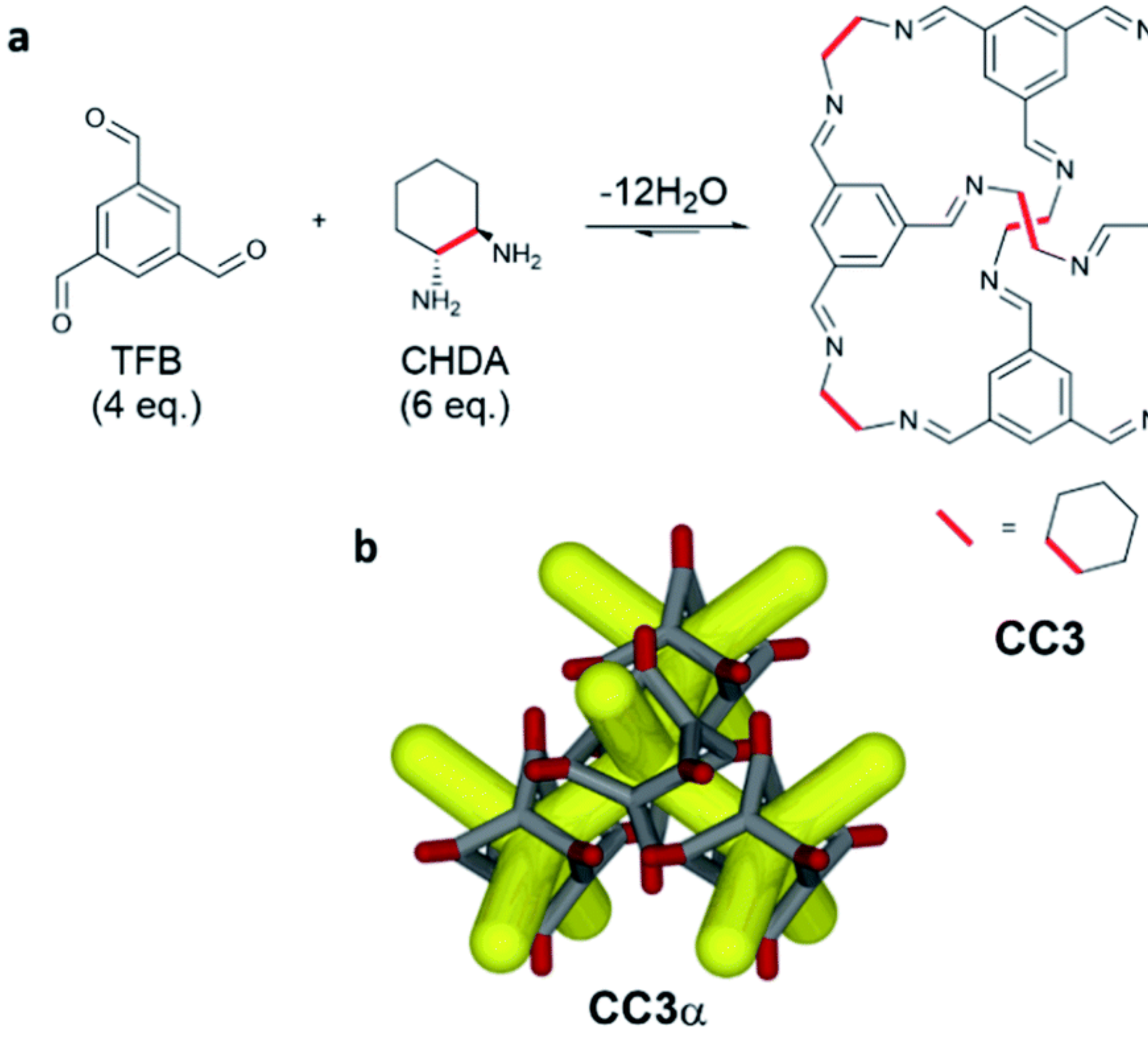
Model Reaction



Chem. Sci., 2015,6, 1645-1649

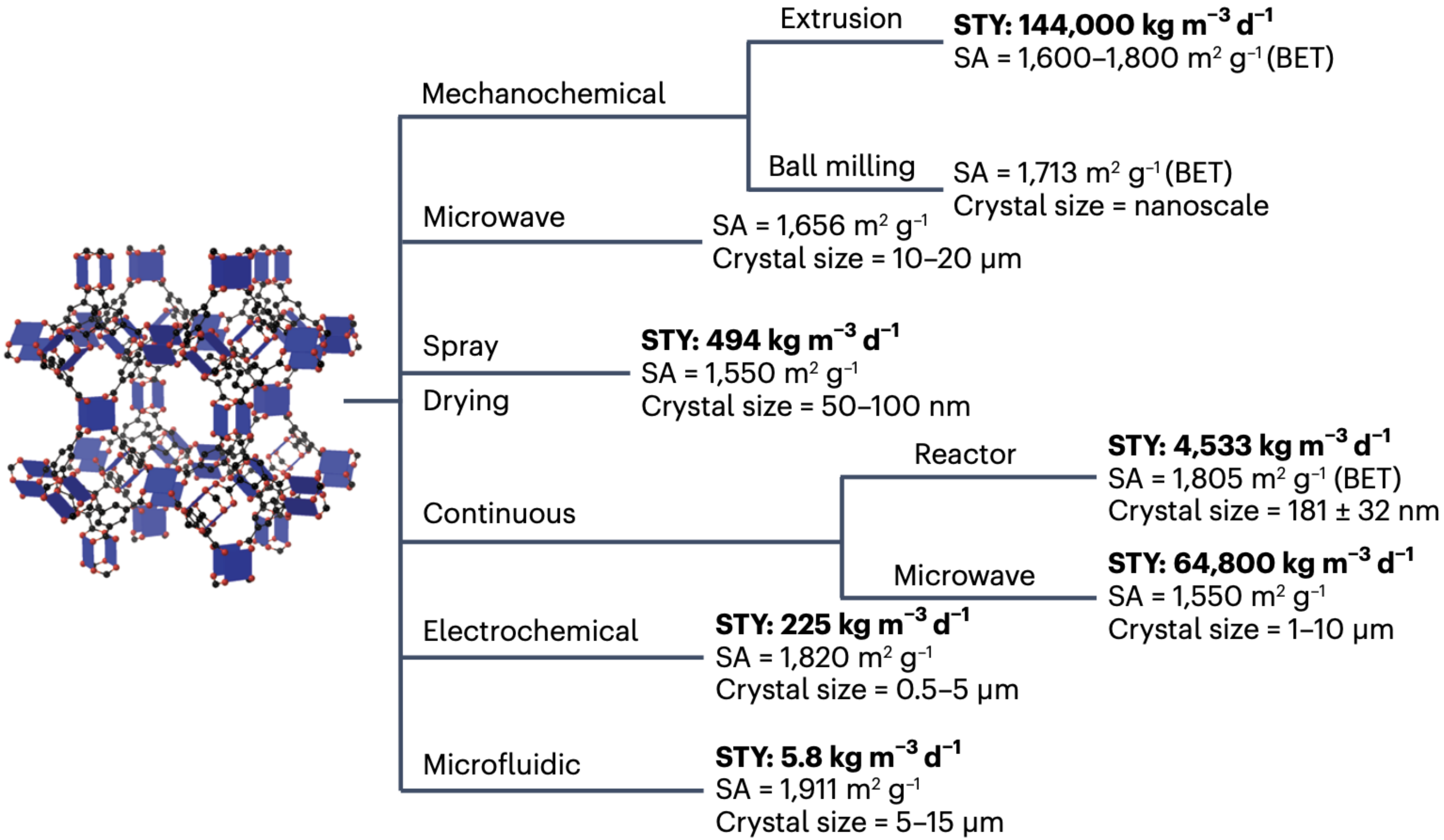
Mechanochemistry

Porous Organic Cage via TSE



Chem. Sci., 2020,11, 6582-6589

PCP/MOF in the world



Nature Materials | Volume 24 | February 2025 | 178–187

Venture Companies for PCP/MOF in the world

MOF Technologies Adsorbent Nanomaterials
UK (2012~)
Queen's University Belfast

ProfMOF
Norway (2013~)
University of Oslo

MOFapps MOF Application Services
Norway (2013~)
University of Oslo, Norway
CNRS Lyon, France

atomis
Japan (2015~)
Kyoto University

ACSYNAM
Canada (2016~)
McGill University

MOFgen
UK (2013~)
University of St Andrews

framergy™
USA (2011~)
Texas A&M University

Immaterial
UK (2015~)
Cambridge University

NuMat TECHNOLOGIES
USA (2012~)
Northwestern University

Tarsis Technology
UK (2016~)
Cambridge University

inmondo tech
USA (2013~)
Georgia Institute of Technology

Axel'One
France (2018~)
University of Lyon

novoMOF
Swiss (2017~)
Swiss Federal Institute of Technology in Zurich (ETH Zurich)
Paul Scherrer Institute(PSI)
École Polytechnique Fédérale de Lausanne (EPFL)

UniSieve
Swiss (2018~)
Swiss Federal Institute of Technology in Zurich (ETH Zurich)

MOF WORX
Australia (2014~)
the Commonwealth Scientific and Industrial Research Organisation (CSIRO)

mosaic materials
USA (2014~)
University of California, Berkeley

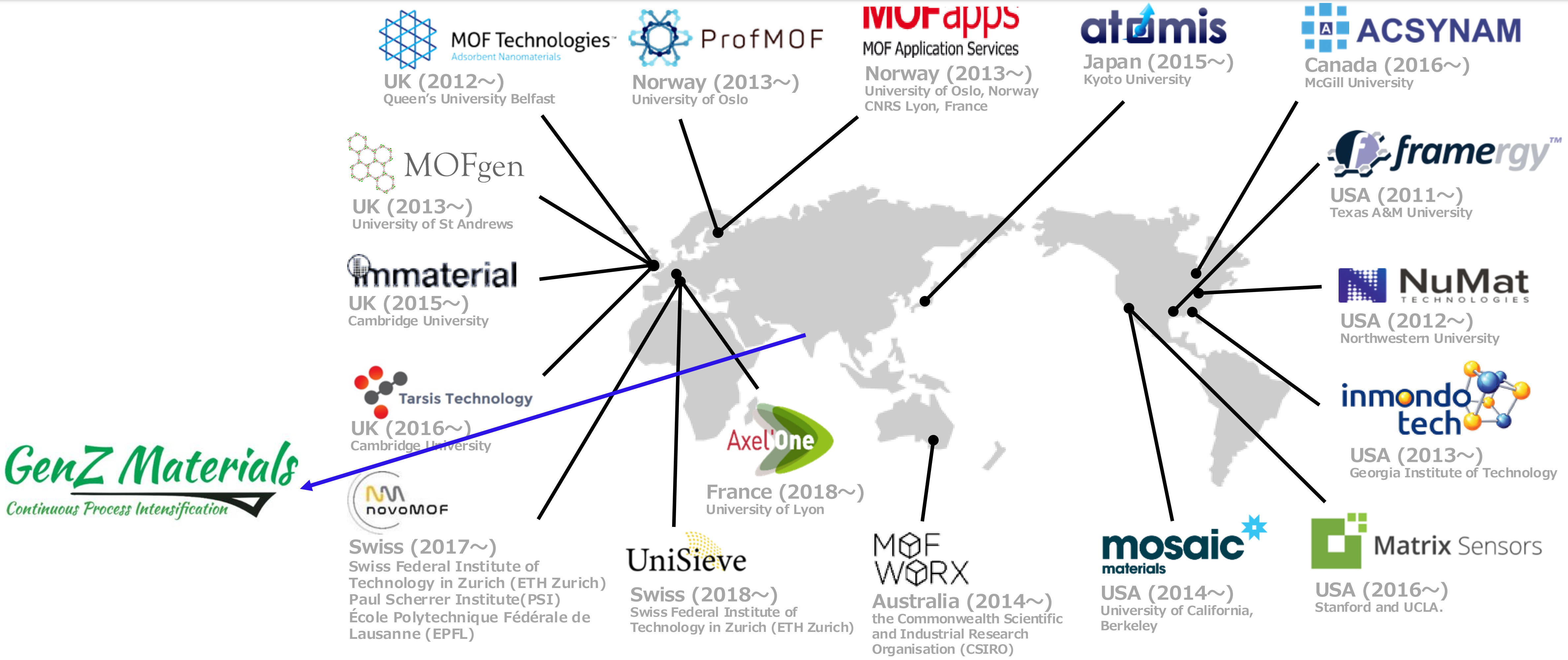
Matrix Sensors
USA (2016~)
Stanford and UCLA.

- 17 start-ups (US:5、UK:4、JPN:1、AUS:1, CAN:1, FRA:1)
- Commercialization by NuMat TECH. and MOF Tech.

NuMat TECHNOLOGIES: Safty cylinder for specific gases in Semicondutor(ION-X)
MOF Technologies: Materials for keeping fruits and vegetables fresh (TrPick^{TM})

Prof. Nagarkar

Venture Companies for PCP/MOF in the world



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NuMat TECHNOLOGIES: Safty cylinder for specific gases in Semicondutor(ION-X)

MOF Technologies: Materials for keeping fruits and vegetables fresh (TrPick™)

Prof. Nagarkar

Mechanochemistry

Mechanochemists want to shake up industrial chemistry

Using mechanical force to drive reactions offers greener routes to molecules, but chemists need to demonstrate that mechanochemistry can work on industrial scales

by ***Fernando Gomollón-Bel, special to C&EN***

August 11, 2022 | A version of this story appeared in **Volume 100, Issue 28**

Credit: MOF Technologies

Researchers at MOF Technologies work with extruders to use mechanochemistry to develop new materials.

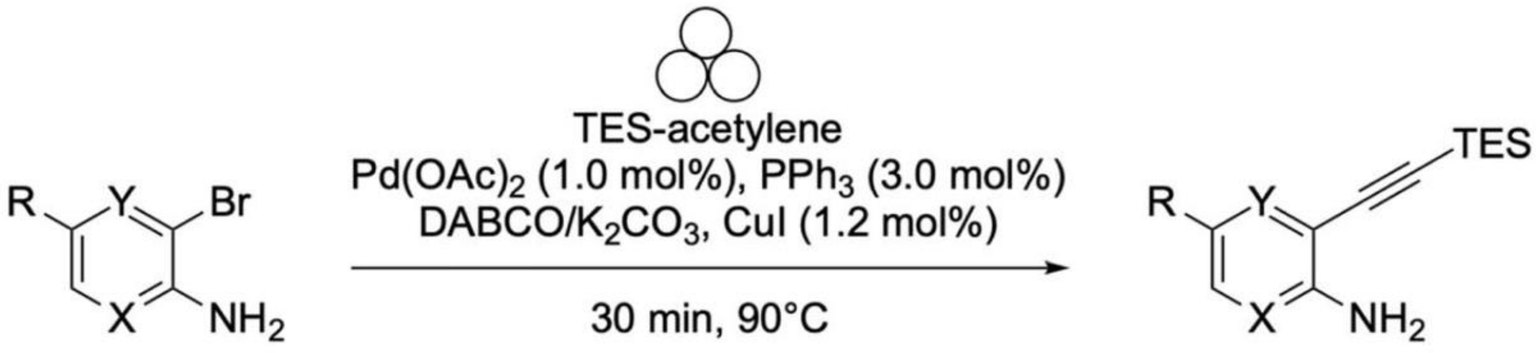
MOST POPULAR IN SYNTHESIS

- **Mechanochemical reaction oxidizes C–H bonds in polymers**
- **Five-membered aryne thought to be impossible synthesized in nickel complex**
- **The elements of a green catalyst**
- **Chemistry in Pictures: Fluorescent filtration**
- **COX-2 radiotracer could pinpoint very early stages of neurodegenerative diseases**

MOF Technologies, based in Belfast, Northern Ireland
15kg/hr MOF

Mechanochemistry

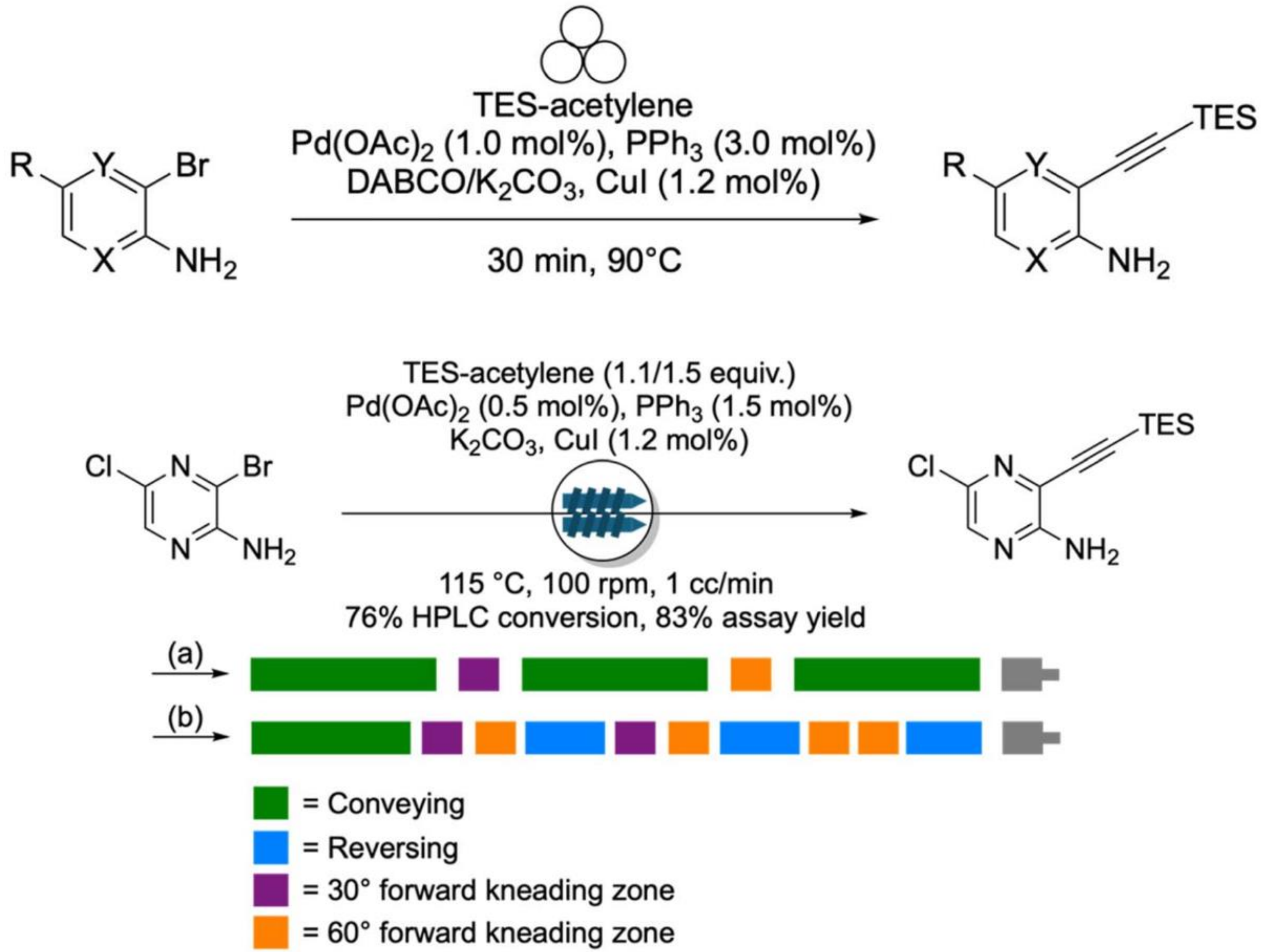
Transition metal-catalysed reactions



Hastings et al. Org. Process Res. Dev., 2023, 27, 1667–1676

Mechanochemistry

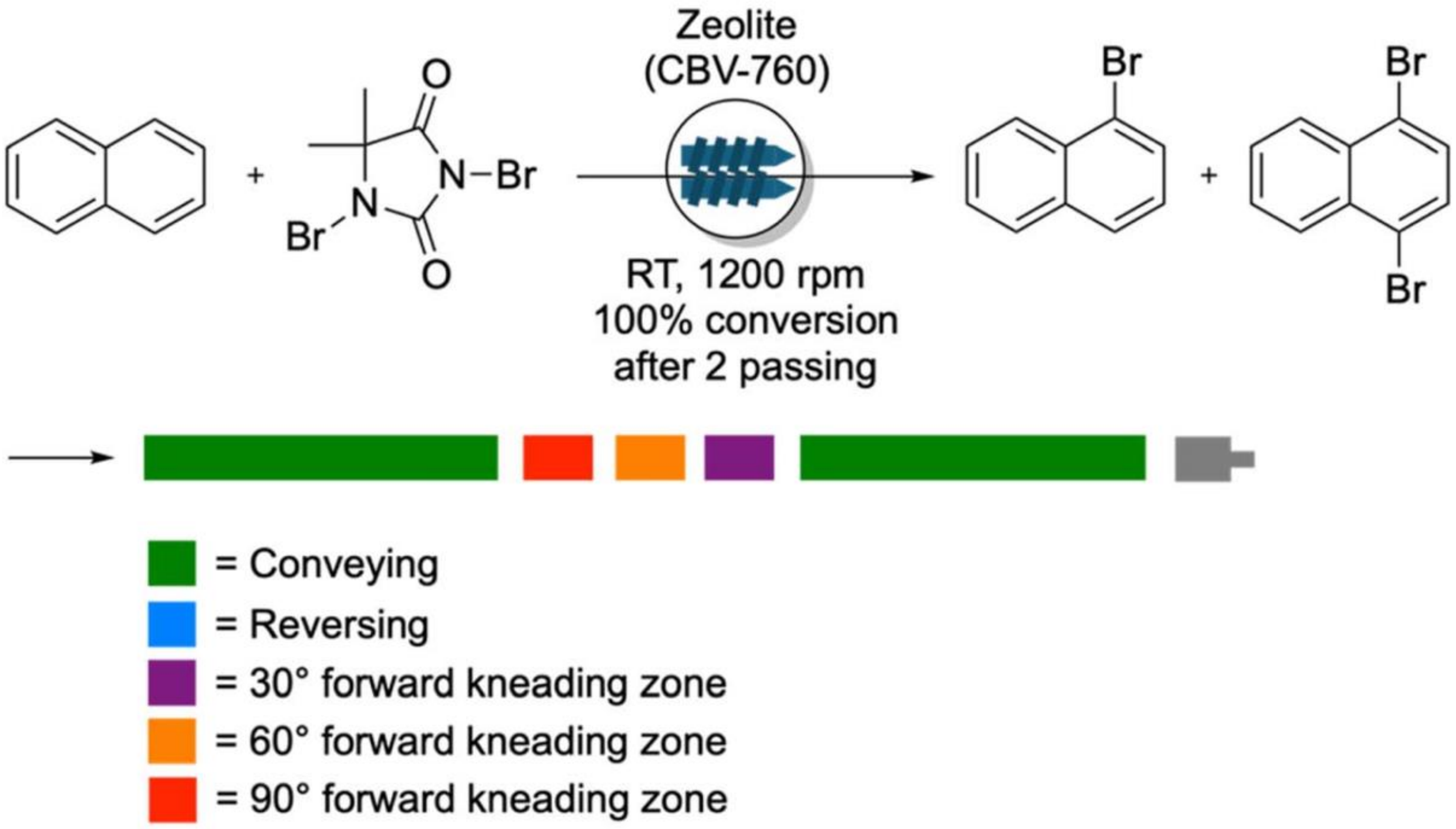
Transition metal-catalysed reactions



Hastings et al. Org. Process Res. Dev., 2023, 27, 1667–1676

Mechanochemistry

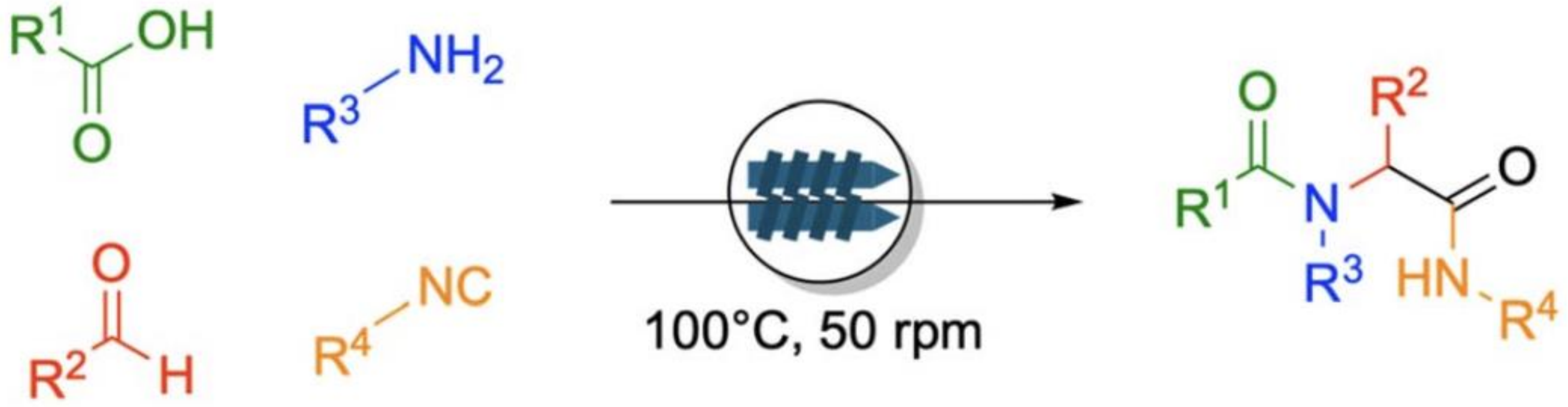
Bromination



Ardila-Fierro et al. Chem.:Methods, 2022, 2, e202200035

Mechanochemistry

Multicomponent reaction (MCRs)



Crawford, D. E.; James, S. L. A Reflection on Synthesis by Extrusion Ten Years on: Achievements, Challenges and Opportunities for Solvent-free, Sustainable, Continuous Chemical Manufacturing (Commentary), Chem. Sci. 2026, 17 (18), 8823 [DOI: 10.1039/D6SC90085B]

Mechanochemistry

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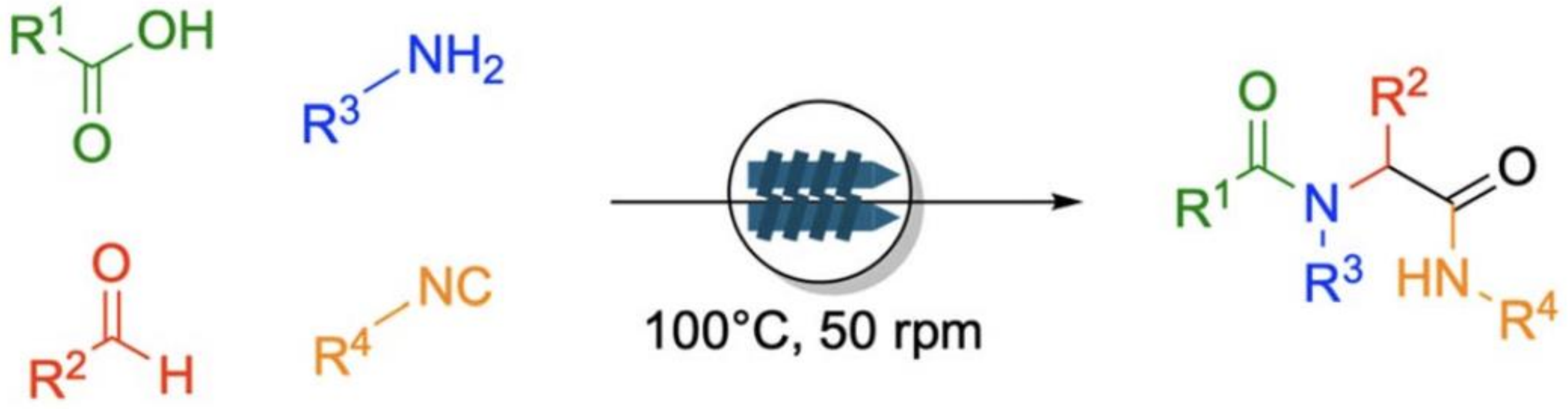

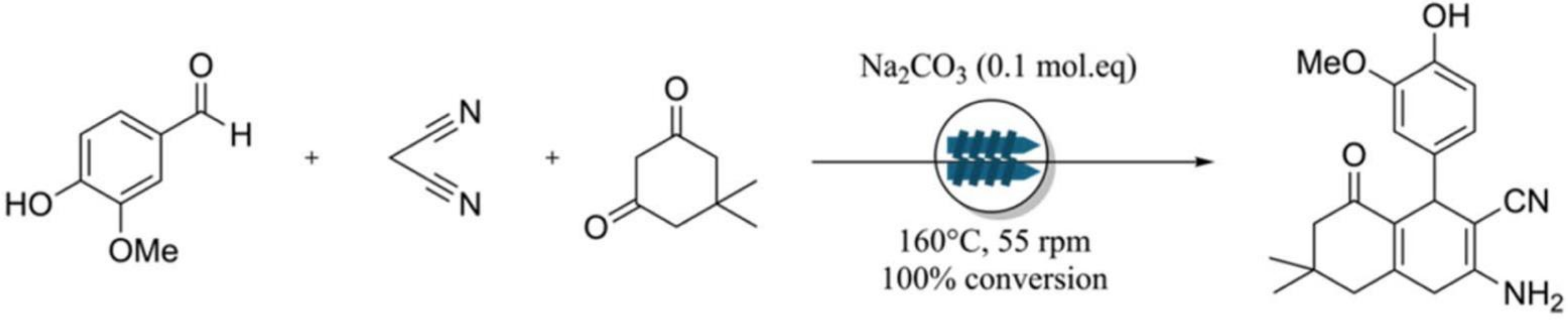

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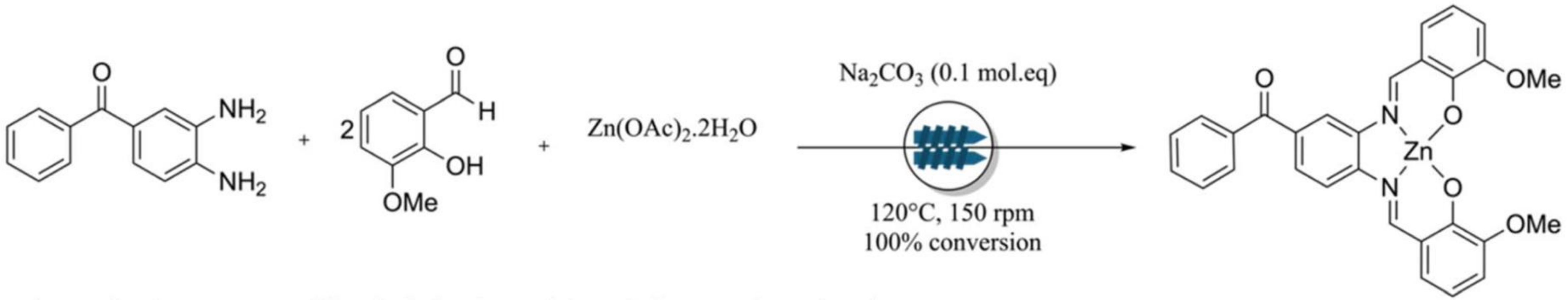

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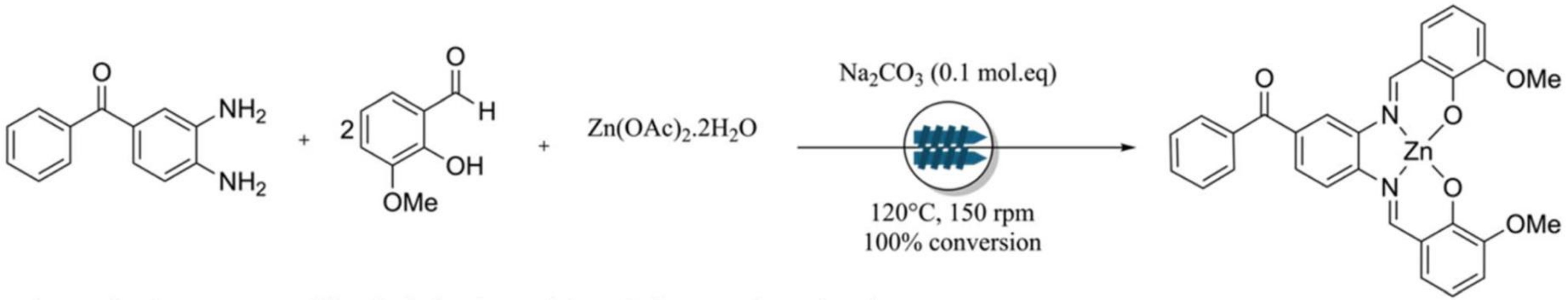

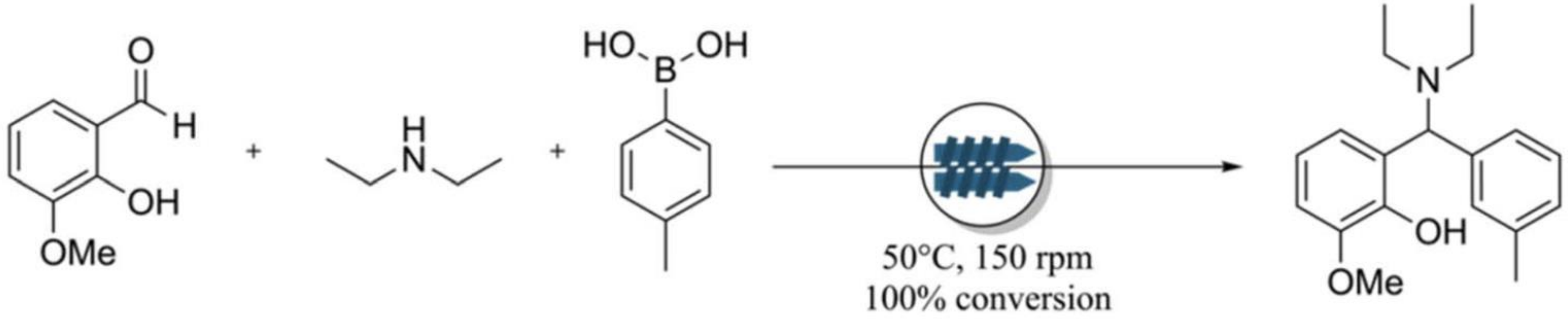

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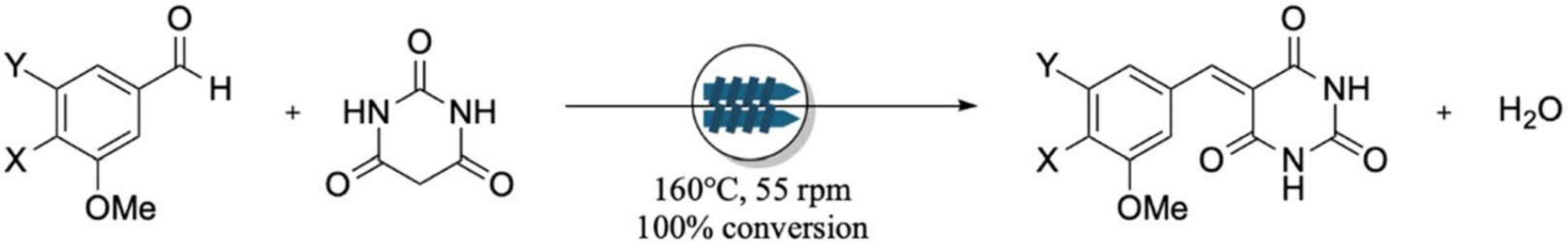
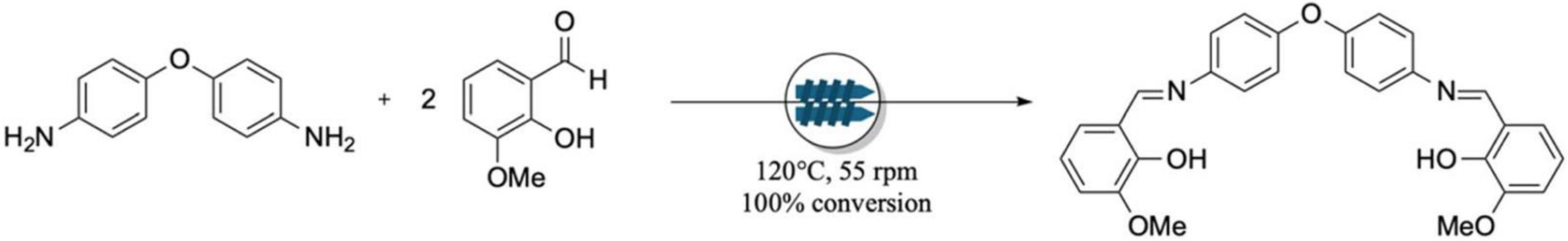
Mechanochemistry

Condensation reaction

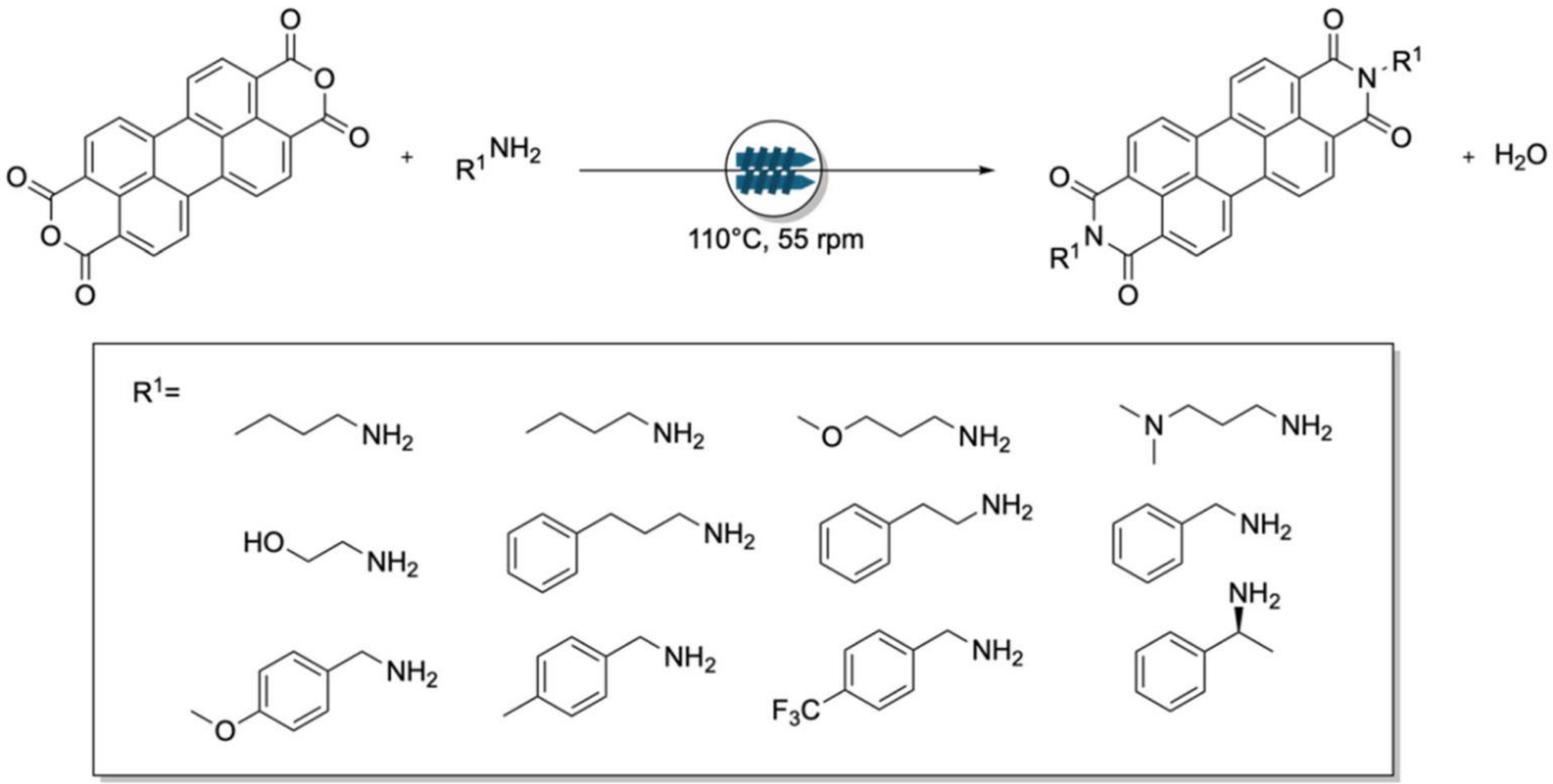




Crawford, D. E.; James, S. L. A Reflection on Synthesis by Extrusion Ten Years on: Achievements, Challenges and Opportunities for Solvent-free, Sustainable, Continuous Chemical Manufacturing (Commentary), Chem. Sci. 2026, 17 (18), 8823 [DOI: 10.1039/D6SC90085B]

Mechanochemistry

Condensation reaction: Perylene Based Dyes



Crawford, D. E.; James, S. L. A Reflection on Synthesis by Extrusion Ten Years on: Achievements, Challenges and Opportunities for Solvent-free, Sustainable, Continuous Chemical Manufacturing (Commentary), Chem. Sci. 2026, 17 (18), 8823 [DOI: 10.1039/D6SC90085B]

Mechanochemistry

nature chemistry

Article

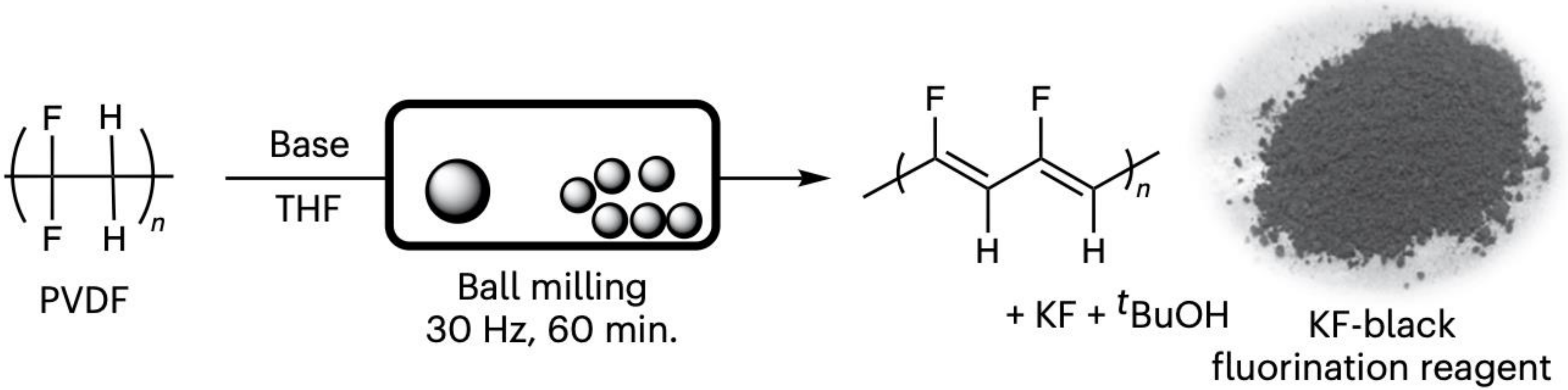
https://doi.org/10.1038/s41557-025-01855-3

Mechanochemical pathway for converting fluoropolymers to fluorochemicals

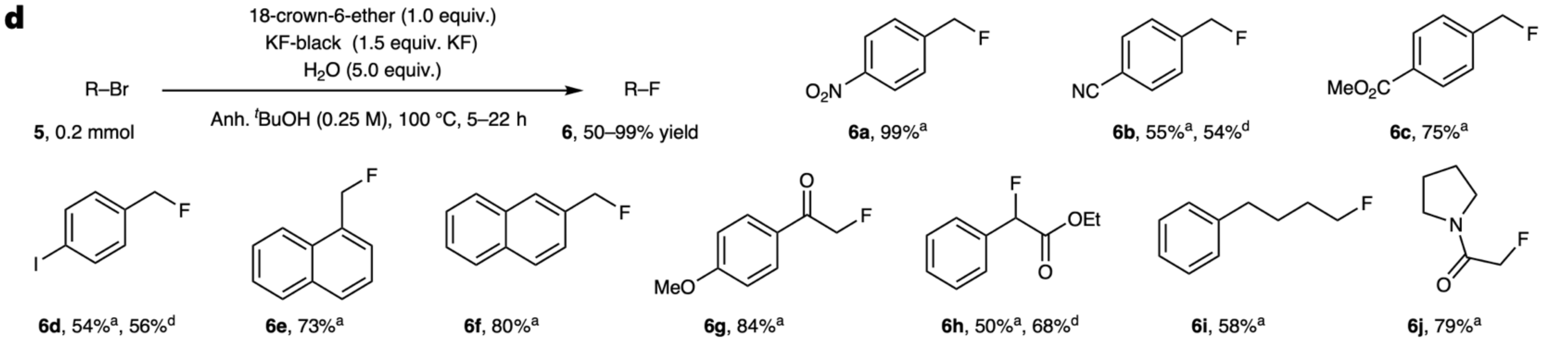
Received: 10 July 2024

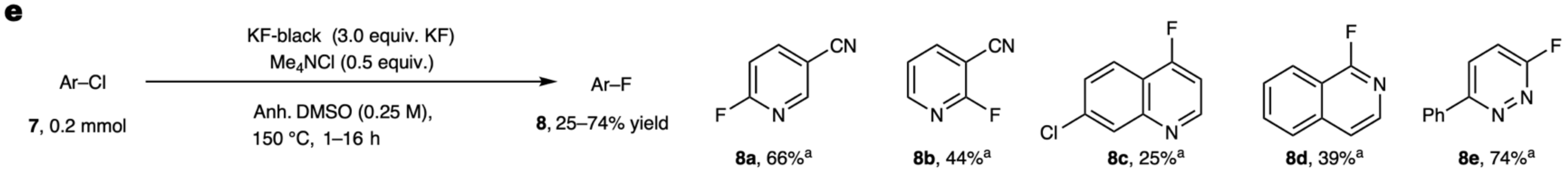
Accepted: 19 May 2025

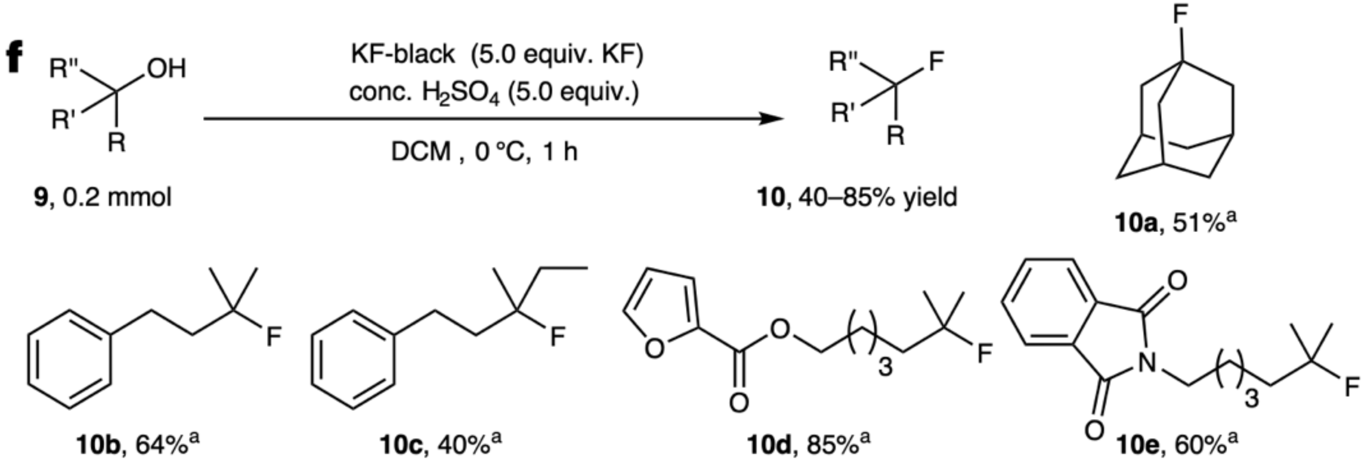
Masashi Hattori[1,3], Debarshi Saha[2,3], Muhamad Zulfaqar Bacho[2] & Norio Shibata[1,2]

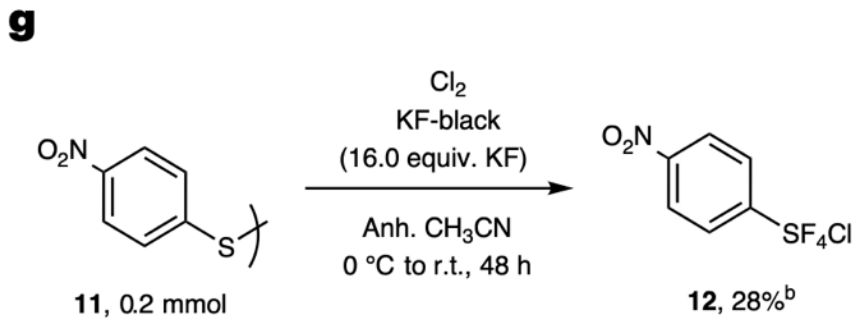


Mechanochemistry









Mechanochemistry

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Single-pot mechanochemically-enabled fluorine atom closed-loop economy using PFASs as fluorinating agents

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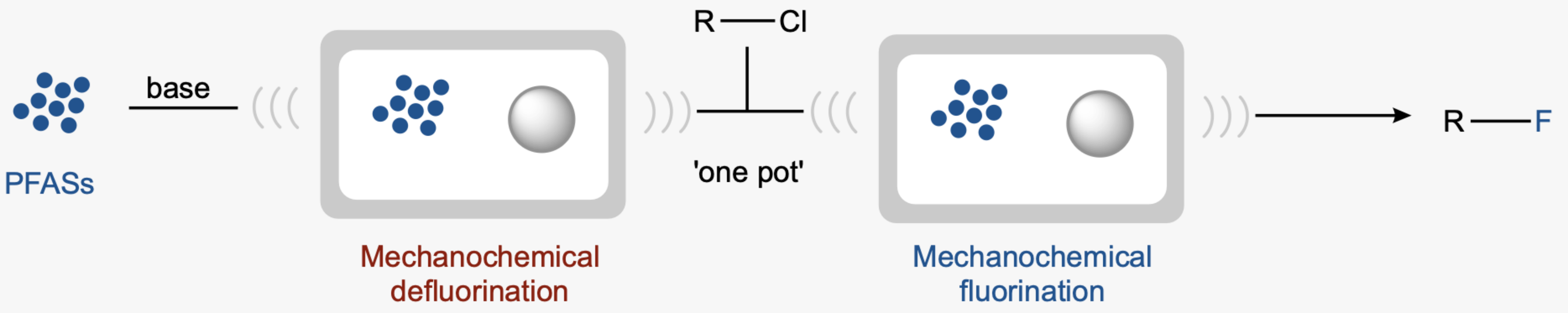
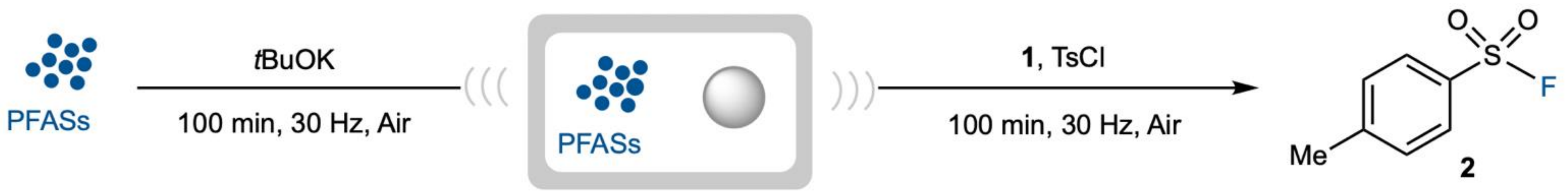


- one-pot defluorination-fluorination process for PFASs treatment
- solvent and column-free
- commercial and daily plastics
- scale up to 10 grams
- compatible with PTFE

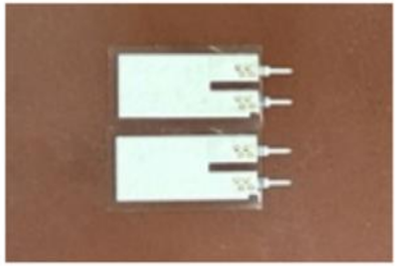
Mechanochemistry

Mechanochemical Recycling of PFASs for SuFEx



a) Robustness of the mechano-recycling of PFASs

38, Sewage filter
93%



39, Sensor
94%

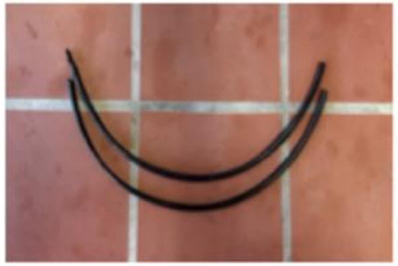
40, Transfer membrane
98%

41, PVDF rod
92%

42, Infusion tube
97%

43, PVDF plate
85%

44, Filter membrane
96%



45, Plastic pipe
95%

End-consumer waste
90% (940 mg)

Continuous Process Intensification

Mechanochemistry: The Oldest Real Chemistry

Anil Kumar