

# Green Chemistry

Cutting-edge research for a greener sustainable future

[rsc.li/greenchem](https://rsc.li/greenchem)

The Royal Society of Chemistry is the world's leading chemistry community. Through our high impact journals and publications we connect the world with the chemical sciences and invest the profits back into the chemistry community.

## IN THIS ISSUE

ISSN 1463-9262 CODEN GRCHFJ 25(12) 4581-4864 (2023)



### Cover

See Peiyuan Yao, Qiaqing Wu, Dunming Zhu *et al.*, pp. 4667–4673.

Image reproduced by permission of Peiyuan Yao from *Green Chem.*, 2023, **25**, 4667.



### Inside cover

See Paweł Mateusz Nowak, pp. 4625–4640.

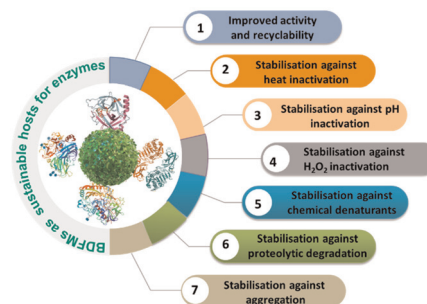
Image reproduced by permission of Paweł Mateusz Nowak from *Green Chem.*, 2023, **25**, 4625.

## CRITICAL REVIEW

4591

### Biomass-derived functional materials as carriers for enzymes: towards sustainable and robust biocatalysts

Meena Bisht,\* Sarath Kumar Thayallath, Pranav Bharadwaj, Gregory Franklin and Dibyendu Mondal\*



## PERSPECTIVE

4625

### What does it mean that “something is green”? The fundamentals of a Unified Greenness Theory

Paweł Mateusz Nowak

## Unified Greenness Theory



## Editorial Staff

### Executive Editor

Michael A. Rowan

### Deputy Editor

Vikki Pritchard

### Development Editors

Bee Hockin, Andrea Carolina Ojeda Porras

### Editorial Production Manager

Gisela Scott

### Publisher

Jeanne Andres

### Senior Publishing Editor

Robin Brabham

### Publishing Editors

Catherine Au, Isobel Darlington, Konoya Das, Alexandre Dumon, Amy Lucas, Kieran Nicholson, Charlotte Pugsley, Hugh Ryan

### Editorial Assistant

Daphne Houston

### Publishing Assistant

Robert Griffiths

For queries about submitted articles please contact Gisela Scott, Editorial Production Manager, in the first instance. E-mail [green@rsc.org](mailto:green@rsc.org)

For pre-submission queries please contact Michael A. Rowan, Executive Editor.

E-mail [green-rsc@rsc.org](mailto:green-rsc@rsc.org)

Green Chemistry electronic:

ISSN 1463-9270 is published 24 times

a year by the Royal Society of Chemistry, Thomas Graham House, Science Park, Milton Road, Cambridge, CB4 0WF, UK.

All orders, with cheques made payable to the Royal Society of Chemistry, should be sent to the Royal Society of Chemistry Order Department, Royal Society of Chemistry, Thomas Graham House, Science Park, Milton Road, Cambridge, CB4 0WF, UK  
Tel +44 (0)1223 432398; E-mail [orders@rsc.org](mailto:orders@rsc.org)

2023 Annual electronic subscription price: £2578; US\$4544. Customers in Canada will be subject to a surcharge to cover GST. Customers in the EU subscribing to the electronic version only will be charged VAT.

If you take an institutional subscription to any Royal Society of Chemistry journal you are entitled to free, site-wide web access to that journal. You can arrange access via Internet Protocol (IP) address at [www.rsc.org/ip](http://www.rsc.org/ip)

Customers should make payments by cheque in sterling payable on a UK clearing bank or in US dollars payable on a US clearing bank.

Whilst this material has been produced with all due care, the Royal Society of Chemistry cannot be held responsible or liable for its accuracy and completeness, nor for any consequences arising from any errors or the use of the information contained in this publication. The publication of advertisements does not constitute any endorsement by the Royal Society of Chemistry or Authors of any products advertised. The views and opinions advanced by contributors do not necessarily reflect those of the Royal Society of Chemistry which shall not be liable for any resulting loss or damage arising as a result of reliance upon this material. The Royal Society of Chemistry is a charity, registered in England and Wales, Number 207890, and a company incorporated in England by Royal Charter (Registered No. RC000524), registered office: Burlington House, Piccadilly, London W1J 0BA, UK, Telephone: +44 (0) 207 4378 6556.

### Advertisement sales:

Tel +44 (0) 1223 432246; Fax +44 (0) 1223 426017;

E-mail [advertising@rsc.org](mailto:advertising@rsc.org)

For marketing opportunities relating to this journal, contact [marketing@rsc.org](mailto:marketing@rsc.org)

# Green Chemistry

Cutting-edge research for a greener sustainable future

[rsc.li/greenchem](http://rsc.li/greenchem)

*Green Chemistry* focuses on cutting-edge research that attempts to reduce the environmental impact of the chemical enterprise by developing a technology base that is inherently non-toxic to living things and the environment.

## Editorial Board

### Chair

Professor Doctor Javier Pérez-Ramírez, ETH Zurich, Switzerland

### Associate Editors

Professor Aiwen Lei, College of Chemistry and Molecular Sciences, The Institute for Advanced Studies, Wuhan University, P. R. China

Dr Elsje A. Quadrelli, CNRS and CPE Lyon, France

Professor Magdalena Titirici, Imperial College London, UK

Dr Keiichi Tomishige, Tohoku University, Japan

### Members

Dr François Jérôme, University of Poitiers, France

Professor Laurel Shafer, The University of British Columbia, Canada

Dr Helen Sneddon, University of York, UK

Dr Tao Zhang, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, China

## Advisory Board

Paul Anastas, Yale University, USA

Isabel Arends, TU Delft, The Netherlands

Gregg Beckham, NREL, USA

Asim Bhaumik, Indian Association for the Cultivation of Science, India

Fabrizio Cavani, University of Bologna, Italy

Yonas Chebude, Addis Ababa University, Ethiopia

James Clark, University of York, UK

Avelino Corma, Universidad Politécnica de Valencia, Spain

Robert H Crabtree, Yale University, USA

Paul Dauenhauer, University of Minnesota, USA

Pierre Dixneuf, University of Rennes, France

James Dumesic, University of Wisconsin-Madison, USA

Peter Dunn, Pfizer, UK

Martin Eastgate, Bristol Myers Squibb, USA

Karen Goldberg, University of Washington, USA

Buxing Han, Chinese Academy of Sciences, China

Mark Harmer, SAC Technologies, USA

Milton Hearn, Monash University, Australia

Steve Howdle, Nottingham University, UK

Andrew J. Hunt, Khon Kaen University, Thailand

Graham Hutchings, Cardiff University, UK

Philip Jessop, Queen's University, Canada

C. Oliver Kappe, University of Graz, Austria

Shu Kobayashi, University of Tokyo, Japan

Mihkel Koel, Tallinn University of Technology, Estonia

Burkhard Koenig, University of Regensburg, Germany

Michael Kopach, Eli Lilly and Company, USA

Dhileep Krishnamurthy, Jubilant Ingrevia Limited, India

Walter Leitner, RWTH Aachen University, Germany

Chao-Jun Li, McGill University, Canada

Bruce Lipshutz, University of California, USA

Rafael Luque, University of Cordoba, Spain

Doug MacFarlane, Monash University, Australia

Tomoo Mizugaki, Osaka University, Japan

Regina Palkovits, RWTH Aachen, Germany

Alvise Perosa, Università Ca Foscari, Italy

Martina Peters, Bayer AG, Germany

Martyn Poliakoff, University of Nottingham, UK

Colin Raston, Flinders University, Australia

Roberto Rinaldi, Imperial College London, UK

Robin D. Rogers, McGill University, Canada

Gadi Rothenberg, University of Amsterdam, The Netherlands

Susannah Scott, University of California, USA

Roger Sheldon, Delft University of Technology, The Netherlands

Christian Stevens, Ghent University, Belgium

Natalia Tarasova, Mendeleev University of Chemical Technology, Russia

Rajender Varma, US Environmental Protection Agency, USA

Peter Wasserscheid, Friedrich-Alexander Universität Erlangen-Nürnberg, Germany

Tom Welton, Imperial College London, UK

Kevin C. W. Wu, National Taiwan University, Taiwan

Ganapati D. Yadav, Institute of Chemical Technology, India

Hisao Yoshida, Kyoto University, Japan

Suojiang Zhang, Institute of Process Engineering, Chinese Academy of Sciences, China

Julie Zimmerman, Yale University, USA

Vânia Zuin, Federal University of São Carlos, Brazil

## Information for Authors

Full details on how to submit material for publication in Green Chemistry are given in the Instructions for Authors (available from <http://www.rsc.org/authors>). Submissions should be made via the journal's homepage: [rsc.li/greenchem](http://rsc.li/greenchem)

Authors may reproduce/republish portions of their published contribution without seeking permission from the Royal Society of Chemistry, provided that any such republication is accompanied by an acknowledgement in the form: (Original Citation)–Reproduced by permission of the Royal Society of Chemistry.

This journal is © The Royal Society of Chemistry 2023.

Apart from fair dealing for the purposes of research or private study for non-commercial purposes, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988 and the Copyright and Related Rights Regulation 2003, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the Publishers or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency in the UK. US copyright law is applicable to users in the USA.

Registered charity number: 207890



4641

### Inverse vulcanization of elemental sulfur catalyzed by trialkyl amines

Jae Hyuk Hwang, Ji Mok Lee, Jong Hwi Seo, Guk Yun Noh, Wonmoo Byun, Seonggeon Kim, Woohwa Lee, Sungmin Park,\* Dong-Gyun Kim\* and Yong Seok Kim\*

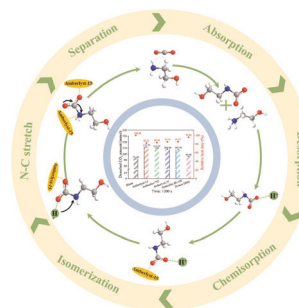
#### Facile and Fast Inverse Vulcanization of Elemental Sulfur (ES) using Unreactive Crosslinkers under Eco-friendly Trialkyl Amines (TAAs) Catalysis



4647

### Evaluation of hybrid amines and alcohol solvent with ion-exchange resin catalysts for energy-efficient CO<sub>2</sub> capture

Qiang Sun, Jia Xiong, Hongxia Gao,\* Teerawat Sema, Wilfred Olson and Zhiwu Liang\*



4656

### An electrochemical-enabled cascaded cyclization of enamines with potassium thiocyanate and alcohols to access 2-alkoxythiazoles

Dandan Li,\* Long Chen, Yang Jin, Xiaochen Wang, Long Liu, Yilin Li, Gongyuan Chen, Guanhao Wu, Yujie Qin, Leilei Yang, Mengke Wang, Lulu Zhao, Zhihong Xu and Jiangwei Wen\*

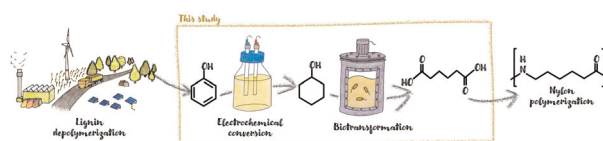


- Metal, external redox reagent free
- Three-component cascade reaction
- Cleavage of C-N bond and high effective construction of C-N/C-O/C-S bonds in one pot

4662

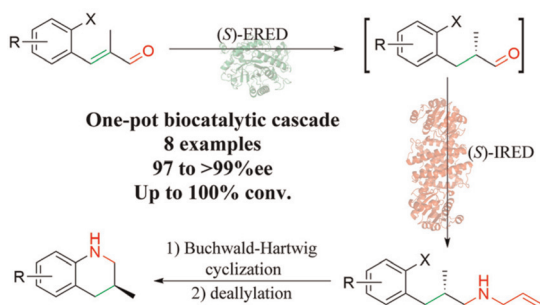
### Integrated electrosynthesis and biosynthesis for the production of adipic acid from lignin-derived phenols

Micjel Chávez Morejón, Alexander Franz, Rohan Karande\* and Falk Harnisch\*



## PAPERS

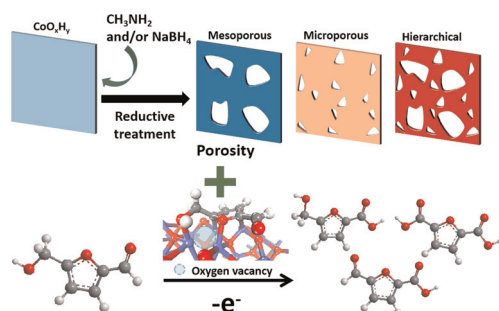
4667



### Chemo-enzymatic synthesis of chiral 3-substituted tetrahydroquinolines by a sequential biocatalytic cascade and Buchwald–Hartwig cyclization

Zefei Xu, Jinhui Feng, Peiyuan Yao,\* Qiaqing Wu\* and Dunming Zhu\*

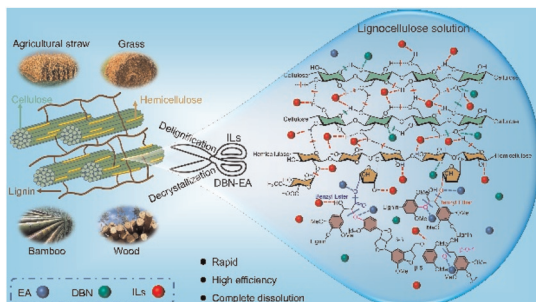
4674



### Room-temperature fabrication of defective CoO<sub>x</sub>H<sub>y</sub> nanosheets with abundant oxygen vacancies and high porosity as efficient 5-hydroxymethylfurfural oxidation electrocatalysts

Ruyi Zhong, Puwei Wu, Qi Wang, Xiting Zhang, Lei Du, Yunhua Liu, Huakang Yang, Meng Gu, Z. Conrad Zhang, Limin Huang\* and Siyu Ye\*

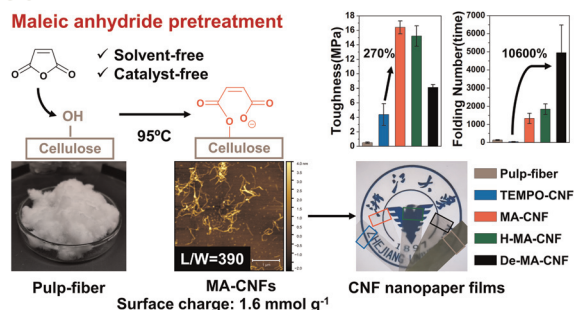
4685



### Robust ionic liquid/ethanolamine-superbase solvents enable rapid, efficient and mild dissolution of lignocellulosic biomass

Yang Wang, Huan Wang, Lan Chen, Weitao Wang, Zhaohui Yang, Zhimin Xue\* and Tiancheng Mu\*

4696



### Eco-friendly cellulose nanofibrils with high surface charge and aspect ratio for nanopaper films with ultrahigh toughness and folding endurance

Da Zhang, Kexia Jin, Khak Ho Lim, Suyun Jie, Wen-Jun Wang and Xuan Yang\*

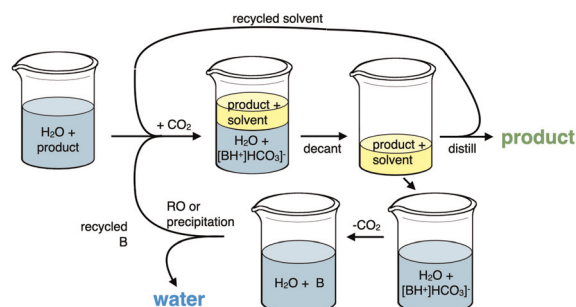


## PAPERS

4705

### A CO<sub>2</sub>-responsive method for separating hydrophilic organic molecules from aqueous solutions: solvent-assisted switchable water

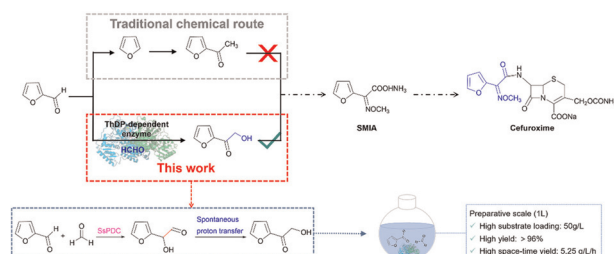
Vanessa Saab Liberato, Tatiana Felix Ferreira, Alex Redmond MacDonald, Bernardo Dias Ribeiro, Maria Alice Zarur Coelho and Philip G. Jessop\*



4713

### Biosynthesis of 2-furylhydroxymethylketone, an intermediate of cefuroxime, from furfural and formaldehyde using a ThDP-dependent enzyme

Xianghe Zhang, Hao Wei, Xinlin Wei, Tengting Qi, Xinrui Zong, Zixi Liu, Jie Qin, Xiuzhen Gao,\* Gengxiu Zheng\* and Qinyuan Ma\*



4723

### High-purity polypropylene from disposable face masks via solvent-targeted recovery and precipitation

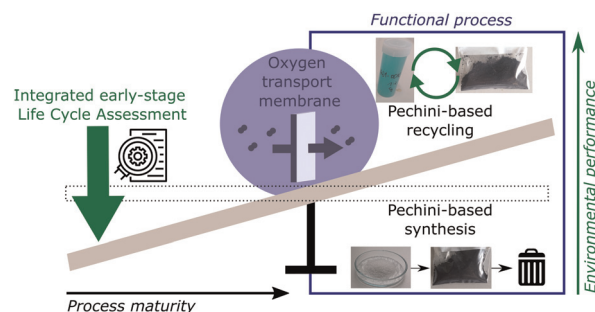
Jiuling Yu, Aurora del Carmen Munguía-López, Victor S. Cecon, Kevin L. Sánchez-Rivera, Kevin Nelson, Jiayang Wu, Shreyas Kolapkar, Victor M. Zavala, Greg W. Curtzwiler, Keith L. Vorst, Ezra Bar-Ziv and George W. Huber\*



4735

### Recycling process development with integrated life cycle assessment – a case study on oxygen transport membrane material

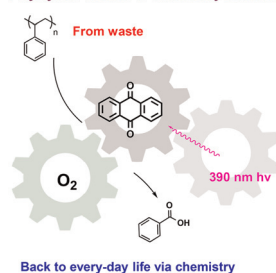
Melanie Johanning, Marc Widenmeyer,\* Giamper Escobar Cano, Vanessa Zeller, Sebastian Klemenz, Guoxing Chen, Armin Feldhoff and Anke Weidenkaff





4750

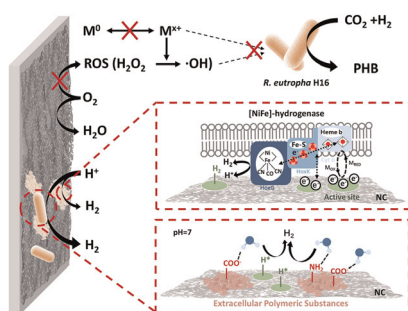
## Photochemical Aerobic Upcycling of Polystyrene Plastics to Commodity Chemicals



## Photochemical aerobic upcycling of polystyrene plastics to commodity chemicals using anthraquinone as the photocatalyst

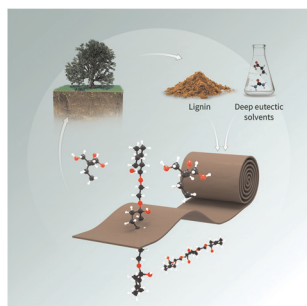
Nikolaos F. Nikitas, Elpida Skolia, Petros L. Gkizis, Ierasia Triandafillidi and Christoforos G. Kokotos\*

4760

Efficient  $CO_2$  conversion by biocompatible N-doped carbon nanosheets coupled with *Ralstonia eutropha*: synergistic interactions between microbial and inorganic catalysts

Jiani Yao, Youzhi Li, Siyuan Xiu, Shujie Zheng, Ying Huang, Zijing Zhou, Yang Hou, Bin Yang, Lecheng Lei and Zhongjian Li\*

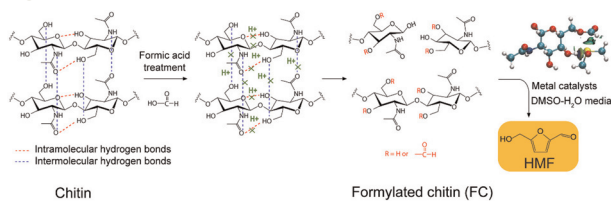
4769



## A lignin-based membrane fabricated with a deep eutectic solvent

Abaynesh Yihdego Gebreyohannes, Sandra L. Aristizábal, Liliana Silva, Eyad A. Qasem, Stefan Chisca, Lakshmeesha Upadhyaya, Daniyah Althobaiti, João A. P. Coutinho and Suzana P. Nunes\*

4781



## Efficient conversion of chitin into 5-hydroxymethylfurfural via a simple formylation step under mild conditions

Chunxiao Gong, Zhaoyang Ju, Kuichuan Sheng and Ximing Zhang\*

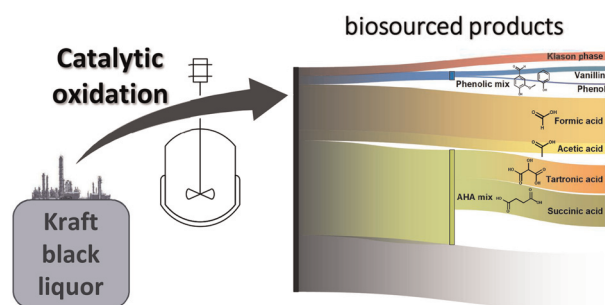


## PAPERS

4793

**Potential of catalytic oxidation of kraft black liquor for the production of biosourced compounds**

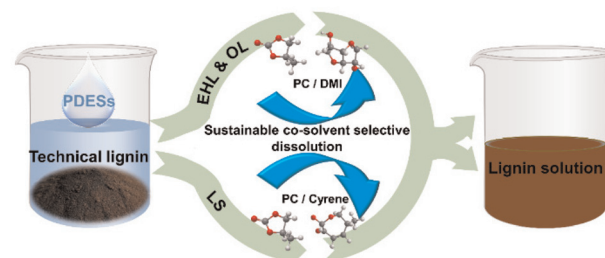
Léa Vilcocq,\* Nicolas Chaussard, Antonio Hernández Mañas, Olivier Boyron, Manel Taam, Frédérique Bertaud, Pascal Fongarland and Laurent Djakovitch\*



4808

**Sustainable polar aprotic/poly-deep eutectic solvent systems for highly efficient dissolution of lignin**

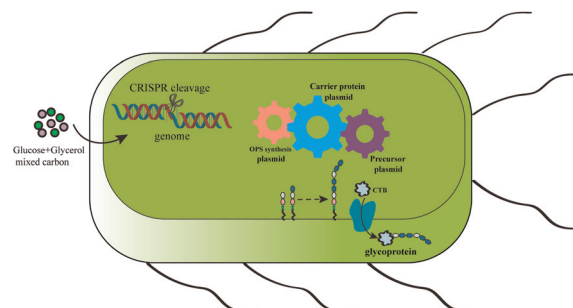
Qiaoling Liu, Yang Wang, Jing Bian, Ming-Fei Li, Jun-Li Ren, Xiang Hao\* and Feng Peng\*



4818

**Sustainable production of a polysaccharide-based glycoprotein by simultaneous conversion of glucose and glycerol in engineered *Escherichia coli***

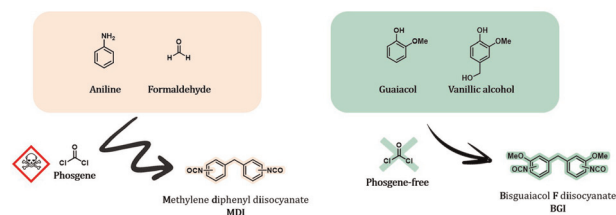
Yuhui Wang, Xiaohan Wang, Guozhen Ma, Lijie Xie, Dan Liu, Yanling Wang, Xinyu Zhao, Yingying Su, Andrei V. Perepelov, Peng Ding, Xiao Zhang, Bo Xu, Bin Liu\* and Di Huang\*



4833

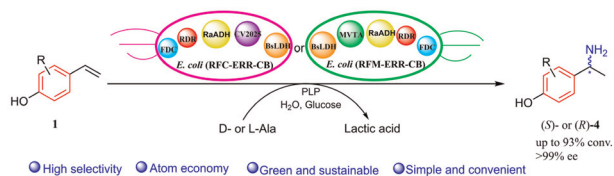
**Lignin-based bisguaicol diisocyanate: a green route for the synthesis of biobased polyurethanes**

Sébastien Lemouzy, Aliénor Delavarde, Frédéric Lamaty, Xavier Bantreil, Julien Pinaud and Sylvain Caillot\*



## PAPERS

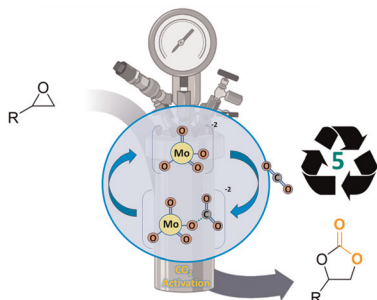
4840



### Biocatalytic formal regio- and enantioselective Markovnikov hydroamination of aryl alkenes to chiral amines

Qi Jin, Jingqi Zhang, Shuangping Huang, Lili Gao, Honghong Chang and Jiandong Zhang\*

4849



### Molybdate ionic liquids as halide-free catalysts for CO<sub>2</sub> fixation into epoxides

Nicola Bragato, Alvise Perosa, Maurizio Selva, Giulia Fiorani\* and Roberto Calmanti\*

## CORRECTION

4861

### Correction: Sustainable pathway to furanics from biomass via heterogeneous organo-catalysis

Sanny Verma, R. B. Nasir Baig, Mallikarjuna N. Nadagouda, Christophe Len and Rajender S. Varma\*

